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THE PRECAMBRIAN GEOLOGY AND SKARN IRON ORES OF THE RAUTUVAARA AREA, NORTHERN FINLAND

by

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with 69 figures and 16 tables in the text and 2 maps

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The lowermost lithostratigraphic unit in the Rautuvaara area is the Niesakero—Kuertunturi quartzite complex composed of sillimanite-bearing gneissose quartzites, arkosic quartzites and orthoquartzites with gneiss and amphibolite interlayers. The basement of deposition for this quartzite complex probably consists of Archean granite gneiss. Overlying this complex in the central part of the area are the basaltic metavolcanites, quartz-feldspar schists, graphite-bearing schists, carbonate and skarn rocks of the Rautuvaara Formation and their associated magnetite deposits. The Kolari Greenstone Formation in the southern part of the area and the Siekkijoki Greenstone Formation in the west contain chiefly mafic and intermediate metavolcanites together with lesser amounts of graphite-bearing schists, chert, carbonate and skarn rocks. No direct observations are available on the relations between the Rautuvaara Formation and the greenstone formations, although they all seem to lie close to one another stratigraphically. The uppermost lithostratigraphic units in the Rautuvaara area are the Tapojärvi Quartzite Formation in the west and the comparable Luosujoki conglomerate and Yllästunturi quartzite in the east. The former contains mainly sericite quartzite with conglomerate interbeds in its lower part and phyllite and mica schist in the upper part.

The folding which dominates the structure of the Rautuvaara area has taken place in relation to a NE—SW-oriented axis. The rocks of the monzonite intrusion in the central area penetrated onto those of the Rautuvaara Formation and into the upper part of this formation approx. 1860 Ma ago, during the main phase of fold activity. The younger microcline granites and pegmatites intruded after folding had taken place. Eleven skarn iron ore deposits are known in the Rautuvaara area. With only one exception, these are associated with the Rautuvaara Formation itself. The skarn ores take the form of plate-like lenses oriented in the direction of lineation. In addition to magnetite the ores contain varying amounts of pyrite, pyrrhotite and chalcopyrite. The copper content reaches economic significance as an addition to the iron in some ore bodies.

These skarn ores were formed metasomatically after the monzonite intrusion under the influence of fluids transporting ore components. The multi-stage metasomatic reactions involved crystallization of the skarn minerals normally prior to that of the ore minerals, amongst which the magnetite and pyrite crystallized before the pyrrhotite and chalcopyrite. A date of approx. 1800 Ma is obtained for the zircon in the skarn.

Key words: stratigraphy, structure, skarn, ore deposits, iron, geochemistry, genesis, Precambrian, northern Finland.

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PREFACE

The skarn iron ores of the Rautuvaara area represent the largest known iron ore reserves in Finland at the present time, amounting to 100 million tonnes according to the latest inventory. The Finnish steel company Rautaruukki Oy has been carrying out extensive research into the iron ore reserves of this area since the mid-1970's, and also began mining in the area in 1975, with an annual production of approx. 500,000 tonnes of magnetite concentrates. The majority of the known iron ore bodies in the area are so small and of such a low iron content, however, that economic exploitation would not seem feasible. Their economic viability is further hampered by the facts that only a small proportion of the ore is accessible to opencast mining and that the resulting magnetite concentrates have to be transported a distance of almost 500 km by rail to the steel works at Raahe.

The aim of the present work is to describe the known skarn iron ore deposits of the Rautuvaara area and their geological environment and to examine the genesis of these ores. As the deposits in question are of the strata-bound type and the ore occurrences are obviously structurally controlled, it is also essential to determine the main features of the lithostratigraphy and geological structure of the area. The first part of the work therefore deals with lithostratigraphical and structural questions related to the whole Rautuvaara area and makes certain comparisons, mainly with stratigraphical interpretations put forward for Northern Sweden. The latter part concentrates on the geological, geochemical and mineralogical description of the skarn iron ores of the Rautuvaara area and presents conclusions concerning their genesis.

PART I: LITHOSTRATIGRAPHY, STRUCTURE AND AGE OF THE BEDROCK IN THE RAUTUVAARA AREA

INTRODUCTION

Location and physiography of the area

The area concerned is located in the western part of Finnish Lapland, extending as far as the Finland—Sweden border (Fig. 1). It has a surface area of approx. 900 km^2 and comprises the northern part of the commune of Kolari and the southern part of that of Muonio. Its eastern boundary is marked by Yllästunturi, with its summit at a height of over 700 m a.s.l., and further north Kukastunturi, some 250 m lower. The central part of the area is composed of undulating hilly terrain with summits normally in the range 250—450 m a.s.l. The southern part of the area is broad, flat mire terrain lying at a height of approx. 140 m a.s.l., and extensive mires are also to be found in the extreme

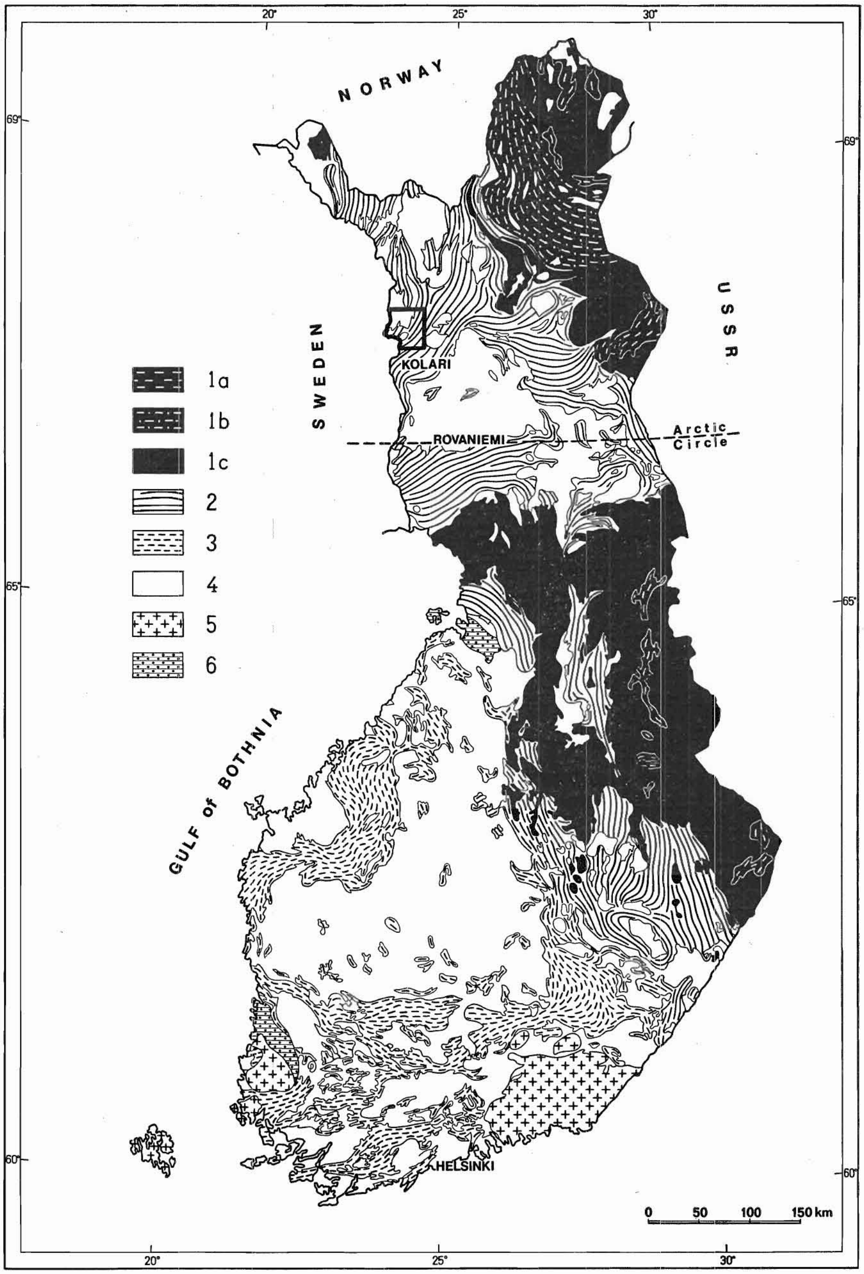

Fig. 1. Main structural units of the Precambrian in Finland, after Simonen (1980). The Rautuvaara (Kolari) area is delimited by heavy lines.

Pre-svecokarelidic: 1a = schist and paragneiss; 1b = granulite; 1c = orthogneiss. *Svecokarelidic:* 2 = Karelidic schist belt; 3 = Svecofennidic schist belt; 4 = orogenic plutonic rocks. *Post-svecokarelian:* 5 = rapakivi granites; 6 = Jotnian sediments.

west, in the vicinity of the border with Sweden.

The incidence of exposed bedrock varies considerably with the terrain, this being generally common on the hills and in some of the river channels, but rare in the mire areas.

Previous work on the area

Interest has been shown in ore prospecting in the Rautuvaara area on a number of occasions prior to this, largely on account of the iron ore deposit at Juvakaisenmaa, known from the late 17th century. The detailed description by Borgström (1928) of the Juvakaisenmaa iron ore and its immediate geological environment also serves as a summary of the work carried out up to that time. Borgström began his investigations in 1917, financed by the company set up to exploit the deposit, Aktiebolaget Kolari. Among the research carried out in earlier times, special mention should be made of that on the practical viability of the deposit in the 1840's (Borgström 1928).

During the Second World War, Vuoksenniska Oy carried out investigations in the area, and from 1956 to 1960 it was studied in more detail by Suomen Malmi Oy. It was during this second period that the inventory of SW-Rautuvaara was completed and that of Cu-Rautuvaara started. The patents and claims on the mine were transferred to Otanmäki Oy in 1960, and investigations were continued by this company throughout the following decade. The main target of these feasibility studies was the Rautuvaara ore. When the decision to commence mining was postponed, prospecting was extended into the surrounding area. Otanmäki Oy was amalgamated with Rautaruukki Oy in 1967, and investigations have been continuing under this company since 1970, when the decision was taken to construct a mine in the area.

The Rautuvaara area is included on the Muonio sheet of the general geological map of Finland produced by E. Mikkola in 1936 with a corresponding key to the rock types in 1941. Brief summaries of the geology and iron ores of the area have been published by T. Mikkola (1960), Schmidt (1960) and Stigzelius and Ervamaa (1962). Unpublished university dissertations, mainly concerned with individual ore deposits, have been produced by Lackschewitz (1958), Shaikh (1964), Lindberg (1976) and Kuivasaari (1980).

The work of Hiltunen and Tontti (1976) on the central part of the Rautuvaara area, which led up to the present investigations, was the first attempt at a detailed determination of the stratigraphy and structure of the area. The research reported was still in its early stages at that time, however, and a great deal of new information has been obtained since then, in addition to which the area which forms the object of this study has been extended considerably.

Recent investigations

Rautaruukki Oy resumed research in the area in 1974, after the decision had been made to open a mine at Rautuvaara. It was at this stage that the largest iron ore deposit known to date, the Hannukainen deposit, was discovered. Although this has subsequently formed the main focus of research, large-scale investigations have also been carried out in the surrounding areas.

Over 400 diamond drillholes have been drilled in the area to date, amounting to a combined length of over 65 km, and drilling is continuing. The drill core samples have then been complemented with bedrock surface samples taken by pneumatic drilling. Low-altitude airborne measurements carried out in 1975 and 1976 covered the whole of the area and local gravimetric measurements about a half of it. Systematic geophysical ground surface measurements have been carried out over an area of approx. 120 km². Geochemical investigations have been commissioned by both the Geological Survey of Finland and Rautaruukki Oy. Geological mapping was carried out in 1974—1977 with the participation of M. Tontti, T. Tukiainen, H. Mattila and the author, together with a number of surveying assistants.

The author has been responsible for directing and carrying out ore prospecting activities for Rautaruukki Oy in the area since 1974, and has had at his disposal the whole of the research material accumulated both prior to and following that date. He has also had access to the maps of the Rautuvaara mine produced by the mine's geologist, and later its manager, A. Juopperi, and also the bedrock maps for some parts of the area constructed by M. Lehtonen, geologist with the Geological Survey of Finland.

Investigation methods

The geological description of the area sets out from an examination of the lithostratigraphy using the stratigraphical classification of Hedberg (1976) where applicable. The geological and structural maps are constructed largely by reference to the mapping carried out in 1974—1977, with revisions of the fieldwork performed by the author in 1979 and 1980. The geological interpretation of the limestone deposit at Äkäsjokisuu and its immediate surroundings is obtained from the detailed mapping of Lackschewitz (1958). The map of the Taporova—Kiuaskero region is based to a great extent on information received from M. Lehtonen of the Geological Survey of Finland. The author has only checked certain minor points in the field in the case of these areas.

In addition to the geological interpretation of the outcrop data and bedrock information obtained by drilling, interpretations are also made use of from the extensive geophysical material compiled by A. Hattula, geophysicist with Rautaruukki Oy. Use is made aero-geophysical and surface geophysical readings obtained by both the Geological Survey and Rautaruukki Oy.

The principal methodology employed in the second part of this paper, which concentrates on the petrographical description of the ore deposits, is the detailed scrutiny of an extensive amount of drill core material. Information gleaned from the research reports of the numerous geologists who have worked in the area is complemented with the author's own revisions of the reports on the most important drill core samples for each of the deposits. This petrographic description is complemented with the results of studies on several hundred thin and polished sections.

The detailed geological maps and cross-sections presented here are constructed by the author and are based on the geological interpretation and also geophysical interpretations by A. Hattula of drillhole and surface measurements. The geological map of Rautuvaara itself and the geological cross-section of NE Rautuvaara were produced by revising the mapping carried out by A. Juopperi.

The ore mineralogy data are based on determinations carried out by K. Heinänen, mineralogist with Rautaruukki Oy, complemented by the author himself. Chemical examinations were performed both on the various rock types occurring in the area and on the ore deposits, particularly in relation to their subsidiary rocks. With one exception, the analyses were made at the research laboratories of Rautaruukki Oy at Raahe under the direction of E. Ojaniemi. The sulphur isotope studies are based on the work of Mäkelä and Tammenmaa (1978) in 1974—1976 in the case of the Rautuvaara deposit and on that of Mäkelä and Mattila (in press) in the case of Hannukainen. The age determinations referred to were all provided by O. Kouvo of the Geological Survey.

GENERAL GEOLOGICAL SETTING

According to Simonen (1980), the Finnish Precambrian can be divided into the following major geological units (Fig. 1):

The oldest fold region (2800—2600 Ma) is the Presvecokarelidic basement complex to be found in Eastern and Northern Finland, containing ortho- and paragneisses. The Lapland granulite complex forms an integral part of this Presvecokarelidic basement, having been recrystallized at the time of the Svecokarelidic movements.

Presvecokarelidic basic intrusive rocks are to be found in the form of sheet or lopolith-like intrusions in the area of the Presvecokarelidic basement or along the contact zones between this basement and the Karelidic schist zones. These intrusives are of an age of 2430—2450 Ma.

The Svecokarelidic rocks, which include both Karelidic and Svecofennidic schist zones, cover the majority of the Precambrian area in Finland. The Karelidic schist zone of Eastern and Northern Finland is characterized by particularly abundant deposits of quartzites, while the Svecofennidic schist zone of Western and Southern Finland typically includes mica-rich schists. Sedimentation of the Svecokarelidic rocks took place approx. 2200—2000 Ma ago. The orogenic Svecokarelidic plutonic rocks intruded into these Karelidic and Svecofennidic schists at the time of the Svecokarelidic movements some 1900—1800 Ma ago.

The resulting stable platform was further penetrated by the Postsvecokarelidic rapakivi granites and mafic intrusive rocks around 1700—1550 Ma ago. The youngest of the Precambrian metamorphic crust sediments, the Jotnian red beds, were deposited on top of the eroded Precambrian surface about 1400—1300 Ma ago. The youngest Precambrian intrusive rocks in Finland are the Postjotnian diabases (1275 Ma).

Up until very recent years our understanding of the main outlines of the geology of the central part of Northern Finland, referred to as »Central Lapland» has been based to a great extent on the research of Mikkola (1941). He regarded the oldest bedrock unit as being the Eastern Lapland supracrustal series, to which he gave the name the Tuntsa—Savukoski series. The extensive, somewhat younger plutonic series comprising gneissose granite and granitic gneiss then forms the basement for the supracrustal rocks of the Lapponian series. This latter overlies in a discordant manner the gneiss-granite complex and is composed of sedimentogenic schists and volcanites which are mainly younger than the sediments themselves. The Lapponian series is overlain by the Kumpu—Oraniemi series, which contains coarse-grained quartzites and conglomerates (Mikkola 1941).

In Mikkola's interpretation, the supracrustal rocks of the Rautuvaara area all belong to the Lapponian, with the exception of the quartzites of the fells in the eastern part, which he assigned to the Kumpu—Oraniemi series. Mikkola (op.cit) did not give any precise diagrams of the stratigraphy, but suggested that the sillimanite gneisses of Western Lapland may form the lowermost horizon of the Lapponian series.

As noted above, Simonen (1960, 1971 and 1980) takes the attitude in his summaries of the Finnish Precambrian that the schist area of Central Lapland is assignable to the Karelidic rocks and thus to the age range 2200—2000 Ma.

Gaál *et al.* (1978) regard the majority of the volcanites of Central Lapland as Archean, the Finnish Archean rocks being divisible into two main units, the granitoid association and the greenstone belt association. Since the granitoid association contains extensive areas of migmatized relicts from the greenstone belt association, it is assumed that the latter covered a much greater area at one time.

The most detailed stratigraphic scheme for northern Finland is that proposed by Silvennoinen *et al.* (1980), based on a summary of the extensive bedrock mapping work in progress in the area, much of which is nevertheless still incomplete. They interpret the majority of the supracrustal rocks of the Central Lapland schist area as being Archean in origin and divide them into the Lower Lapponian and Upper Lapponian Groups. These groups correspond to a great extent to the Lapponian system of Mikkola (1941). The Lapponian series is then overlain by the Karelian and Svecofennian Supergroups, Proterozoic in age, which are divided into three Jatulian groups and two Kalevian groups (Silvennoinen *et al.* 1980). They claim that all three of the Jatulian Groups are represented, although some only marginally, in the sedimentary rock units of Central Lapland, and that the quartzites and conglomerates of the Kumpu—Oraniemi series of Mikkola (1941) largely fall into these. Very few sediments belonging to the Kalevian Group are to be found in Central Lapland. The authors do not name any stratigraphical units below group level in their paper.

Silvennoinen *et al.* (1980) place the majority of the supracrustal rocks of the Rautuvaara area within the Upper Lapponian Group, while the quartzites of the fells in the east represent the Lower and Middle Jatulian. No outcrops of granite gneiss are known in the Rautuvaara area. Silvennoinen *et al.* (op.cit.) regard the plutonic rocks of the monzonite intrusion in the central part of the area as comparable in age to the Kalevian Group, and also the granites of the northwestern part.

LITHOSTRATIGRAPHY

Stratigraphic sections for the eastern and western parts of the Rautuvaara area are presented in Fig. 2. The base of the oldest lithostratigraphic unit, the Niesakero—Kuertunturi quartzite complex, was not encountered, but the presence of gneissose plutonic rock fragments in the conglomerate of the lower parts of the quartzite suggests that this may have been deposited on top of granite gneiss.

The crucial stratigraphic position of the Rautuvaara Formation and the Kolari Greenstone Formation is not entirely indisputable, as these formations largely occur in separate geographical locations and contain in part the same rock types. They coincide only in

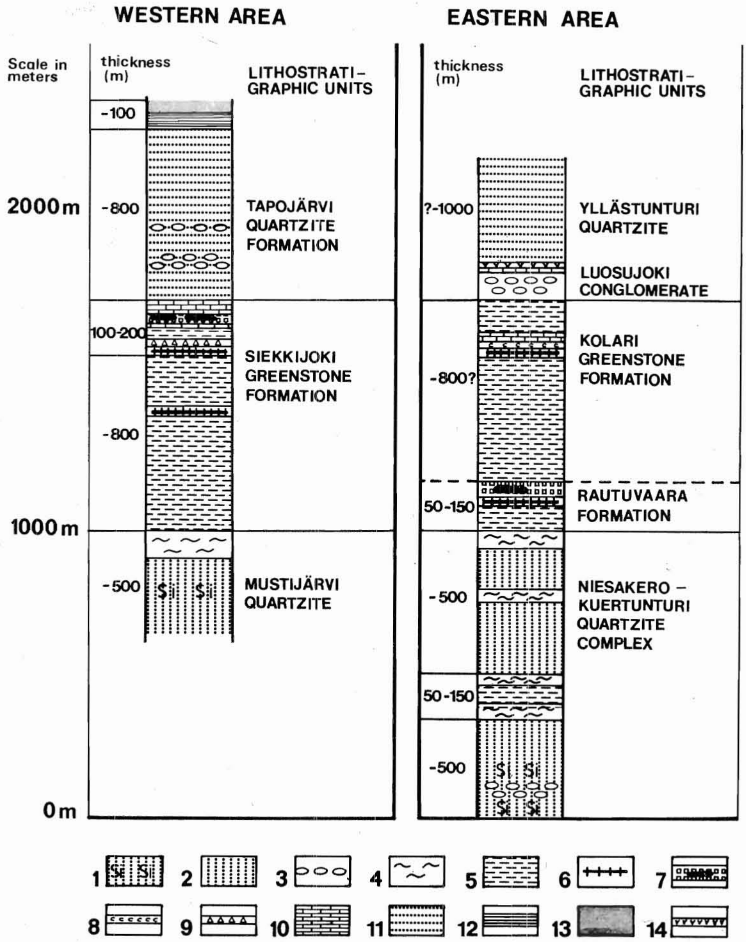

Fig. 2. Stratigraphic sections from the Rautuvaara area. 1 = sillimanite-bearing quartzite; 2 = quartzite, mainly orthoquartzitic or arkosic; 3 = conglomerate beds; 4 = mica gneiss and quartz–feldspar gneiss; 5 = amphibolite; 6 = graphite-bearing schist, quartz–feldspar schist; 7 = skarn and magnetite; 8 = chert; 9 = keratophyre; 10 = carbonate rocks; 11 = sericite quartzite; 12 = phyllite; 13 = mica schist; 14 = albite schist.

the south-western part of the area, where the structural interpretation would suggest that rocks correlative with those of the Rautuvaara Formation are to be found beneath the Kolari Greenstone Formation.

Similarly the Kolari and Siekkijoki Greenstone Formations occur in discrete areas and would appear to be correlative in their stratigraphic position, even though differing somewhat lithologically. The uppermost stratigraphic unit in the western part of the area, the Tapojärvi Quartzite Formation, overlies the Siekkijoki Greenstone Formation, while in the east one finds the Luosujoki conglomerate lying between the Yllästunturi quartzite, apparently correlative with the Tapojärvi Quartzite Formation, and the Kolari Greenstone Formation.

The description below follows the lithostratigraphic order, from the oldest rocks to the youngest. Amongst the plutonic rocks, the principal attention is devoted to the syntectonic monzonite intrusion, on account of its critical position in relation to the origins of the iron ores in the area. The youngest rock is the pegmatite granite, which cuts into both the rocks of the lower lithostratigraphic units and the monzonite intrusion and also those of the Tapojärvi Quartzite Formation.

The Niesakero—Kuertunturi quartzite complex

Definition

The lowermost lithostratigraphic unit in the Rautuvaara area is termed the Niesakero—Kuertunturi quartzite complex after the highest peaks in the area and the predominant rock types. Since no detailed description is given of the internal structure of this complex, and since it represents only the southernmost part of a more extensive area of similar rocks, it is not defined formally in the present context. The majority of the rocks belonging to this quartzite complex are to be found in the eastern part of the area, where they form numerous hills, often with boulder-covered summits, the most prominent of these hills being Paloselkä, Niesaselkä, Niesakero, Hyyverova, Lompolovaara and Malmivaara to the south of the river Äkäsjoki and Kuervaara, Kuertunturi, Kaupinselkä and Tiuraselkä to the north. Structurally, the rocks of this complex form two extensive anticlinoria following the chains of hills. The complex is overlain by a thin deposit of rocks of the Rautuvaara Formation in the west, while in the east it borders on younger deposits of quartzite and volcanic conglomerate. In the south it lies beneath the Rautuvaara Formation and the Kolari Greenstone Formation. Other isolated areas included in this complex are found at Juurakkovaara, Äkäsjokisuu and Mustijärvi.

This quartzite complex takes the form of a broad area of minimum values on the magnetic map, with weak peaks within it arising from the magnetite associated with beds of gneiss.

The rocks of the complex are principally *quartzites,* with a composition varying from quartzites rich in mica or feldspar to pure orthoquartzites. The interbeds comprise *gneisses* containing mica and calcium silicate and *amphibolites.* That part of the Niesakero—Kuertunturi quartzite complex lying to the south of Äkäsjoki is said by Mikkola to consist almost entirely of sillimanite gneiss, while that remaining to the north is quartzite and schist. These are closely allied, however, and are thus described here as constituting a single lithostratigraphic unit.

The rocks of the complex have suffered pronounced metamorphism and are frequently granitized to some extent. Thus the primary structures are visible only in a few exceptional cases. For this reason it has not been possible here to examine the internal stratigraphy or structure of the complex.

The rocks of the complex are divided stratigraphically into three main groups. Observations suggest that the lower part consists of gneissose quartzite, typically containing sillimanite and in places sillimanite—quartz aggregations. Associated with this at Hevoslaki, to the south-east of Niesaselkä, is a polymictic conglomerate containing gneissose fragments in addition to quartzite and amphibolite fragments. It has not been possible to ascertain precisely the stratigraphic position of this conglomerate, but the fragment material suggests it may be an interbed in the lower part of the complex. This lower part reaches a maximum thickness of at least 500 m.

The gneisses and amphibolite usually occur in alternate interbeds in the quartzite complex, but since they have not been encountered in the typical sillimanite quartzite of the lower part, they would seem to belong stratigraphically to the middle and/or upper part of the complex. The thickness of this amphibolite-gneiss sequence may be 100—150 m.

The upper part of the quartzite complex consists of purer rock types, partly arkosic, but in places even orthoquartzitic, with gneiss interlayers. With this upper part reaching

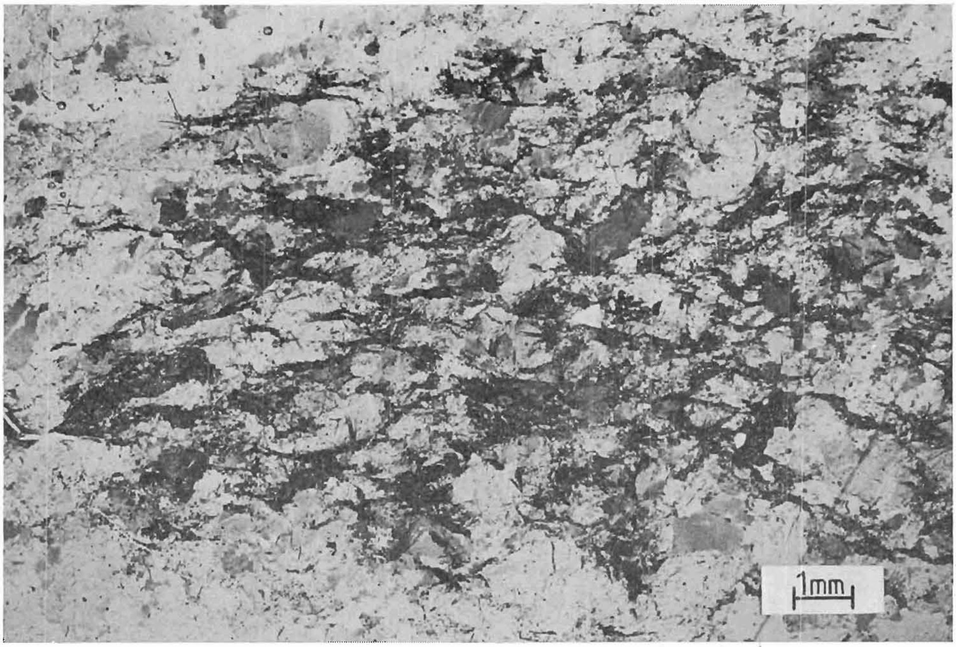

Fig. 3. Sillimanite nodule in the gneissose quartzite of the lower part of the *Niesakero—Kuertunturi quartzite complex.* The light-coloured grains are quartz, with dark schlieren of fibrolite between them. Thin section 18/4, crossed nicols.

thicknesses of over 500 m, that of the whole complex may easily amount to over 1000 m.

The lower part of the quartzite complex

The dominant rock type in the lower part of the quartzite complex is a reddish, nonhomogeneous gneissose quartzite containing alongside quartz, microcline, biotite, muscovite and occasionally plagioclase. Although sillimanite may be regarded as a typomorphic mineral for this rock, it usually accounts for no more than a few percent of its total composition and is frequently absent entirely.

The proportions of the minerals mentioned can vary considerably, but there is always a high percentage of quartz, in the range 50—80 %. Microcline may vary from just a few percent to over 20 %, while micas normally account altogether for less than 10 %, although they can exceptionally reach over 20 %. Accessory minerals include opaque, and also zircon, epidote, apatite and tourmaline.

This rock has a pronounced schistose character and has entirely recrystallized, its grain-size varying in the range Ø 0.1—2.5 mm. The quartz appears mainly in elongated grains and grain aggregates, interspersed with finer-grained feldspar, mica and sillimanite. The sillimanite forms long, flexible needle bunches in between the quartz grains, and muscovite is frequently found in association with these. In cataclastic rocks the sillimanite occurs at the seams of movement.

The most outstanding, although not the most common, feature is the occurrence of sillimanite forming nodules with quartz. These nodules are oval in cross-section, elongated in the direction of lineation, and may be as much as 10 cm in diameter, although they are normally only a few centimetres across. They are composed of quartz grains interspersed with large quantities of sillimanite needles (Fig. 3) and in places muscovite. They are found in feldspar-rich quartzite, either individually or as clusters. The nodules themselves contain very little, if any, feldspar.

Numerous theories have been put forward concerning the genesis of these nodular sillimanitic rocks. In his summary of these, J. Losert (1968) suggest that the late stages of local metamorphism, once the principal fold movements, metamorphic crystallization and syntectonic migmatization are completed, involve a residual late-metamorphic intergranular solution in non-homogeneous complexes of metamorphic rocks, in which local removal of alkalis, e.g. Ca, Fe and Mg, occurs at those points in the anisotropic pressure field at which the nodules form. This gives rise to an immediate excess of aluminium and silicon locally at the points concerned. Thus where conditions correspond to the stabilization field for sillimanite this mineral is formed (Losert 1968). This dealkalization does not affect the whole host rock, but is governed by the anisotropy of the rock, in particular its bedding and axial-plane cleavage, the nodules most commonly being associated with these features.

Although there is an almost complete absence of primary sedimentary structures in

Table 1

Chemical compositions of the rocks of the Niesakero — Kuertunturi quartzite complex (% by weight), determined by the following methods: SiO_2, CO_2, and H_2O gravimetrically, FeO by the wet chemical method, Na_2O by atomic absorption and the others by x-ray fluorescence.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO_2	85.25	77.70	85.39	82.28	60.08	66.52	68.59	90.16	51.90
TiO_2	0.18	0.22	0.13	0.45	0.75	0.50	0.50	0.13	1.21
Al_2O_3	7.64	12.20	8.05	7.38	13.30	14.46	11.90	3.99	13.78
Fe_2O_3	0.88	1.18	1.45	1.12	6.44	4.04	3.58	1.24	3.36
FeO	0.83	1.40	0.30	1.90	1.60	1.00	1.00	0.30	9.60
MnO	0.02	0.04	0.02	0.01	0.04	0.03	0.13	0.06	0.31
MgO	0.61	0.50	0.20	1.50	4.60	1.60	2.17	0.15	5.90
CaO	0.10	0.70	0.07	0.37	2.54	2.69	3.37	1.96	7.95
Na_2O	0.52	0.61	0.15	0.44	1.00	2.49	4.15	0.23	3.33
K_2O	3.21	3.84	3.47	3.15	6.89	5.02	2.86	0.89	0.74
P_2O_5	n.d.	0.14	0.07	0.07	0.11	0.14	0.18	0.07	0.18
CO_2	n.d.	0.00	0.00	0.00	0.00	0.30	0.20	0.30	0.10
H_2O+	0.49	0.80	0.70	1.00	2.20	0.90	1.30	0.50	1.40
H_2O-	0.06	0.11	0.15	0.23	0.19	0.34	0.14	0.07	0.22
S	n.d.	0.00	0.00	0.00	0.00	0.16	0.00	0.01	0.00
Total	99.79	99.44	100.15	99.90	99.89	100.19	100.07	100.06	99.98
— O						0.08			
						100.27			

n.d. = not determined
1. Sillimanite quartzite, Lompolovaara, anal. H. Lönroth (Mikkola 1941)
2. Sillimanite quartzite, Niesakero, anal. 969 2022
3. Sillimanite quartzite, Niesakero, anal. 969 2015
4. Sillimanite quartzite, Mustijärvi, anal. 969 2017
5. Mica gneiss, Mäntyvaara, anal. 969 2018
6. Quartz-feldspar gneiss, Kuerlinka, anal. 969 2013
7. Arkose quartzite, Kuerlinka, anal. 969 2014
8. Orthoquartzite, Jakunlaki, anal. 969 2019
9. Amphibolite, Hyyverova, anal. 969 2016

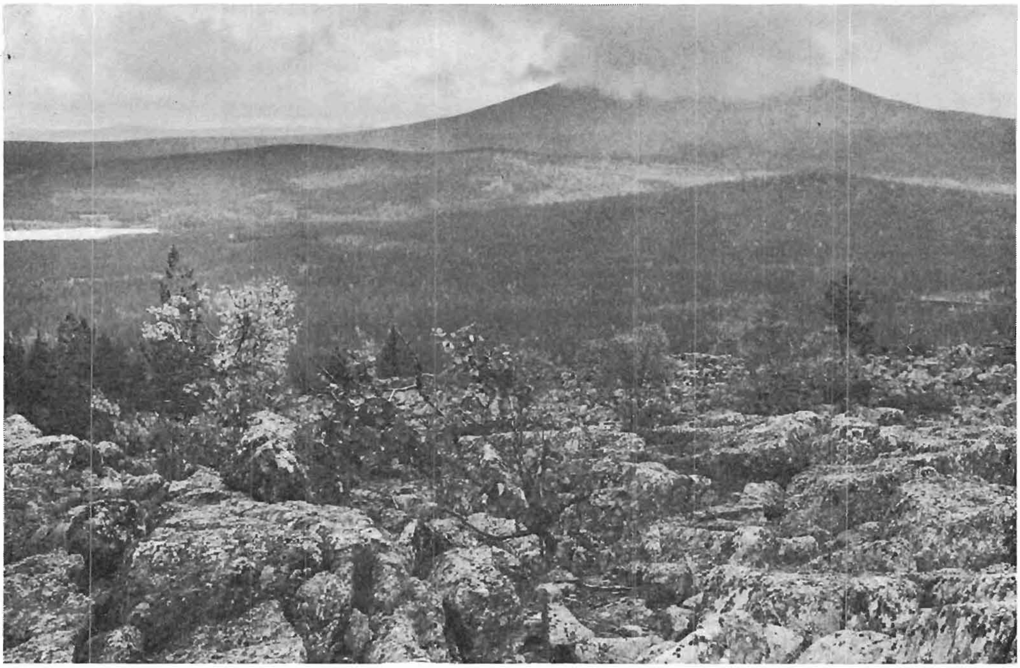

Fig. 4. Quartzite with sillimanite nodules in the *Niesakero—Kuertunturi quartzite complex* at Niesakero. In the background is Yllästunturi with its summit in cloud. Luosujärvi is to be seen at the left-hand edge of the picture, with Lompolovaara to its right and the summit of Hyyverova on the right-hand edge.

the rocks of the lower part of the quartzite complex, a certain bedded structure can be distinguished in them macroscopically. The sillimanite nodule-bearing layers often alternate with more quartzitic layers with no such nodules, and some layers contain higher proportions of mica. This layering may be partially metamorphic in origin, although the majority would presumably be due to primary local differences in composition. The sillimanite quartzites correspond in their chemical composition (Table 1, nos. 1—4) to arkose or mica-rich sandstones, the sedimentary composition of which was assumed by Mikkola (1941) to have remained largely unchanged in spite of pronounced metamorphism.

The sillimanitic rocks of the quartzite complex are to be seen at their most typical in the area of the axis culmination of Niesakero. This may be assumed on the basis of its tectonic position to represent the lowermost parts of the complex. Corresponding rocks occur in well exposed positions at Malmivaara and to the north-east of Kuertunturi. Occasional beds with a higher quartz content are to be seen within the sillimanite quartzite on the slopes of Niesakero, and there are extensive fields of coarsely nodular gneissose quartzite on the summit (Fig. 4).

The anticline structure on the summit of Pikku Hevosmaa, to the south-east of Niesakero, appears to contain polymictic conglomerate (Fig. 5), with fragments of quartzite and amphibolite, and also of schistose plutonic rock. The latter are mainly composed of potassium feldspar, plagioclase (An 15 %) and quartz, and also contain a certain amount of hornblende (Fig. 6). The accessory minerals are opaque, apatite, titanite, carbonate,

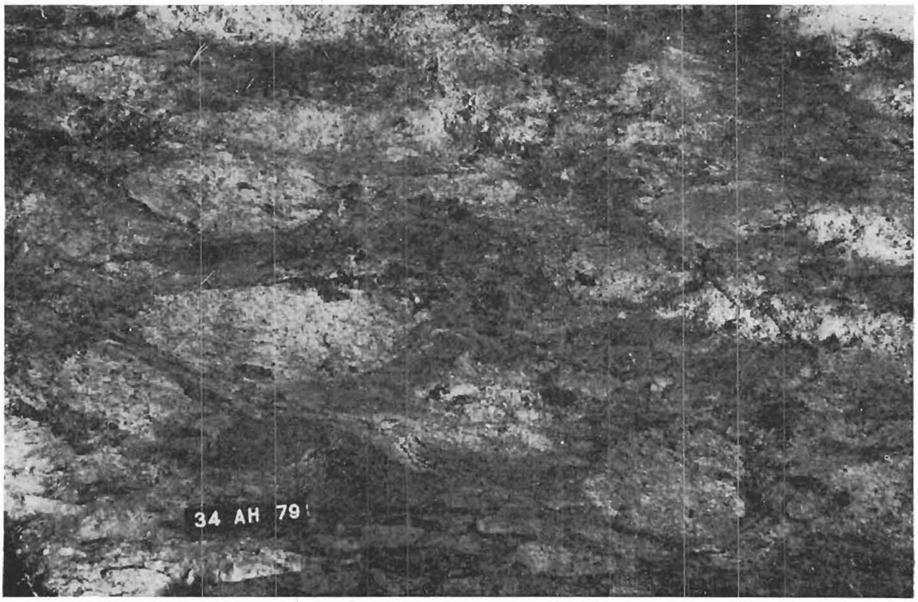

Fig. 5. Polymictic conglomerate in the *Niesakero—Kuertunturi quartzite complex* at Pikku Hevoslaki. The fragments are of quartzite, quartz monzonite and amphibolite. The name-plate is 16 cm in length.

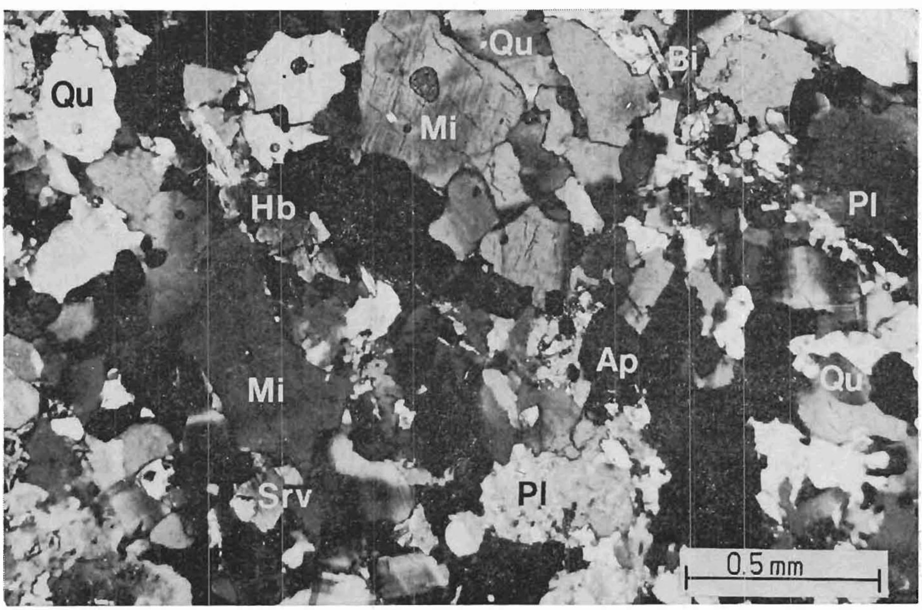

Fig. 6. Gneissose quartz monzonite with a fragment of conglomerate in the *Niesakero—Kuertunturi quartzite complex* at Pikku Hevoslaki. Mi = microcline; Pl = plagioclase; Qu = quartz; Hb = hornblende; Bi = biotite; Ap = apatite. Thin section 17/37, crossed nicols.

epidote, allanite, biotite and muscovite. This rock is quartz monzonite in composition, although it differs markedly in its appearance from the rock of practically the same composition described later in connection with the monzonite intrusion. The plutonic rock fragments may originate from the granite-gneiss basement, not found exposed at any point, which underlies the quartzite complex. The quartzite fragments contain in addition to quartz varying amounts of potassium feldspar, a little plagioclase (oligoclase—andesine) and biotite or light amphibole. They are markedly recrystallized in texture, those with a greater abundance of quartz being somewhat vitreous in character. The conglomerate fragments are elongated in the direction of lineation and vary in length from a few centimetres to around 40 cm. The matrix is composed of quartz, amphibole, epidote and diopside in varying proportions. Clusters of magnetite and garnet are found in places. To the south of Hevoslaki, where the number of fragments decreases, the conglomerate resembles skarn in its external appearance. The occurrence of quartzite fragments suggests that some of these may originate from the complex itself. Thus it is not a question of a basement conglomerate to the complex.

The gneiss and amphibolite interlayers

It has not been possible to define precisely the stratigraphic position of the gneisses and amphibolites belonging to the quartzite complex. The lower part of the complex possesses relatively few mica-rich interlayers, but such gneiss layers alternate with the quartzite in a regular manner in the upper part. Only the most extensive continuous occurrences of gneiss are indicated separately on the geological map.

There is distinctly less amphibolite than gneiss, and in places the two occur together in the same interlayer. The gneisses of the quartzite complex are for the most part light grey, fine-grained rocks rich in feldspar and quartz (Fig. 7), usually with a biotite concentration of approx. 10 %. They may thus be referred to on the basis of their composition largely as quartz-feldspar gneisses, although some biotite-rich mica gneisses are also found. One clear difference compared with the quartzite of the lower part of the complex lies in the common occurrence of plagioclase (oligoclase). It is also typical of these gneisses that the green minerals hornblende, diopside and epidote appear in thin streaks and larger clusters. In places there are even skarn layers several metres in thickness.

Sillimanite and garnet are also found occasionally in the mica-rich gneisses. Granitic veins and lenses occur regularly, and the most pronouncedly granitized gneisses are reddish in colour. Table 1 contains the results of analyses on a typical mica gneiss and a lighter quartz—feldspar gneiss (Nos. 5 and 6). No great differences exist in their chemical composition although the presence of mica is clearly reflected in No. 5.

The gneisses usually show pronounced folding, and thus it is difficult to measure the thickness of the beds. At its greatest this may be some 100—150 m. It has not been possible to determine the relative stratigraphic positions of the various gneiss sequences indicated on the geological map. Although some of them will naturally represent the same stratigraphic unit, some undoubtedly occur in different positions. Some of the gneisses visible in the form of syncline structures may be equivalent to the schists of the Rautuvaara Formation overlying this complex.

The relation between the light gneiss and the quartzite is visible at Kuertunturi, the eastern slope of which features interlayers of gneiss some tens of metres thick falling

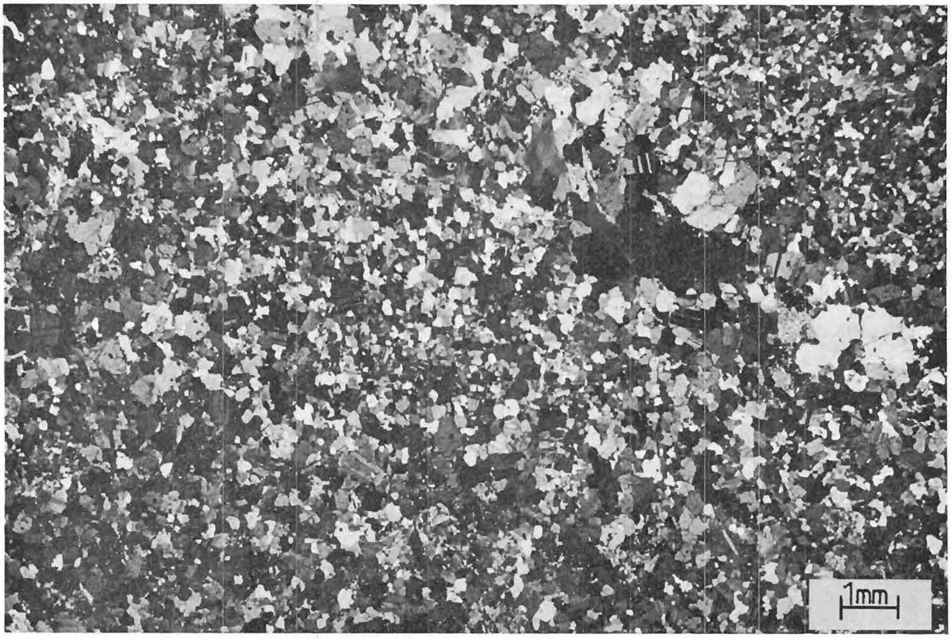

Fig. 7. Quartz–feldspar gneiss in the *Niesakero—Kuertunturi quartzite complex* at Kuerlinka. Thin section 17/13, crossed nicols.

away gently to the north-west and located within the quartzite. Since the area to the east of Kuertunturi features layers of sillimanite quartzite with a dip towards the west, this region represents a fairly comprehensive cross-section through the whole complex.

The river bank at the mouth of Kuerjoki gives evidence of a gradation from reddish gneiss containing hornblende and epidote to a grey gneiss overlain by glassy quartzite. Mica gneiss with sillimanite occurs at Mäntyvaara and Luosuvaara, for example. Mica gneiss containing garnet and in places cordierite and some graphite-bearing layers and amphibolite interbeds, can be found to the east of Hyyverova.

The major amphibolite sequence is located to the south-east of Hannukainen. It is exposed only at the southernmost edge of a north-east-facing anticline. The deposit is some 100 m thick at that point. Immediately below it lies the sillimanite and mica-rich gneiss of the lower part of the complex. This amphibolite is overlain by a thin layer of mica gneiss, and above this is granitized, arkose quartzite, containing sillimanite in parts. Samples were obtained from the northern end of this amphibolite sequence by means of two diamond drillholes and pneumatic drilling. The maximum thickness of the amphibolite at that point is approx. 150 m, about a third of which figure is accounted for by the mica gneiss interlayers. The amphibolite is fine or medium-grained and contains andesinic plagioclase and also hornblende, cummingtonite, diopside and in places hypersthene. The mica gneiss of the interlayers contains graphite in places. Cordierite has also been encountered. There is also a 10 m bed of diopside—scapolite skarn with cracks and cavities filled with zeolite. Lithologically, this amphibolite sequence corresponds to the gneiss sequence east of Hyyverova, although the proportion of mica gneiss is higher in the latter. The chemical

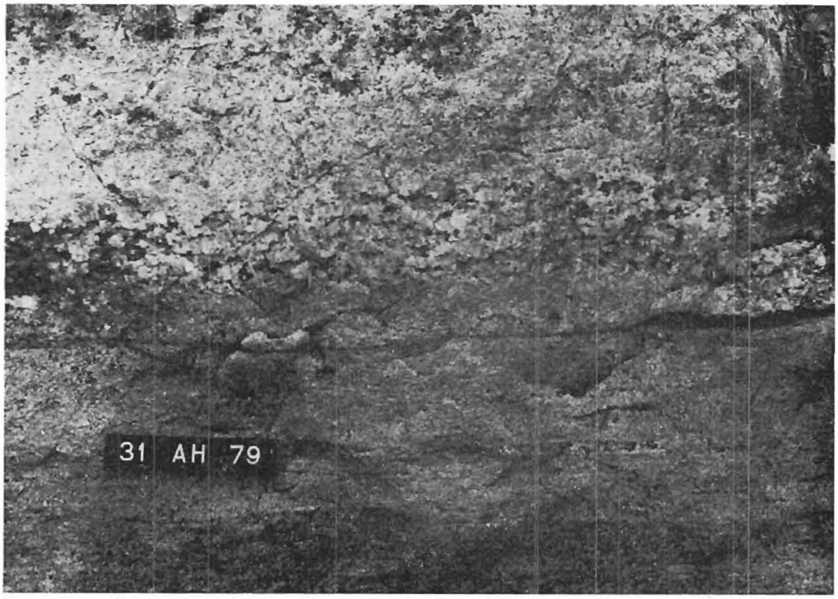

Fig. 8. Groove structures in the quartzite of the upper part of the feldspar-rich bed in the *Niesakero—Kuertunturi quartzite complex* at Rytijänganharjut. The name-plate is 16 cm in length.

composition of the Hyyverova amphibolite, which corresponds to tholeiitic basalt in the classification of Middlemost (1972), is given in Table 1 (no. 9).

The upper part of the quartzite complex

The dominant rock in the upper part of the quartzite complex is a vitreous, relatively pure quartzite containing feldspar-rich arkosic interlayers. It is difficult to estimate the thickness of this upper part accurately, but it must be several hundred metres. Layering frequently takes the form of an alternation between feldspar-rich and quartz-rich beds. Grooves on the upper surface of the arkose-quartzite layer at the Rytijängänharjut serve to indicate the top of the bedding (Fig. 8).

The most typical rock in the upper part of the complex is a white, highly recrystallized, tectonized quartzite with green flecks and clusters of epidote. Its colour becomes more reddish as the feldspar content increases. The quartz-rich layers are more coarse-grained than the red arkose layers. The quartz occurs in greatly undulating, elongated grains of diameter 1—2 mm (Fig. 9) with varying amounts of plagioclase, potassium feldspar, biotite, muscovite and occasionally scapolite. The accessory minerals are opaque, apatite, zircon and allanite. Epidote is normally an accessory mineral, but reaches proportions of approx. 10 % in rock samples from the mouth of the river Kuerjoki. The quartz in the orthoquartzite contains inclusions of plagioclase (andesine) which are rounded in shape and generally highly saussuritized. The typical quartzites of the upper part of the complex contain little or no sillimanite. The chemical compositions of the arkosic quartzite and orthoquartzite are indicated in Table 1 (nos. 7 and 8).

A continuous sequence of quartzite in the upper part of the complex occurs between Hannukainen and Kuerjoki, from where it

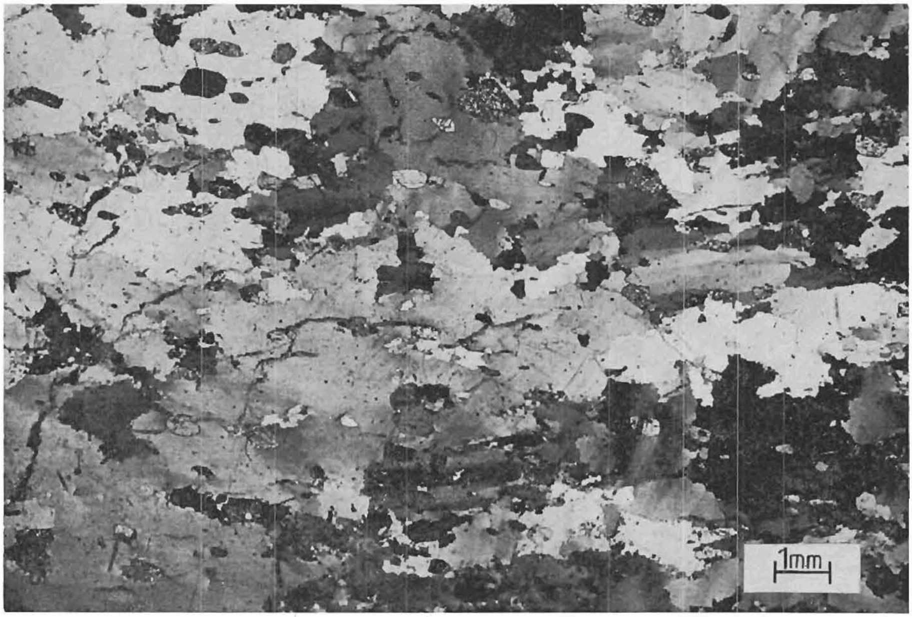

Fig. 9. Orthoquartzite in the *Niesakero—Kuertunturi quartzite complex* at Paloselkä. Thin section 7/33, crossed nicols.

extends northwards to Tiuraselkä, passing to the east of the Rautuvaara Formation. The eastern part of the sequence, at Kuertunturi, comprises gneiss interlayers of the kind described above, and to the east of these sillimanite quartzite. A similar cross-section is found at Malmivaara, the summit of which contains sillimanite quartzite, with layers of gneiss to the west, gently dipping westwards, and above these orthoquartzite.

Perhaps the most extensive area of orthoquartzite, however, is to be found at Niesaselkä, to the south of Niesakero. Its tectonic position suggests that it overlies the Niesakero sillimanite quartzite.

Areas correlated to the quartzite complex

Small, isolated areas of quartzite or gneiss exist in the north-western and south-western parts of the study area which possess rocks comparable to those of the quartzite complex in their stratigraphic position and/or their lithology. These areas are dealt with here in broad outline only.

A gneissose quartzite containing sillimanite occurs at Mustijärvi, in the north-west of the study area, which is lithologically of the same type as that of the lower part of the complex, as also denoted by the similarity in chemical composition (Table 1, no. 4). Similarly the mica gneiss of Mustijärvi corresponds to the gneisses of the quartzite complex, and stratigraphically appears to overlie the sillimanite quartzite.

The quartzite of Äkäsjokisuu contains sillimanite, is highly granitized in places and has suffered deformation in the northern part of the area. A distinct bedding is to be seen in the south, however, even with current bedding structures, enabling the top of the bedding to be determined. A thin layer of a comparable quartzite occurs to the north of Ristimellanjärvi, where it exists between the monzonite and the schists of the Rautuvaara Formation, lying stratigraphically beneath these schists.

There is a fairly broad area of mica gneiss to the north of Äkäsjokisuu which has been correlated with the gneisses of the quartzite complex, and a poorly exposed fine-grained quartzite occurs at Juurakkovaara which may correspond in type to the quartzite of the upper part of the complex.

The Rautuvaara Formation

Definition

The name, 'Rautuvaara Formation' is used to signify the formation composed of amphibolites, schists, skarn and carbonate rocks and the magnetite deposits contained in these. The formation is located in the centre of the area studied and forms a narrow continuous chain on the western edge of the quartzite complex. Stratigraphically it lies on top of the quartzite complex. This conclusion is based on observations of the bedding, top determinations and also structural interpretation and drilling results. The formation has not been described previously and is proposed here as a new lithostratigraphic unit. The name is taken from the Rautuvaara mine, opened in 1975, which constitutes one of the type localities for the formation.

Previous published research on the formation includes the work of Borgström (1928) on the Juvakaisenmaa iron ore deposits, Schmidt (1960) on the iron ores of Kolari and Hiltunen and Tontti (1976) on the regional geology of Rautuvaara. There are also the unpublished doctoral thesis of Shaikh (1964) and a degree dissertation by Kuivasaari (1980), both dealing with the geology of the Rautuvaara deposits. The geology of the Rautuvaara Formation is discussed in detail in the second part of this work. The intention here is to give a general description of it and to refer for the type sections to the material in the second part, e.g. Figs. 41, 42 and 53.

Although the formation is visible at only a few outcrops, it is known in great detail in many places as a result of the intensive ore prospecting carried out in the area. The best cross-sections, besides the drill core material, are at the Rautuvaara mine and the opencast working at Hannukainen. Exposed bedrock is to be seen at Rautuhelukka, Sivakkalehto, Juvakaisenmaa and Ristimella, for example. The formation stands out clearly on the aeromagnetic map as a narrow string of anomalies arising from the presence of magnetite-rich lenses of varying size and quality.

The thickness of the formation at the sections studied varies from some 20 m up to about 200 m, and is generally in the range 100—150 m. One exception to this is found at Sivakkalehto, where the scapolite skarn separated off from the main formation by monzonite is at least 300 m thick. The NE—SW-oriented part of the formation to the east of Sivakkalehto has been studied by drilling only at its southern and northern ends, the central sector being assumed to exist on the basis of geophysical indicators.

The majority of the formation is located between the quartzite complex and a monzonite intrusion. There are also rock sequences in the Ristimella area in the south-west of the study area which are equivalent to the Rautuvaara Formation in their stratigraphic position, but are geologically sufficiently different as to warrant discussion in a separate chapter.

The members of the Rautuvaara Formation typically grade one into the other. The most consistent in its occurrence is the amphibolite, which is regularly found in a bed of some 20—60 m in thickness in the lowermost part of the formation. It is then separated from the underlying quartzite by a highly granitized gneiss layer usually some 10—20 m thick, which is itself interpreted as belonging to the quartzite complex, since it is overlain in places by quartzite. There is a sharp contact between the amphibolite and the quartzite complex.

Rock descriptions

The *amphibolite* is a fine-grained, banded or homogeneous granoblastic rock with plagioclase (oligoclase—andesine) and hornblende as its main constituents. Biotite is generally present, and cummingtonite may be found in places alongside or instead of the hornblende. The plagioclase can be replaced either totally or partially by scapolite, and hypersthene is occasionally also found as a dark mineral. Titanite, magnetite, epidote, apatite, carbonate and zircon occur as accessory minerals. The granitized amphibolites contain secondary microcline and quartz as their main constituents, these forming augens or veins. As the amphibolite grades to skarn, diopside appears, forming streaks of its own. As the dark minerals decrease in amount the amphibolite grades to a plagioclase-dominated schist. Schist and skarn are to be found in places as interlayers in the upper parts of amphibolite. Mica gneiss with garnet occurs as an interlayer within granitized amphibolite at Rautuoja, for instance.

The chemical composition of the amphibolites of the Rautuvaara Formation is examined in detail in the second part of this paper. It should be noted that these amphibolites have a composition (Table 10) which comes close to that of the schists of the Kolari Greenstone Formation that are interpreted as metatuffs and metatuffites (Table 3, Fig. 13), although differing from these mineralogically and in their lithology.

The *schists,* which are located on top of the amphibolite and also in part in interlayers within its upper part, form a stratum which varies in thickness from a few up to about fifty metres. They are fine-grained (∅ = 0.1—0.5 mm) and clearly layered, with a colour varying from light to dark grey. The layering is manifested in variations in both grain size and the amount of dark minerals, while the thickness of the layers ranges from a few millimetres to some tens of centimetres (Fig. 10). The schists are referred to in general as quartz-feldspar schists after their most common type, but this rock is characteristically heterogeneous both in its mineral composition and in the proportions of the main constituents. The feldspars normally are the most abundant minerals, and show a composition ranging from those with plagioclase dominant (albite—oligoclase) to those with a predominance of microcline, the former being the more frequent. Quartz is usually present in small quantities (= 10 %). Exceptionally even some 30 % can be found. Graphite, tremolite—actinolite, cummingtonite, biotite, scapolite, diopside and sometimes hypersthene can occur among the main constituents, and tourmaline, titanite, epidote, muscovite, apatite, garnet, zircon and pyrite, pyrrhotite and chalcopyrite have been encountered as accessory minerals.

Graphite schists are abundant in the Ristimella area, but they also occur commonly elsewhere, particularly at Rautuvaara itself. Where the schists grade to skarn, diopside and/or colourless amphibole becomes the main constituent, in addition to which graphite, pyrrhotite and pyrite are frequently found. Scapolite-rich schists are distributed irregularly throughout the formation, although they are most common in the Ristimella area. The scapolite occurs both in granoblastic grains and as poikiloblasts.

The biotite-rich schists do not differ greatly from the mica gneisses of the quartzite com-

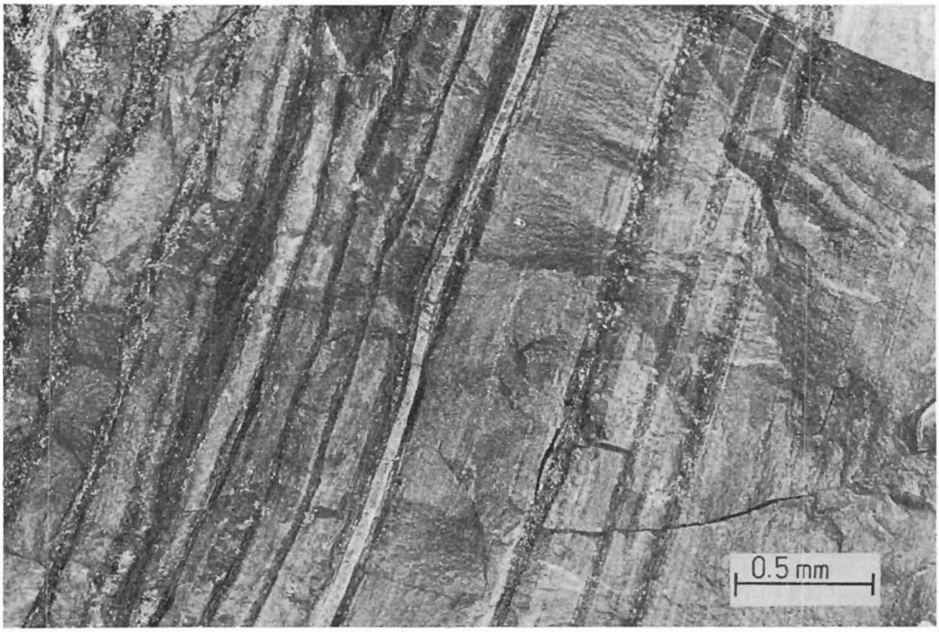

Fig. 10. Quartz–feldspar schist in the *Rautuvaara Formation* at the Rautuvaara mine.

plex in their composition. It is possible that the graphite–mica gneiss described in places at Hyyverova, for instance, could be correlated with the schists of the Rautuvaara Formation.

The *skarn* rocks, associated magnetite lenses and the few carbonate rock layers occur in a layer 10—70 m thick over the majority of the upper part of the Rautuvaara Formation. The skarns grade downwards to schists and amphibolite, which also occur as interlayers within the skarn. Overlying the skarn horizon are the intrusive rocks of the monzonite series, which again are also found within the skarn, in conformable tongues. Assimilation has occurred at the contact with the intrusions, resulting in the formation of contaminated rocks of varying composition. A detailed description of these contact phenomena is given in the second part of this paper.

The most common type of skarn is a fine-grained, banded rock in which lighter plagioclase-rich bands alternate with darker bands of diopside–hornblende. This rock is an intermediate form between the amphibolite lying below it and the more massive diopside skarn. The main skarn mineral, and in places the only one, is diopside, but plagioclase is usually also present in a composition varying from albite to andesine. Hornblende is dominant in the rarer, darker-coloured hornblende skarn, whereas in the normal case varying amounts of it are found alongside the diopside and plagioclase. Other minerals are quartz, potassium feldspar, garnet, biotite, olivine, carbonate and scapolite, which is the most abundant mineral at Sivakkalehto. Titanite, epidote, apatite, zircon, chabazite and anhydrite occur as accessory minerals. The chemical composition of the skarn is discussed in the second part of this paper (see Table 11).

The *magnetite* deposits take the form of lenses oriented in the direction of regional lineation in one or two layers, but rarely more, in the upper part of the skarn horizon. Magnetite is also found in some contact varieties of the intrusive and sedimentary rocks, e.g. at Cu-Rautuvaara and Sivakkalehto. The ore and skarn regularly contain pyrrhotite, pyrite and chalcopyrite as accessory minerals.

Carbonate rocks are occasionally found in layers a few metres in thickness in the lower part of the skarn horizon. The thickest layer encountered is at Tiuraselkä, where the skarn is underlain by a carbonate bed some 20 m in thickness.

The Ristimella area

The Ristimella area differs somewhat from the typical Rautuvaara Formation described above in its rock type distribution. Its stratigraphic position would seem to be the same, however, and there are sufficient similarities even in the rock types to justify its correlation with the Rautuvaara Formation.

Structurally the Ristimella area is a syncline with amphibolites of the Kolari Greenstone Formation at its centre, bent around the south-western end of the monzonite intrusion. The northern side of this syncline is well exposed, but the southernmost edge features outcrops only in the vicinity of the lake Ristimellanjärvi. At Halinjärvi there are schists containing graphite overlying sillimanite quartzite and gneiss belonging to the quartzite complex. The monzonite contact possesses stratified grey gneiss, to the west of which one finds schists of the Rautuvaara Formation. Pegmatitic granite occurs between the gneiss and schist. The form of the syncline stands out well on airborne electromagnetic maps on account of the graphite and pyrite content of the schists in its lower part.

A highly representative section from the formation, about 60 m broad, is to be seen 700 m north-west of Ristimellanjärvi. Further north, and stratigraphically at a lower level, one finds grey, highly tectonized biotite and oligoclase-rich quartzite which contains partly martitized magnetite. The dip of the bedding is 75° to the south-east. The quartzite is correlated with that of the Niesakero—Kuertunturi complex on the basis of its stratigraphic position.

This quartzite is overlain by a schist layer some 20—30 metres thick, the lower part of which is light-coloured quartz—feldspar schist, changing to a rusty-surfaced schist containing graphite and pyrite further south from the contact. The schist also gains partially boudinaged diopside skarn layers and amphibole-dominated layers containing a colourless amphibole, cummingtonite, and also biotite, chlorite, highly sericitized plagioclase and quartz. The sulphides scattered in the rock and as veins in the cracks are largely pyrite and pyrrhotite which has been partially altered to pyrite. A small amount of chalcopyrite is also found in association with the pyrrhotite.

The upper part of the schist layer consists of fine-grained, banded oligoclase—potassium feldspar-dominated schist with narrow, partly skarnified carbonate layers (Fig. 11). Overlying the schists is a pure carbonate layer, which forms the uppermost stratum in the section described here.

A banded iron formation is found about 100 m to the south of Ristimellanjärvi, on the southernmost, and least well exposed, flank of the syncline, occurring in a layer 20—30 m thick superimposed upon the schists and carbonate rocks. The well-developed axial plane cleavage has led to disruption of the bedding structure in places (Fig. 12). The gangue in this iron formation consists of both quartz and cummingtonite. This deposit is described in detail by Borgström (1928).

To the east of the syncline, and cut off from it by intrusive rocks, one finds in some places

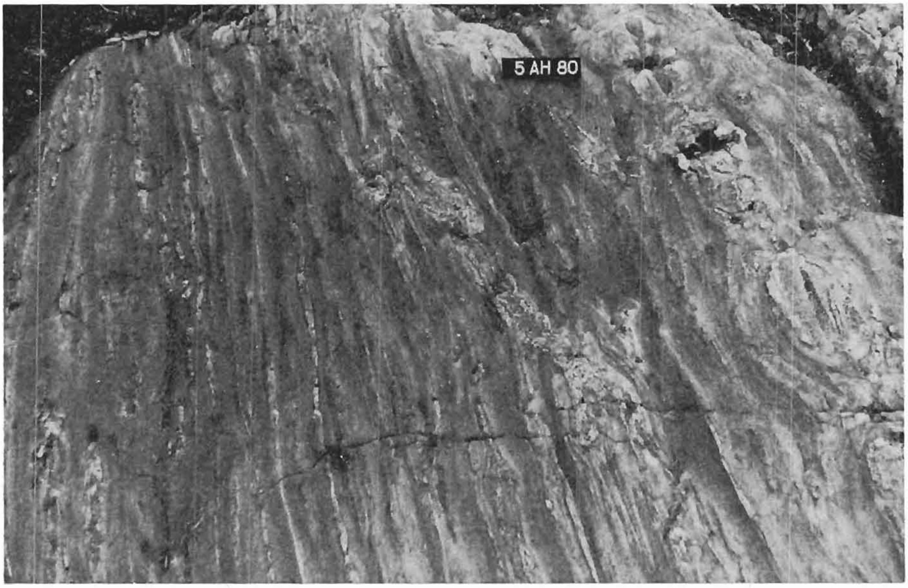

Fig. 11. Boudinized and partly skarnified carbonate interlayers in the quartz—feldspar schist of the *Rautuvaara Formation* at Ristimella. The name-plate is 16 cm in length.

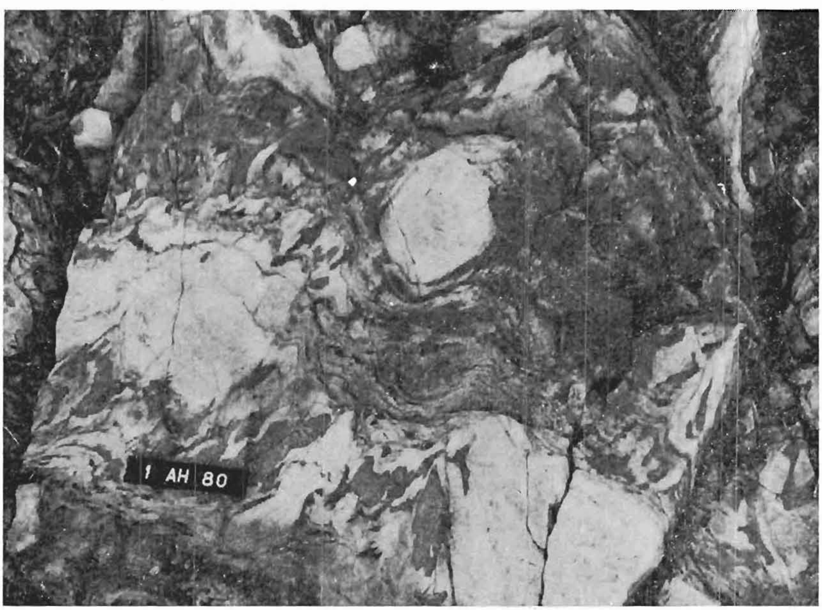

Fig. 12. Brecciated iron ore formation in the *Rautuvaara Formation* at Ristimella. The name-plate is 16 cm in length.

a scapolitized schist containing skarn layers which is comparable to the schist deposit described above.

The central part of the syncline is exposed only beside the river Muonionjoki and in a number of road cuttings. Here the rocks are amphibolites of the Kolari Greenstone Formation. There are also some poorly exposed schist sequences to the south-east of the Ristimella area which are comparable in their stratigraphic position and composition to the schists of Ristimella itself.

A highly graphite-rich schist is found at Juurakkojärvi, for instance. Here the graphite content of the fine-grained, 160 m thick schist layer containing scapolite porphyroblasts extends to over 20 % and reaches a mean value of approx. 9 % in one core obtained. The sulphur content is also high, in the range 4—17 % S, with a mean value of 7.4 % S. These graphite-rich schists are intensely folded, which may explain the local thickness of the deposits.

The above areas differ from the typical Rautuvaara Formation particularly in the absence of amphibolite in the lower part and in the fact that the structural interpretation points to an overlying rock belonging to the amphibolites of the Kolari Greenstone Formation. Thus its comparability with the Rautuvaara Formation still remains open to doubt in spite of the apparent identity of its stratigraphic position.

Table 2

Chemical compositions of the rocks of the Kolari Greenstone Formation (% by weight), determined as detailed in Table 1.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	49.20	50.40	47.04	56.13	48.00	54.88	55.16
TiO_2	0.78	0.70	1.70	0.72	1.32	1.43	1.20
Al_2O_3	14.26	13.40	13.91	14.03	15.20	11.35	14.60
Fe_2O_3	2.64	3.78	4.32	5.32	4.96	3.94	5.52
FeO	10.70	10.70	12.00	4.00	7.50	6.60	7.10
MnO	0.25	0.36	0.28	0.06	0.06	0.19	0.19
MgO	6.20	6.50	6.50	10.20	6.40	7.81	6.10
CaO	11.19	9.98	8.13	2.30	6.43	6.16	3.15
Na_2O	2.40	2.28	3.35	3.50	5.11	4.79	2.18
K_2O	0.27	0.28	0.29	1.14	1.59	0.57	2.17
P_2O_5	0.14	0.12	0.11	0.09	0.14	0.09	0.14
CO_2	0.00	0.00	0.10	0.00	0.60	0.10	0.40
H_2O+	1.60	1.50	1.50	2.40	2.00	1.60	1.50
H_2O-	0.23	0.16	0.04	0.23	0.23	0.16	0.18
S	0.02	0.01	0.09	0.00	0.25	0.00	0.00
Cl_2	0.00	0.13	0.16	n.d.	1.40	0.19	0.00
Total	99.88	100.30	99.52	100.12	101.19	99.86	99.59
— O	— 0.01	— 0.03	— 0.08		— 0.44	— 0.04	
	99.87	100.27	99.44		100.75	99.82	

n.d. = not determined

1. Amphibolite, Saaripudas, anal. 969 2002
2. Amphibolite, Ristimella, anal. 969 2010
3. Amphibolite, Saaripudas R 2, 103.5 m, anal. 969 2029
4. Amphibolite, Pissilehto, anal. 969 2006
5. Scapolite-amphibolite, Ylläsjokisuu, anal. 969 2004
6. Amphibolite, Luosujoki, anal. 969 2009
7. Cummingtonite-garnet-biotite schist, Ristimella, anal. 969 2005

The Kolari Greenstone Formation

Definition

The Kolari Greenstone Formation is the name applied to the formation composed of amphibolites, amphibolite-rich schists and graphite schists which stretches in an ENE direction from north of the village of Kolari, and which also contains minor layers of skarn—carbonate rocks and chert. The chemical composition (Tables 2 and 3) and structure of the members of this formation suggest that they probably represent mafic—intermediate volcanites including both lavas and tuffs and tuffites. In the classification of Middlemost (1972) the chemical compositions of these volcanites correspond to subalkaline and alkaline basalts and andesites, while on the AFM diagram of Irvine and Baragar (1971) they would lie in the fields corresponding to the tholeiite series and the alkaline and calc-alkaline series (Fig. 13). In examining the composition data it should be borne in mind that the chemical composition of metavolcanites does not always correspond to their primary composition.

This formation has not been defined previously and is put forward here as a new lithostratigraphic unit, gaining its name from

Table 3

Chemical compositions of the rocks of the Kolari and Siekkijoki Greenstone Formations (% by weight), determined as detailed in Table 1.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO_2	51.01	54.08	54.08	51.70	63.00	51.70	48.90	57.00	61.90
TiO_2	0.73	0.85	1.07	0.93	0.70	0.88	0.83	0.40	0.38
Al_2O_3	11.52	11.58	14.22	13.53	9.66	10.80	10.90	17.50	16.70
Fe_2O_3	2.73	3.57	2.67	3.36	3.30	2.96	1.53	3.44	0.54
FeO	6.60	8.60	10.60	10.80	10.10	4.80	3.90	3.20	1.10
MnO	0.16	0.09	0.06	0.08	0.23	0.07	0.12	0.06	0.09
MgO	6.64	7.60	6.55	7.06	0.15	7.90	10.70	2.59	1.75
CaO	8.17	3.97	1.63	2.38	5.39	10.40	9.28	3.70	3.39
Na_2O	3.14	3.50	3.17	3.03	5.01	4.60	2.90	8.56	10.00
K_2O	2.94	2.87	3.71	2.16	0.27	0.21	3.28	1.07	0.16
P_2O_5	0.14	0.11	0.07	0.14	0.23	0.10	0.11	0.27	0.23
CO_2	3.90	0.10	0.00	0.10	0.40	4.10	5.50	1.30	2.30
H_2O+	1.90	1.70	1.80	3.80	0.70	0.90	1.80	0.60	0.30
H_2O-	0.26	0.06	0.13	0.17	0.27	0.85	0.37	0.17	0.10
S	0.02	0.01	0.05	1.39	0.73	0.25	0.20	0.08	0.43
Cl_2	0.92	0.62	0.46	0.18	0.00	n.d.	n.d.	n.d.	n.d.
Total	100.78	99.31	100.27	100.81	100.14	100.52	100.32	99.94	99.37
— O	— 0.22	— 0.14	— 0.13	— 0.73	— 0.36	— 0.12	— 0.10	— 0.04	— 0.21
	100.56	99.17	100.14	100.08	99.78	100.40	100.22	99.90	99.16

n.d. = not determined

1. Biotite-plagioclase schist, Kurtakko R 1, 56 m, anal. 696 2032
2. Biotite-plagioclase schist, Kurtakko R 1, 96.2 m, anal. 969 2033
3. Tremolite-biotite-plagioclase schist, Kurtakko R 1, 130.6 m, anal. 969 2034
4. Cummingtonite-biotite-plagioclase schist, Kurtakko R 2, 14.8 m, anal. 969 2035
5. Albitite, Saaripudas, anal. 969 2001
6. Amphibolite, Jaaravinsa R 2, 39.5 m, anal. 960 2004
7. Amphibolite, Jaaravinsa R 2, 168.5 m, anal. 960 2005
8. Keratophyre, Jaaravinsa R 2, 18.6 m, anal. 969 2043
9. Keratophyre, Jaaravinsa R 2, 74.5 m, anal. 969 2044

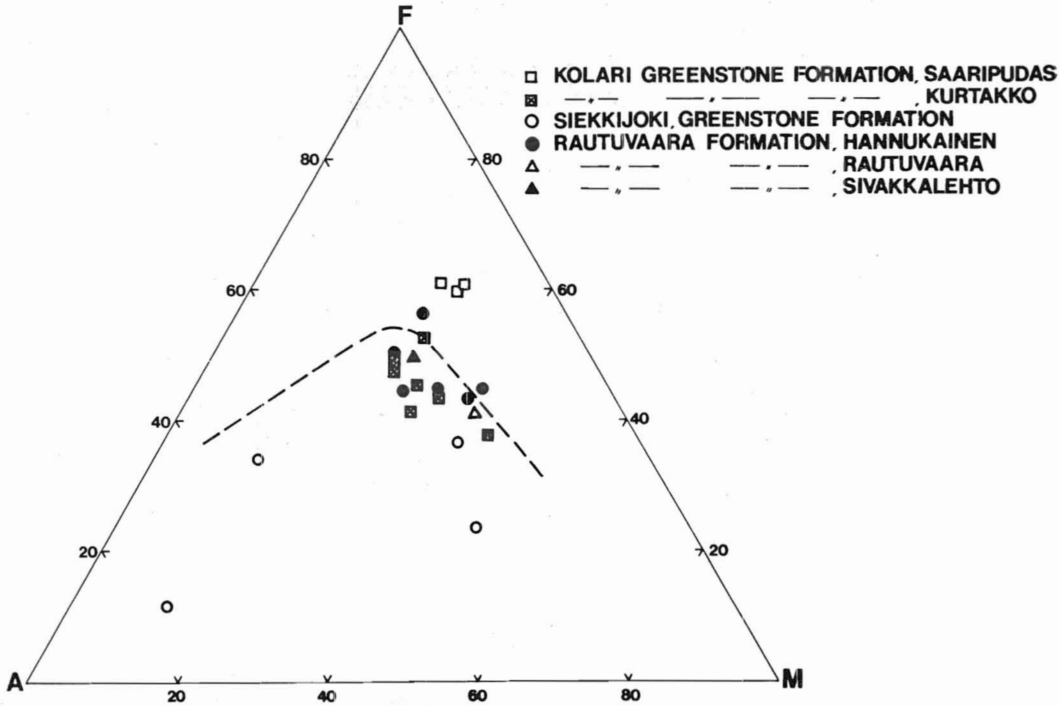

Fig. 13. AFM diagram for the metavolcanites of the Rautuvaara area. The tholeiite field (above) is divided from the calc-alkali field by a broken line (Irvine and Baragar 1971):

the village of Kolari lying to the south-west, about 3 km beyond the southern boundary of the present study area. The type section is a road cutting at Saaripudas, 4.5 km north of Ylläsjokisuu.

Borgström (1928) described rocks of the Kolari Greenstone Formation as amphibolites in the area to the south of Juvakaisenmaa. Mikkola (1941) regarded the rocks of the formation as amphibolites and dark schists with mafic interlayers, assuming them to have been formed as weathering products of greenstone.

It has not been possible to determine the thickness of the Kolari Greenstone Formation accurately, but its areal extent and lithological variability would suggest that it may well be several hundred metres thick. The formation also includes the amphibolite areas of Juurakkojärvi and Ristimella. The only good exposed outcrops are at Saaripudas and the western part of Ristimella, sites from which further data were also obtained by means of six diamond drillholes. In the case of the Juurakkojärvi amphibolite the small number of outcrops were complemented with data from a drillhole at the contact with the Rautuvaara Formation.

To the east of Saaripudas outcrops occur only in the southern part of the area. Althought additional data were obtained by means of two drillholes at Kurtakko and by pneumatic drilling, the network of sites is so sparse that the delimitation of the formation has to be based to a considerable extent upon low-altitude aerogeophysical mapping. No detailed description is available of the internal stratigraphy of the formation. The areas stand out as clear anomaly zones on the aeromagnetic map (Appendix 2) on account of the irregularities in magnetite content. It has also been possible to connect the graphite-

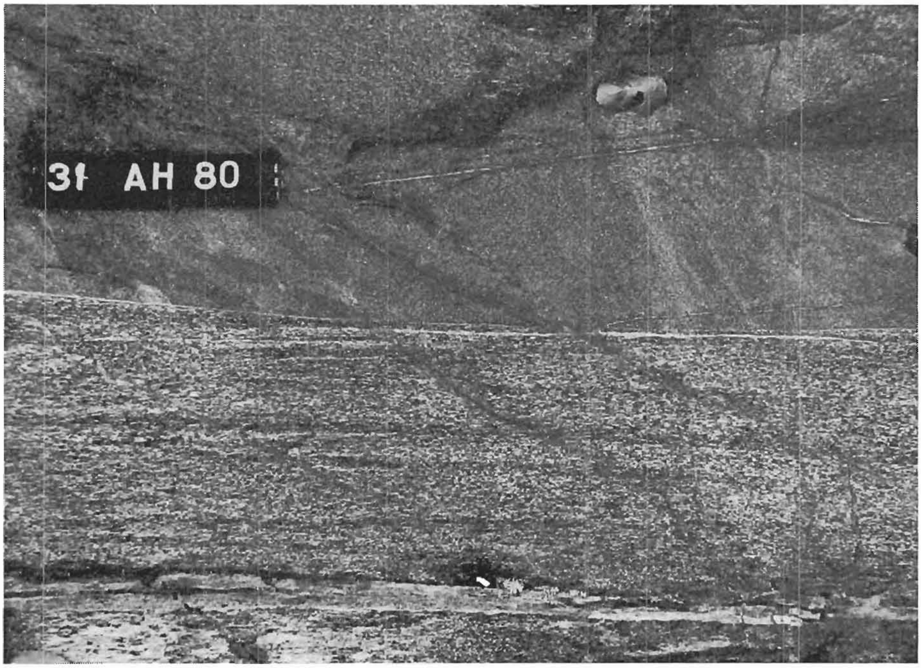

Fig. 14. Contact between fine-grained and coarse-grained layers of amphibolite in the *Kolari Greenstone Formation* at Saaripudas. The name-plate is 16 cm in length.

rich schist zones on the basis of electrical measurements.

On account of the shortage of outcrops, the stratigraphic interrelations between the Kolari Greenstone and Rautuvaara Formations remain unresolved. The interpretation in Fig. 2 is obtained on the basis of the stratigraphic position of the rocks in the Ristimella area, which are regarded as comparable with the Rautuvaara Formation. The contact has been observed only at the Juurakkojärvi drillhole. Here the contact with the amphibolite typical of the Kolari Greenstone Formation features first 5 m of diopside skarn, then graphite schist, quartz—feldspar schist and at the exposed surface quartzite belonging to the quartzite complex lying below the Rautuvaara Formation.

To the north of the eastern part of this volcanite formation lies the extensive Luosujoki conglomerate deposit, the material of which would appear on the basis of its composition to be derived mainly from the Kolari Greenstone Formation. Thus the Luosujoki conglomerate belongs to the younger rocks. In the absence of outcrops no direct observations on the rock type relations are available.

Rocks of the Saaripudas area

The volcanite formation is exposed best in the northern road cutting at Saaripudas, which represents a cross-section of about 200 m through the rocks of the formation.

The most common rock type is a fine or medium-grained homogeneous *amphibolite* with a highly developed lineation. There are just occasional light-coloured streaks with a higher feldspar content running parallel to the direction of schistosity. The finer and coarse-grained amphibolites occur in alternate layers up to about 30 metres thick. There exists a sharp boundary between these in places (Fig. 14), although elsewhere a gradation takes place from the finer to the coarser type.

The central part of the section contains a layer of thickness approx. 10 m comprising a uralitic-porphyritic rock in which the fine-grained plagioclase-rich groundmass contains 2—5 mm grains of hornblende. Both the even-grained amphibolite and the porphyritic type are composed of dark-green hornblende and plagioclase (andesine—labradorite) which is partly scapolitized in places. The rock is of a granoblastic texture, with no crystalline forms visible in the hornblende grains. The genesis of the amphibolite cannot be determined with certainty on the basis of the observations. It is probably a matter of a primarily mafic lava in which the various layers may represent distinct lava beds. The chemical composition corresponds to that of tholeiite-basalt (Table 2, Nos. 1—3). The corresponding points on the AFM diagram (Fig. 13) are located close together within the tholeiite field, standing out markedly from those representing the metavolcanites of the Kurtakko area, which lie in the calc-alkali field.

To the south of the amphibolite, the section shows a layer of 40 m of grey-coloured amphibolite-biotite schist, marked off by a sharp, tectonized contact. This is followed further to the south by more amphibolite, so that it would seem to be an interlayer. The schist is fine-grained, obviously bedded and composed of quartz, plagioclase (oligoclase—andesine), amphibole and biotite. Some beds contain garnet as porphyroblasts, in which case the rock contains cordierite in places. The most frequent amphibole is cummingtonite, but the coarser-grained layers containing garnet feature anthophyllite in long lamellae, following the schistosity in an indeterminate manner. The accessory minerals in the schists are magnetite, sulphides, tourmaline and apatite. Some 400 m to the east of the road cutting there is a small outcrop of banded schist which is poorer in quartz. In this rock dark bands containing hornblende alternate with lighter ones in which cummingtonite or diopside are predominant.

These schists would appear to represent metamorphosed tuffites in which varying amounts of epiclastic material have become intermixed with the volcanic material. The one analysis carried out suggests that its chemical composition corresponds to that of a subalkaline andesitic rock (Table 2, No. 7) and is close to that of the schists of the Kurtakko area (Table 3, Nos. 1—4).

The amphibolites of the Ristimella area with their schist interlayers correspond lithologically to the amphibolites of the Saaripudas road cutting. The schists near to the Muonionjoki valley also present fold structures, the axis of which plunges towards the south-west.

The amphibolite encountered at the contact with the Rautuvaara Formation at Juurakkojärvi contains as its dark minerals both hornblende and cummingtonite, the latter generally being in intergrowths with the former. A similar amphibolite is also observed close to the graphite-bearing schist in the drillholes at Saaripudas.

Measurements obtained by the airborne electromagnetic method suggest that the *graphite schist* forms a long, narrow zone turning towards the north at its western end. This is not evident at all in bedrock outcrops, and our information is based entirely on geophysical measurements together with evidence from four drillholes at Saaripudas and some pneumatic drilling.

The graphite schists at Saaripudas occur in a layer of maximum thickness 60 m within the amphibolite, and have interlayers of amphibolite and skarn. The schist is very fine-grained and is composed of feldspar, quartz, biotite and graphite. The parts that

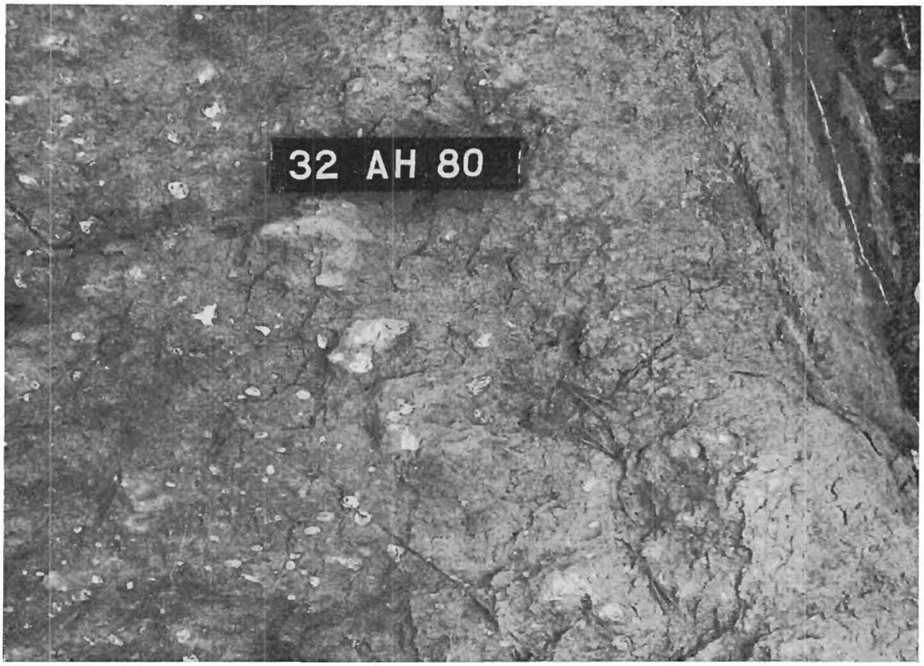

Fig. 15. Quartz and carbonate amygdules in a metavolcanite of the *Kolari Greenstone Formation* at Pissilehto, Kurtakko. The name-plate is 16 cm in length.

are richest in graphite are massive in structure, while the poorer ones are layered. Thin veins of quartz and pyrite are common. The graphite content exceeds 30 % at its maximum, but mostly it remains below 20 %. The skarn interlayers, of thickness less than 20 m, are composed of tremolite, olivine, chlorite and biotite. A little carbonate has also been found in connection with this skarn.

This graphite schist unit appears to be located entirely within the greenstone formation. Thus it differs in position from the graphite-rich schists occurring on the edge of the formation and attributed here to the Rautuvaara Formation.

Rocks of the Kurtakko area

The few outcrops available suggest that the eastern part of the Kolari Greenstone Formation differs from the Saaripudas area described above. A fine-grained, schistose amphibolite consisting of cummingtonite, plagioclase (An 30 %) and biotite and with elongated, quartz and carbonate amygdules is found at Pissilehto. This is texturally the most obvious lava rock in the formation (Fig. 15), and has a chemical composition (Table 2, no. 4) corresponding to the subalkaline andesite, icelandite (Middlemost 1974). A few outcrops in the area between Pissilehto and Saaripudas reveal a highly scapolitized amphibolite (Fig. 16) which consists of poikiloblastic scapolite grains with green amphibole, biotite, plagioclase and diopside in the interspaces. The biotite and amphibole are partially chloritized. Magnetite, sulphides, titanite, carbonate and quartz are present as accessory minerals. The chemical composition (Table 2, no. 5) corresponds to that of the alkaline basalt havaiite, although it should be noted that the primary composition may well have been altered during the scapolitization. Simi-

Fig. 16. Scapolitized amphibolite in the *Kolari Greenstone Formation* at Saaripudas. Thin section 17/4, crossed nicols.

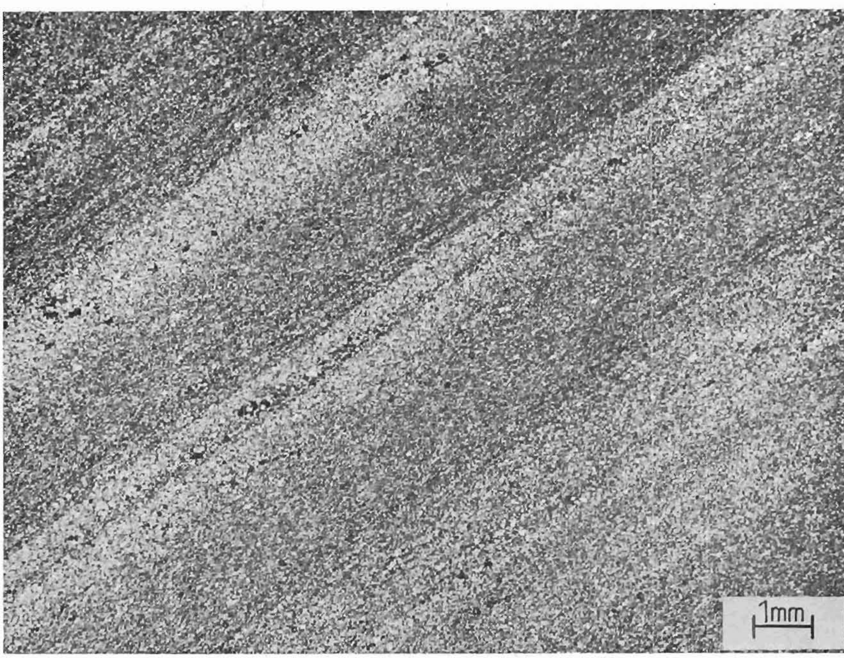

Fig. 17. Cummingtonite–biotite–plagioclase schist in the *Kolari Greenstone Formation* at Kurtakko, drillhole R 2, depth 56.0 m. Thin section 7/3, crossed nicols.

lar scapolitized and in places biotite-rich amphibolites are encountered in outcrops beside the river Ylläsjoki beyond the eastern border of the present study area. It is for this reason, together with the aeromagnetic survey evidence, that the greenstone formation is indicated as continuing right up to the eastern boundary of the area. One feature common to all the amphibolites of the greenstone formation is the occasional occurrence of aggregates and fissure veins of carbonate containing chalcopyrite and pyrite.

The evidence of two drillholes suggests that the dominant rock type at Kurtakko consists of clearly layered, and even graded, fine-grained amphibole—biotite—plagioclase (andesine) schists, also containing varying amounts of quartz (Fig. 17). The amphibole minerals are most frequently cummingtonite and tremolite, and in places also hornblende. Pronounced scapolitization has taken place in many of the layers. The interlayers are composed of schist containing graphite and brecciated chert layers several metres thick.

Since amphibole—biotite-rich schists have also been encountered in samples obtained from the greenstone formation by pneumatic drilling, it would seem that they are more widely distributed than one would conclude from the few outcrops visible. On the basis of their structure and chemical composition (Table 3, Nos. 1—4), these schists can be regarded genetically as basic—intermediate metatuffs corresponding in chemical composition to alkaline basaltic and andesitic rocks. The metavolcanites of the Kurtakko area are located in the calc-alkaline field on the AFM diagram (Fig. 13), but are close to the border with the tholeiite field, as was the case with the amphibolites of the Rautuvaara Formation.

Some of the positive magnetic anomalies in the area of the volcanite formation may be attributed to albite-diabase dykes, of which two identified at oucrops and one established from a pneumatic drilling sample are marked on the bedrock map. The diabase is fine-grained and ophitic in texture, and contains as its main constituents both albitic plagioclase and also hornblende and biotite.

The Saaripudas dyke

The more southerly road cutting at Saaripudas features a rusty-surfaced, homogenous and practically non-oriented rock in which the amount of dark minerals increases towards the south. At the northern end of the cutting it has the composition of albitite, containing a little hornblende and diopside among its dark minerals in addition to albite and quartz. Relatively large amounts of magnetite, pyrrhotite and titanite are found as the accessory minerals, along with a little apatite. The chemical composition of this rock is detailed in Table 3 (No. 5). The composition then becomes more mafic towards the south as the plagioclase becomes richer in anorthite (An 40 %), while the proportion of quartz decreases and that of the dark minerals increases. Although the rock has undergone a certain degree of deformation, it is subhypidiomorphic in texture. This rock type is visible on the magnetic map in the form of an S-shaped anomaly some 2 km in length, so that it is presumably a dyke-like differentiated intrusion cutting across the greenstone formation. An age determination by Kouvo for the albitite gives a minimum age for the volcanite formation of approx. 2000 Ma (p. 52).

The Siekkijoki Greenstone Formation

Definition

The Siekkijoki Greenstone Formation is defined as the formation composed of mafic and intermediate metavolcanites, and also some graphite-rich schists and carbonate rocks, located in the western part of the study area. The Mannakorpi skarn iron ore deposit is associated with the skarn occurring in connection with these carbonate rocks. No exact data are available on the thickness of this formation, but it may reach almost 1000 m at its maximum. The name is derived from the river which flows through the formation.

The Siekkijoki Greenstone Formation resembles lithologically the Kolari Formation, with which it is evidently correlative stratigraphically. In the Siekkijoki case, however, the dominant rocks are mafic—intermediate metatuffites characterized by an albitic—oligoclasic plagioclase, with no evidence of the massive amphibolites described for the Kolari Greenstone Formation at Saaripudas (p. 31). The volcanites of the Siekkijoki Greenstone Formation are richer in alkalis than the amphibolites at Saaripudas, having a chemical composition corresponding to alkaline basalts and andesites (Table 3, Nos. 6—9). These volcanites are located well away from the tholeiite field on the AFM diagram (Fig. 13).

On account of the poverty of outcrops, the data on this formation are essentially based on geophysical interpretations and bedrock samples obtained from excavations, diamond drillholes and pneumatic drilling. This naturally introduces some uncertainty into the stratigraphic conclusions.

The best outcrop showing the rocks of this formation is at Luhtakinkallio on the banks of the river Muonionjoki, where one finds an east—west oriented layered biotite-rich amphibolite with a dip towards the south, and to the north of this dolomitic limestone and skarn. The western part of this outcrop consists of fine-grained quartzite largely resembling the quartzites of the Tapojärvi Formation. There are nevertheless too few exposed surfaces, and the rocks are too highly tectonized, to allow any reliable stratigraphic observations to be made.

Geologically, the Siekkijoki Greenstone Formation lies on a continuation of the Kaunisvaara area in Sweden. Swedish research (Lundberg 1967, Lindroos 1974, Padget 1977) has shown the lowest stratigraphic unit of the Kaunisvaara area to consist of volcanic greenstone. This is overlain by graphite-rich phyllites, and the uppermost stratum contains dolomite and skarn with their associated skarn iron ores. Thus the dolomite-skarn iron ore deposit at Mannakorpi may be regarded as representing stratigraphically the uppermost part of the Siekkijoki Formation, with graphite-rich schists lying below it in the eastern part of the Mannakorpi area.

The largest limestone deposits in the Rautuvaara area, those at Äkäsjokisuu are also assigned to the Siekkijoki Greenstone Formation on the geological map. It was nevertheless impossible within this research to determine their geological position any more precisely.

A section representing the structural interpretation for the area is presented in Fig. 21. According to this the Siekkijoki Greenstone Formation is overlain by the Tapojärvi Quartzite Formation. No observations are available for the lower part of the Siekkijoki Formation, but this structural interpretation would suggest that the sillimanite-rich gneisses of Mustijärvi (p. 22) in the northeast may lie beneath this formation.

The best section representing this formation has been obtained at Jaaravinsa, by means of two drillholes extending some 350 m

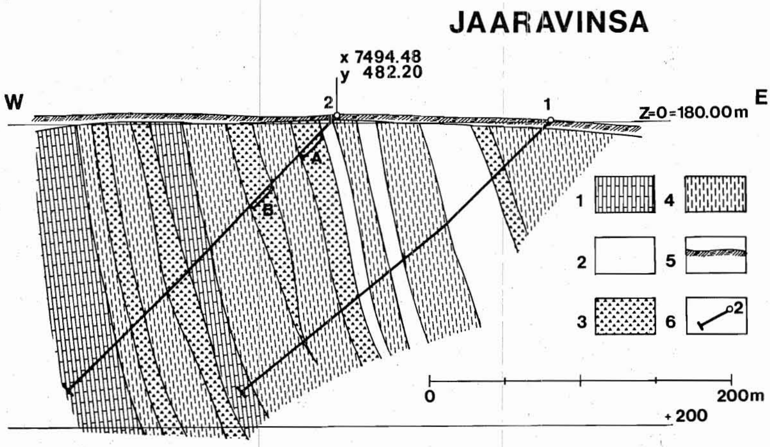

Fig. 18. Geological cross-section of the *Siekkijoki Greenstone Formation* at Jaaravinsa. 1 = carbonate rock; 2 = graphite-bearing schist; 3 = keratophyre; 4 = amphibolite; 5 = ground surface; 6 = drillhole with number; A and B = samples taken for age determination (A 994, Fig. 31).

through the formation (Fig. 18). The eastern part of this section consists of alternate beds of amphibolite and graphite-rich schist and a keratophyre layer 10 m in thickness. In the western part one finds an alternation between keratophyre layers, carbonate-rich amphibolites and carbonate beds. These layers are 10—30 m thick.

Rock type description

The *amphibolite* is fine-grained and prominently layered and is composed mainly of plagioclase (albite—oligoclase), light-green hornblende and biotite. There may also be some quartz, and opaques, titanite, apatite and carbonate may be found as accessory minerals. There are thin interlayers of schist and chert, which also occurs in some places as small, lens-like inclusions (Fig. 19). This rock corresponds to an alkaline basalt (Table 3, No. 6) or a trachybasalt (No. 7) in its chemical composition. The descriptions suggest that the amphibolite corresponds to the volcanites of Kaunisvaara, which are regarded as tuffs or tuffites (Lundberg 1967), a group

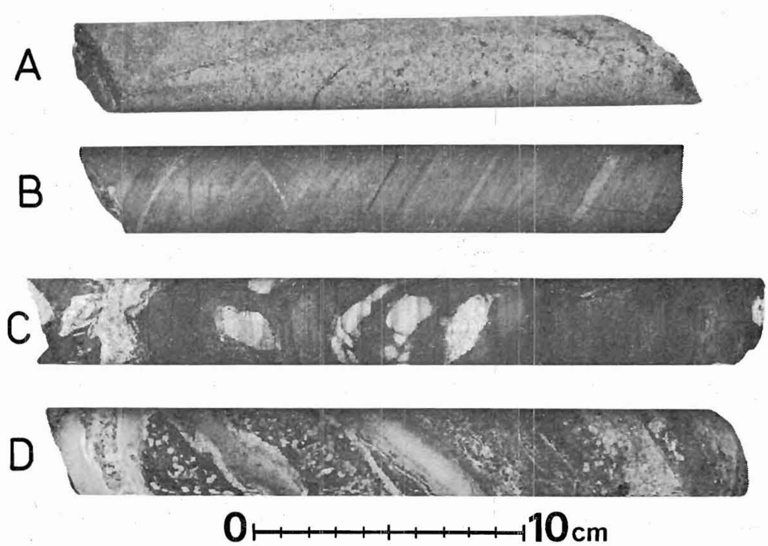

Fig. 19. Rocks of the *Siekkijoki Greenstone Formation*. A = keratophyre, Jaaravinsa, drillhole R 2, depth 182.2 m; B = metatuffite, Jaaravinsa, R 2, depth 168.0 m; C = chert fragments in the metatuffite, Jaaravinsa, R 2, depth 123.0 m; D = magnetite streaks in the metatuffite, R 2, depth 47.0 m.

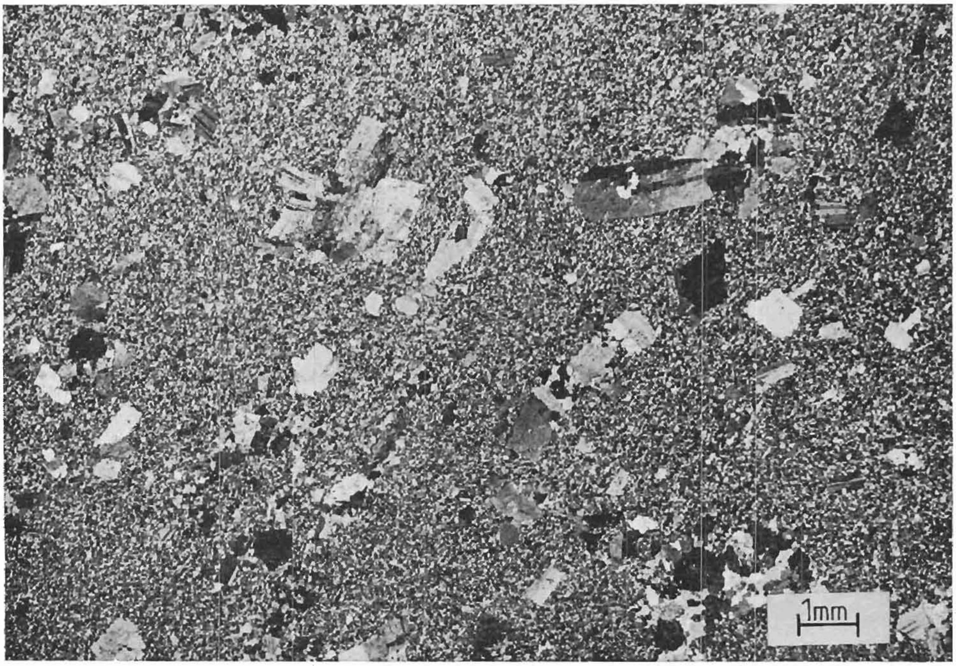

Fig. 20. Keratophyre in the *Siekkijoki Greenstone Formation*, with phenochrysts of albite and a groundmass of albite, carbonate, biotite and hornblende. Jaaravinsa, drill-hole R 2, depth 74.2 m. Thin section 19/4, crossed nicols.

to which the layered amphibolites of the Siekkijoki Formation would most naturally belong in respect of their structure and composition.

At Mannajärvi, to the north of a limestone deposit which dips gently to the north-east, we find an exposed, brecciated amphibolite rich in carbonate and consisting predominantly of light-green amphibole. This rock corresponds in its composition to the carbonate-rich amphibolite at Jaaravinsa and is correlated with this.

The *graphite-rich schist* is a very fine-grained (grain size 0.05 mm), layered schist composed of feldspar, quartz, biotite and graphite, with alternating darker and lighter bands. Some of the layers contain scapolite or tremolite porphyroblasts. The schist has undergone pronounced small-scale folding and regularly contains thin veins or scattered grains of pyrrhotite and pyrite. Its graphite content is 3—8 % C and its sulphur content 5—8 % S.

The *carbonate* rock forms grey banded units in which there are also varying amounts of tremolite, biotite and scapolite. Fragments of graphite schist and amphibolite also occur. The amount of carbonate rock in the Jaaravinsa section increases towards the west, which must, by analogy with Kaunisvaara, represent the upper part of the deposit, suggesting that the whole formation has been overturned to the west.

The interlayers of *keratophyre* are composed of a massive porphyric rock with a groundmass mainly of albite and to a lesser extent carbonate. Biotite and light-coloured hornblende are also present in places. The phenochrysts are idiomorphic zoned plagioclase albite—oligoclase in composition (Fig.

20). The largest of these grains encountered measure 4 mm, while the grain size of the groundmass varies in the range ∅ 0.01—0.1 mm. The rocks are generally homogeneous and non-oriented. The contacts are usually schistose and can even have a banded structure of probably tectonic origin. Small amounts of chalcopyrite and pyrrhotite are regularly found as disseminated grains or fissure veins. Other accessory minerals are titanite, apatite and zircon. Two keratophyre analyses are given in Table 3 (Nos. 8 and 9). These correspond to andesitic volcanites.

An age determination for the zircon in this rock (p. 53) gives an Archean age, suggesting that the whole Siekkijoki Formation may be Archean. This presupposes, of course, that the zircon is cogenetic with the keratophyre and not from some external source.

One of the amphibolite beds between the layers of keratophyre has been found to contain bands of magnetite (Fig. 19) some 4 m thick. This magnetite itself features inclusions consisting of albite—carbonate spots of size less than 5 mm and of a composition corresponding to the keratophyre, with which the magnetite would thus seem to be linked genetically.

The Tapojärvi Quartzite Formation

Definition

The term Tapojärvi Quartzite Formation is applied to the formation comprising principally quartzite metasediments which dominates the western part of the study area. The other members are conglomerate, forming the interlayers, and phyllite and mica schist in the upper part. The formation takes its name from the lake and village of Tapojärvi about which it is centred. Mikkola (1941, p. 167) referred to the area as the Tapojärvi quartzite area and correlated it with the quartzite of Kuertunturi, regarding both of them as older than the »Kumpu quartzite». Even so, the Tapojärvi quartzite does differ markedly from its counterpart at Kuertunturi both lithologically and stratigraphically, and would best be classified as the »Kumpu quartzite» in Mikkola's terminology.

The rocks of the Tapojärvi Quartzite Formation are visible in the topography as a series of NE—SW-oriented elongated hills having a fairly large number of outcrops. On the aeromagnetic map the quartzite areas are more or less free of anomalies, but a few narrow, weak positive anomalies are associated with the schist areas, giving evidence of layers containing disseminated magnetite. The formation may be more than 1000 m thick at its maximum.

Structurally, the Tapojärvi Formation takes the form of a series of broadish synclines, the easternmost of which is crossed by a fault between Táporova and Tahkovaara. The westernmost syncline is less well exposed and is disturbed by intrusions. The most clearly defined and best exposed of the synclines is that lying to the west of Tapojärvi. A section to the west of this lake serving as the type section for this formation (Fig. 21).

The dominant rock in the lower part of the formation, on the edges of the synclines, is a grey sericite quartzite which is usually obviously schistose. The lower contact has not been observed at Tapojärvi itself, but that between the quartzite and the schists below it in the Tahkovaara syncline would seem to involve a gradation. At Jaaravinsa the quartzite would seem to be lying on top of the Siekkijoki Greenstone Formation, but again the contact itself is not visible.

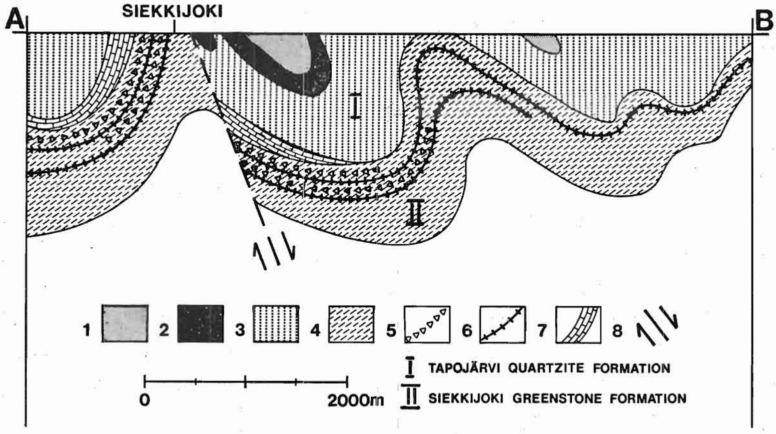

Fig. 21. Geological cross-section of the interval Jaaravinsa—Tahkovaara (cf. geological map). *I Tapojärvi Quartzite Formation:* 1 = mica schist; 2 = phyllite; 3 = sericite quartzite. *II Siekkijoki Greenstone Formation:* 4 = amphibolite; 5 = keratophyre; 6 = graphite-bearing schist; 7 = carbonate rock; 8 = fault line.

Rock types of the lower part

The *sericite quartzite* consists of quartz grains some 0.2—1 mm in size separated by flakes of mica (Fig. 22). Both muscovite and biotite are found, but the latter in much smaller quantities. There are also varying amounts of plagioclase (oligoclase) and potassium feldspar. The accessory minerals include opaque (mostly hematite), apatite, zircon, tourmaline, rutile and titanite. The quartzite varies in mineral composition from something approaching a sericite schist to a variety poorer in mica and richer in feldspar. Chemical compositions for the sericite quartzite and its arkosic interlayers are given in Table 4 (Nos. 1 and 2). No actual orthoquartzites have been encountered, however. The bedding

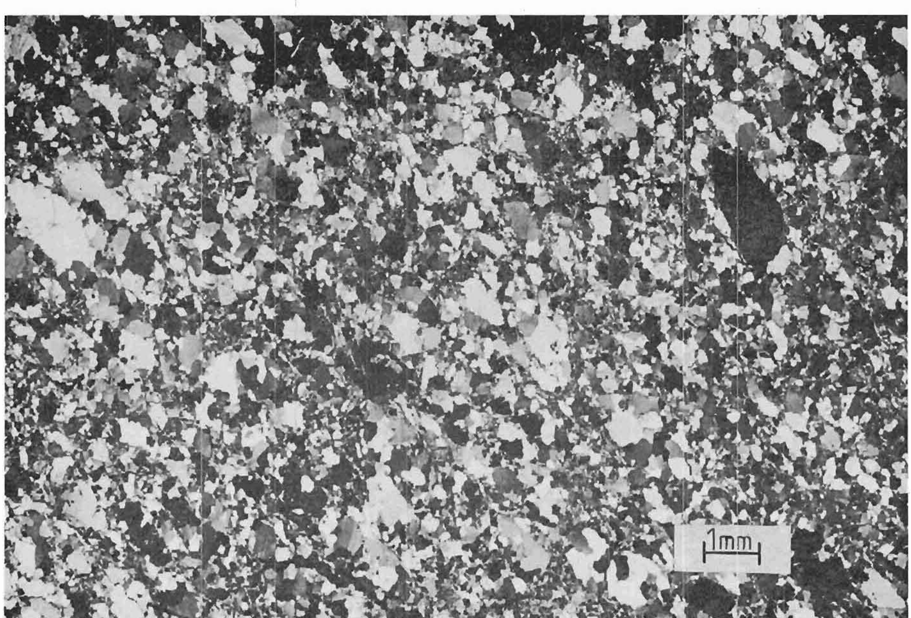

Fig. 22. Sericite quartzite of the *Tapojärvi Quartzite Formation* at Mustivaara. Thin section 17/25, crossed nicols.

Table 4

Chemical compositions of the rocks of the Tapojärvi Quartzite Formation (%/o by weight), determined as detailed in Table 1.

No.	1.	2.	3.
SiO_2	78.00	83.00	68.46
TiO_2	0.22	0.28	0.75
Al_2O_3	10.50	9.19	15.20
Fe_2O_3	0.46	0.36	1.79
FeO	0.40	0.20	1.30
MnO	0.00	0.00	0.03
MgO	0.40	0.17	2.19
CaO	0.34	0.31	2.19
Na_2O	2.70	5.07	1.78
K_2O	5.94	0.10	4.44
P_2O_5	0.16	0.14	0.27
CO_2	$<$ 0.1	$<$ 0.1	0.10
H_2O+	0.70	0.30	1.40
H_2O-	0.05	0.07	0.11
S	0.00	0.00	0.00
Total	99.87	99.19	100.01

1. Sericite quartzite, Taporova, anal. 969 2020
2. Arkose quartzite, Taporova, anal. 969 2021
3. Metasilt, Jaaravinsa, anal. 969 2042

is usually well preserved, and cross bedding is clearly visible in many places, e.g. in road cuttings on both flanks of the syncline to the west and north of Tapojärvi. A neat slumping structure occurs in the cross-bedded, almost silt-like quartzite on the top of Alainenvaara (Fig. 23).

Characteristic of the quartzites are their interlayers of polymictic *conglomerate,* which vary in thickness from less than a metre to some tens of metres. Narrow beds of conglomerate are visible on the slope of Mustivaara to the north of Tapojärvi and at Jaaravinsa, for instance. The matrix of this conglomerate is sericite quartzite or a quartzite containing feldspar and poorer in mica. The fragments are predominantly of quartzite and contain both a grey or white, usually fine-grained quartzite and the red grains of jasper quartzite regarded by Mikkola (1941) as typical of the »Kumpu conglomerate». Some of the fragments are apparently vein quartz, and there are also some occasional dark schist fragments, many containing hematite. These fragments are rounded and somewhat elongated in the direction of lineation, and they vary in size from less than

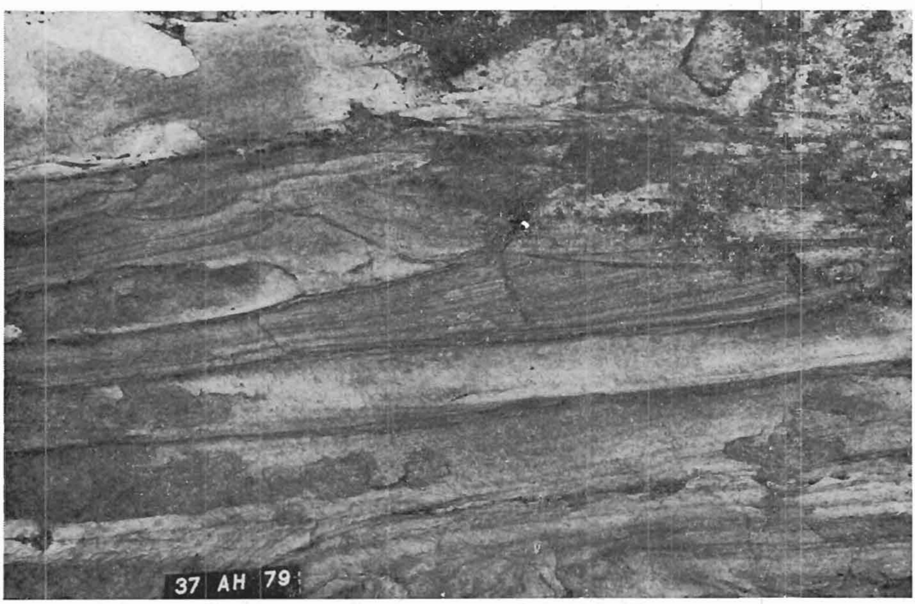

Fig. 23. Cross-bedding and a slumping structure in the sericite quartzite of the *Tapojärvi Quartzite Formation* at Alainenvaara. The name-plate is 16 cm in length.

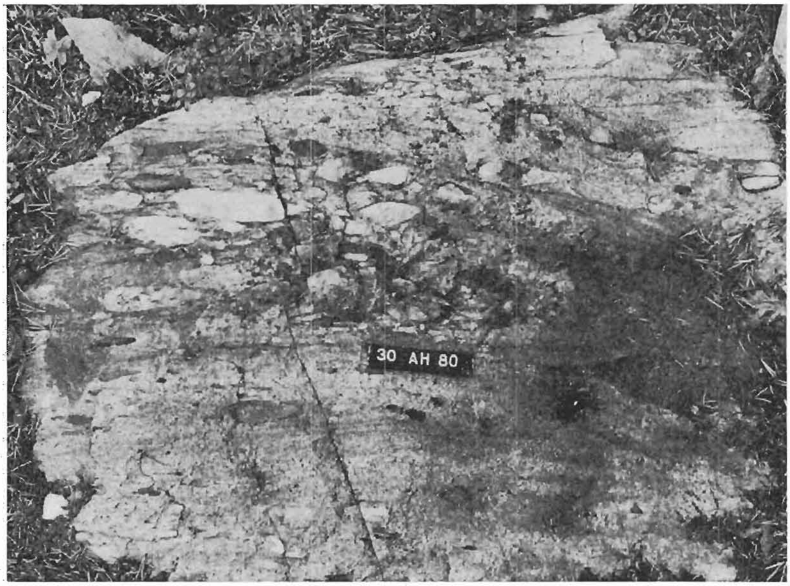

Fig. 24. Conglomerate bed within the sericite quartzite of the *Tapojärvi Quartzite Formation* at Mustivaara. The fragments are chiefly of light-coloured quartzite, with some red chert and hematite-bearing schist. The name-plate is 16 cm in length.

1 cm to about 10 cm (Fig. 24). The incidence of these fragments varies from individual ones occurring in the quartzite to conglomerate beds with high numbers of these.

Rock types of the upper part

Mica-rich schists occur on top of the quartzite at the centre of the Tapojärvi syncline. The contact is visible at Alainenvaara, where the feldspar-rich quartzite grades to a dark, fine-grained *phyllite* within a few metres. A similar gradation is also visible in exposed bedrock to the north of the Jaaravinsa road. The phyllite is of a grain size of 0.05—0.1 mm and is composed of quartz, accounting for about a half of the material, and also biotite, muscovite, oligoclase and potassium feldspar. The phyllite layer may be over 100 m in thickness.

The western part of the syncline, to the south of the Jaaravinsa road, is composed of fine-grained, light-coloured silt-like schist corresponding in position to the phyllite in the eastern part, but differing from it in that the mica is almost entirely muscovite and instead of the plagioclase is potassium feldspar. In both cases the accessory minerals are tourmaline, apatite and opaque. The chemical composition of the metasilt is indicated in Table 4 (No. 3).

The very centre of the syncline, and therefore the uppermost part of the formation, is composed of grey, folded *mica schist* containing partly sericititized andalusite porphyroblasts. This rock differs from the phyllite both in the presence of these porphyroblasts and in having biotite as its principal mica and muscovite only as an accessory mineral. This rock can be seen in the form of local boulders beside the Jaaravinsa road and in outcrops to the west of the main Muonio road. The contact with the phyllite is not visible, but would seem on the evidence of boulders beside a local road in the south-eastern part of Paannejänkä to involve a gradation. The thickness of this mica schist formation is most likely of the same order as that of the phyllite, although the intense folding makes more precise estimation difficult.

The Taporova area

The dominant rock in the Taporova—Tahkovaara area consists of quartzites with interlayers of conglomerates. The outcrops on the eastern slope of Taporova provide particularly good examples of the grading of sericite quartzite to arkosic quartzite, while purer quartzites are to be found in the southwestern part of Taporova. The top of Taporova features a highly schistose conglomerate with pebbles of quartz and lenses of a skarn-like rock. On the southern slope the quartzite grades to an andalusite-rich mica schist which would seem to correspond to the andalusite mica schist of the Tapojärvi syncline.

Associated with the schists in the eastern part of Taporova are the Taporova hematite deposit, containing baryte in places, and the Suuoja hematite deposit (Hiltunen and Tontti 1976, Lindberg 1976).

The Luosujoki conglomerate

To the east of the Niesakero quartzite area there is a conglomerate occurrence over a kilometre in width running in a north-south direction and possessing a contact with the quartzite complex on its western edge, along the river Luosujoki. On its eastern edge, between the conglomerate and the Yllästunturi quartzite, there is a thin bed of carbonate rock, and on top of this a layer about 20 m thick of banded, highly deformed red schist composed mainly of fine-grained albite and containing a little amphibole and some micas.

Stratigraphic observations show that this conglomerate runs below the Yllästunturi quartzite. Its contact with the quartzite complex to the west is obviously tectonic in character, as suggested by the extremely pronounced schistosity of the conglomerate and the westward dip in this schistosity. The fragments in the conglomerate are composed of quartzite, schists, amphibolite and plutonic rocks (Fig. 25). The majority of the quartzite pebbles are white orthoquartzite, apparent derived from the quartzite complex. In places there are also pebbles of a dark, fine-grained tourmaline-rich quartzite not known elsewhere in the study area. The schist fragments contain quartz-feldspar schist and biotite-plagioclase schist, apparently derived, like the majority of the amphibolite fragments, from the Kolari Greenstone Formation. The plutonic rock pebbles consist of both gabbroic and light-coloured aplitic rocks. The fragments are elongated rod-like in the direction of lineation. The matrix is composed of biotite-rich amphibolite containing plagioclase (oligoclase), hornblende and biotite, and also a little quartz and a large amount of magnetite, which also occurs in some of the fragments. Thus the conglomerate stands out as an obvious positive anomaly on the magnetic map. The composition of the material contained in the conglomerate would suggest that the majority of this is derived from the greenstone formation, above which it is located stratigraphically. With the southernmost outcrop of this conglomerate being found to the south of Niesaselkä, the whole occurrence reaches some 16 km in length.

The stratigraphic position of the conglomerate would seem clear at the local level, but its relation to the stratigraphy of the whole study area is more difficult to demonstrate. Its formation will in any case have required a significant period of erosion to have elapsed after the formation of the quartzite complex, but must have taken place before the deposition of the Yllästunturi quartzite. Rastas (1980) assumes that the Luosujoki conglomerate belongs to the Lower Jatulian Group.

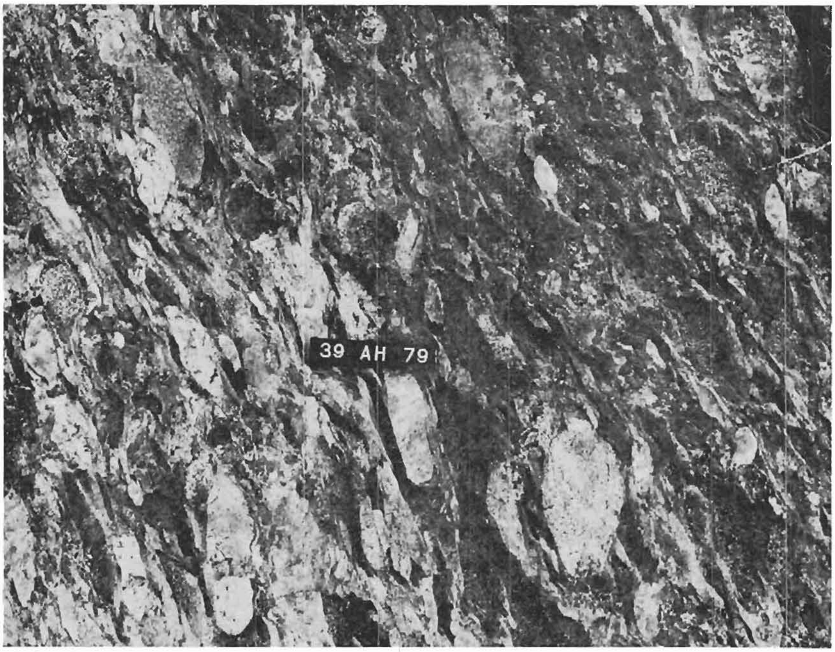

Fig. 25. A polymictic conglomerate at Luosujoki. The fragments are of orthoquartzite, tourmaline-bearing quartzite, quartz–feldspar schist, biotite-plagioclase schist, amphibolite, and intrusive rocks, and the matrix is amphibolite containing biotite and magnetite.

The Yllästunturi—Kukastunturi quartzite area

The Ylläs—Kukastunturi unit overlies both the Luosujoki conglomerate and the Niesakero—Kuertunturi quartzite complex and falls within the group of »Kumpu quartzites» as defined by Mikkola (1941). Rastas (1980) places the Ylläs—Kukastunturi quartzite in the Middle Jatulian Group. At least its contact with the quartzite complex, to the west of Kukastunturi, is tectonic.

Lithologically the Ylläs quartzite resembles that of the Tapojoki Formation, and they are obviously stratigraphically correlative.

Intrusive rocks

The albite—diabase dykes encountered in the Kolari Greenstone Formation and the »Saaripudas dyke» are described briefly in connection with the formation concerned (p. 35). The other intrusive rocks comprise the gabbro massif in the western part of the area, the monzonite intrusion with its marginal varieties, which dominates the central part, and the microcline granite which appears to cut across all the other rocks.

The Jakokoski gabbro

A positive anomaly in the extreme west of the study area on the aeromagnetic map denotes a gabbro massif which is exposed at a number of points beside the river Muonionjoki, e.g. at Jakokoski. The differentiation of this medium-grained, homogeneous plutonic rock is evident in the variation in the composition of the plagioclase, from An 32 % to

Table 5

Amounts and magnetite, Fe, Ti and V content (% by wt.) of magnetic concentrates in samples of the Jakokoski gabro obtained by pneumatic drilling.

Locality	Anal. no.	Mass of mag. conc.	Magnetite content	Fe	Ti	V
Pyytieva	837 1062	7.7	99.5	63.8	0.08	0.27
	837 1058	2.8	96.4	64.9	0.32	0.23
Rantavuoma	837 1064	10.8	87.9	65.5	1.10	0.49
	837 1077	5.5	93.0	67.3	0.28	0.42
	837 1078	6.6	99.3	69.0	0.63	0.38

An 60 %. The main dark minerals are orthopyroxene, clinopyroxene, hornblende and biotite, and the accessory ones opaque, apatite, titanite and secondarily scapolite and epidote. The majority of the opaque consists of magnetite, containing a greater than usual amount of vanadium and titanium (Table 5). One cannot be certain about the age of this gabbro, although Mikkola (1941) regards it as a mafic differentiate belonging to the Western Lapland syenite series.

The monzonite intrusion

The monzonite intrusion comprises the feldspar-rich plutonic rocks of the central part of the study area, which vary in composition from quartz monzonites to quartz diorites and belong to the intrusions described by Mikkola (1941) under the rocks of the syenite series. In the classification of Streckeisen (1973), this rock type representing the southern part of the plutonic rock area and referred to by Mikkola as the Lakkavaara syenite would correspond in its mineral composition to monzonite (Table 6, No. 1). The determinations carried out on samples from Hannukainen and Rautuoja would represent quartz monzonite and quartz monzodiorite (Table 6, nos. 2—5). The chemical compositions of the main rock types are presented in Table 7 (nos. 1—3).

Table 6

Mineral compositions of the rocks of the monzonite intrusion (% by volume).

Mineral	1.	2.	3.	4.	5.
Potassium feldspar	25.0	34.3	36.0	31.5	18.0
Plagioclase	45.0	44.7	34.5	46.0	55.5
Hornblende	15.0	9.4	11.8	9.8	10.6
Diopside	7.0	—	—	—	—
Quartz	2.0	7.3	8.1	7.4	8.3
Biotite	0.5	2.1	6.2	1.0	5.9
Opaque	3.0	0.6	1.3	1.8	0.5
Titanite	1.2	0.7	1.1	1.3	0.3
Apatite	1.3	0.7	0.8	0.6	0.3
Others		0.2	0.2	0.6	0.6

1. Monzonite, Lakkavaara (E. Mikkola 1941)
2. Quartz monzonite, Hannukainen R 62, depth 5.00 m
3. Quartz monzonite, Rautuoja R 18, depth 92.00 m
4. Quartz monzonite, Laurinoja R 91, depth 182.9 m
5. Quartz monzodiorite, Kivivuopio R 162, depth 95.0 m

The monzonite is visible on the aeromagnetic map as an area of even magnetism at a higher level than that of the quartzite areas and possessing a number of isolated weak positive anomalies. The Paloselkä monzonite area is delimited on the bedrock map by reference to pneumatic drilling samples and the aeromagnetic map, and the area in the south-east indicated as monzonite by reference to the aeromagnetic map and a number

Table 7

Chemical compositions of the rocks of the monzonite intrusion and its marginal zone (%o by weight), determined as detailed in Table 1.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	60.78	59.20	57.29	56.00	52.50	53.60	52.90
TiO_2	0.73	0.77	1.10	0.75	0.30	0.33	0.95
Al_2O_3	15.10	15.60	15.70	16.60	19.90	21.20	17.10
Fe_2O_3	3.98	3.70	3.24	2.89	5.78	5.23	3.62
FeO	2.89	3.32	4.00	4.68	5.54	3.41	3.76
MnO	0.09	0.12	0.14	0.12	0.08	0.06	0.16
MgO	1.90	2.30	2.98	3.20	2.50	1.40	3.20
CaO	3.59	4.12	5.18	5.51	1.41	3.51	9.65
Na_2O	4.80	4.91	4.66	5.80	5.70	6.96	5.46
K_2O	4.29	4.22	4.32	2.45	3.72	1.78	0.83
P_2O_5	0.25	0.30	0.59	0.32	0.25	0.30	0.39
H_2O+	0.60	0.50	0.47	0.90	1.50	1.10	0.80
H_2O-	0.00	0.03	0.06	0.12	0.12	0.11	0.05
S	0.00	0.00		0.15	0.23	0.11	0.13
Total	99.00	99.09	99.73	99.49	99.53	99.10	99.00
— O				— 0.07	— 0.11	— 0.05	— 0.06
				99.42	99.42	99.05	98.94

1. Quartz monzonite, Hannukainen R 72; 90 m, anal. 936 0016
2. Quartz monzonite, Cu-Rautuvaara R 109; 159 m, anal. 936 0062
3. Monzonite, Lakkavaara (E. Mikkola 1941)
4. Monzodiorite, Cu-Rautuvaara R 109; 200 m, anal. 936 0064
5. Monzodiorite, Hannukainen R 112; 80 m, anal. 936 0010
6. Diorite, Hannukainen R 112; 101 m, anal. 936 0012
7. Diorite (vein in skarn), Hannukainen R 72; 208 m, anal. 936 0027

of outcrops falling beyond the eastern boundary of the study area. This latter rock would seem to belong to the Kallio syenites described by Mikkola (1941).

The rocks of the monzonite intrusion show, broadly speaking, conformable contacts with the sedimentary rocks. The most common rock in the intrusion is a gneissic, reddish, or less often grey, homogeneous monzonite or quartz monzonite (Table 6, Nos. 1—4). At least the more weakly schistose types have retained their hypidiomorphic texture. The grain size is 0.5—3 mm, with the larger grains consisting of plagioclase (An 10—25 %) or potassium feldspar. Quartz is regularly encountered, and the mineral determinations show it to be generally sufficiently abundant as to justify designation of the rock as quartz monzonite. The most common dark mineral is hornblende, which forms aggregates of grains several millimetres in length and oriented in the direction of lineation. Biotite is found to a minor extent and diopside occasionally. The most frequent accessory minerals are apatite, opaque and titanite, the latter occurring both as independent grains and in rims around the opaque. Other accessory minerals are epidote carbonate and zircon.

In addition to this major type, other rocks are found in the western part of the monzonite intrusion which differ markedly from monzonite but are evidently associated genetically with the intrusion. At Kiuaskero, representing the roof of the intrusion, one finds an extensive area of small-grained, light-coloured porphyric rock close to quartz diorite in composition, referred to by Mikkola (1941) as »syenite porphyry». This would seem to be a more superficial type belonging to the monzonite intrusion. Similarly a grey, subophitic rock is found at Mannajärvi, to the south-west of Kiuaskero, in which the main constituents are plagioclase (oligoclase), scapolite, hornblende, quartz, biotite and epidote. This rock has the composition of quartz diorite and presumably falls among the more basic variants of monzonite.

The marginal zone between the monzonite intrusion and the Rautuvaara Formation

The area between the monzonite and the Rautuvaara Formation is occupied by a discontinuous intrusive unit varying in thickness from about 30 m to almost two hundred metres, in which the dominant rocks are dioritic (Table 8). The most abundant mineral, plagioclase, is usually oligoclase, but may also be albite or andesine. In places scapolite occurs as the light mineral instead of plagioclase. The main dark minerals are biotite, diopside and hornblende, and the accessory minerals potassium feldspar, quartz, epidote, apatite, titanite, carbonate, zircon and the magnetite, pyrite and sometimes chalcopyrite which are especially typical as scattered grains within diorite.

Table 8

Mineral compositions of the rocks of the marginal zone of the monzonite intrusion in the Hannukainen area (% by volume).

Mineral	1.	2.	3.	4.	5.	6.
Potassium feldspar	10.4	6.5	13.1	0.3	0.2	—
Plagioclase	67.0	69.4	66.2	83.0	78.3	48.9
Quartz	15.7	10.8	2.8	—	—	—
Hornblende	—	0.5	1.9	—	16.9	42.3
Diopside	—	11.0	8.2	—	—	6.1
Biotite	3.0	—	6.1	11.5	2.4	1.0
Opaque	1.9	—	0.7	4.9	0.8	0.1
Titanite	—	0.5	0.9	—	—	0.4
Apatite	0.7	0.4	0.1	0.3	0.1	0.5
Others	1.3	0.3	—	—	1.3	0.7

1. Quartz monzodiorite, light zone adjacent to monzonite, Laurinoja R 95, depth 118.0 m
2. Quartz diorite, light zone adjacent to monzonite, Vuopio R 60, depth 79.4 m
3. Monzodiorite, light zone adjacent to monzonite, Laurinoja R 91, depth 186.8 m
4. Diorite, central part of the marginal zone, Laurinoja R 91, depth 208.5 m
5. Diorite, dark zone close to skarn, Laurinoja R 91, depth 246.0 m
6. Diorite, dark zone close to skarn, Laurinoja R 91, depth 255.7 m

The composition of the diorite at Hannukainen has been shown to alter from the monzonite contact towards the skarn in the sense that the most common dark mineral, biotite, decreases in quantity in that direction and increasing amounts of hornblende appear in the rock, and eventually even diopside. At the same time the rock changes in external appearance from light-grey to a darker shade. This gradation is seen clearly in Table 8, in which No. 4 represents the type with biotite dominant, No. 6 the type containing diopside and No. 5 an intermediate type.

Fig. 26 depicts the analyses of the composition of the rocks of the monzonite intrusion, as listed in Table 7, arranged on a triangular graph after Sangster (1969) constructed from the mean values for the composition of plutonic rocks given by Nockolds (1954). The deviation of the points for the monzonite intrusion well to the right of the mean concentration is an indication of a higher concentration of $Na_2O + K_2O + Al_2O_3 + Fe_2O_3$. The variation in chemical composition among the rocks of the monzonite intrusion (nos. 1—4) implies as far as the components indicated in the diagram are concerned only a change in the proportion of SiO_2 in the same manner as the mean concentrations change in the direction of a more mafic status. In the case of Nos. 5 and 6, however, which represent rocks on the marginal zone of the intrusion, a sudden jump has taken place towards the right-hand corner of the diagram as a result of increases in the proportions of alumi-

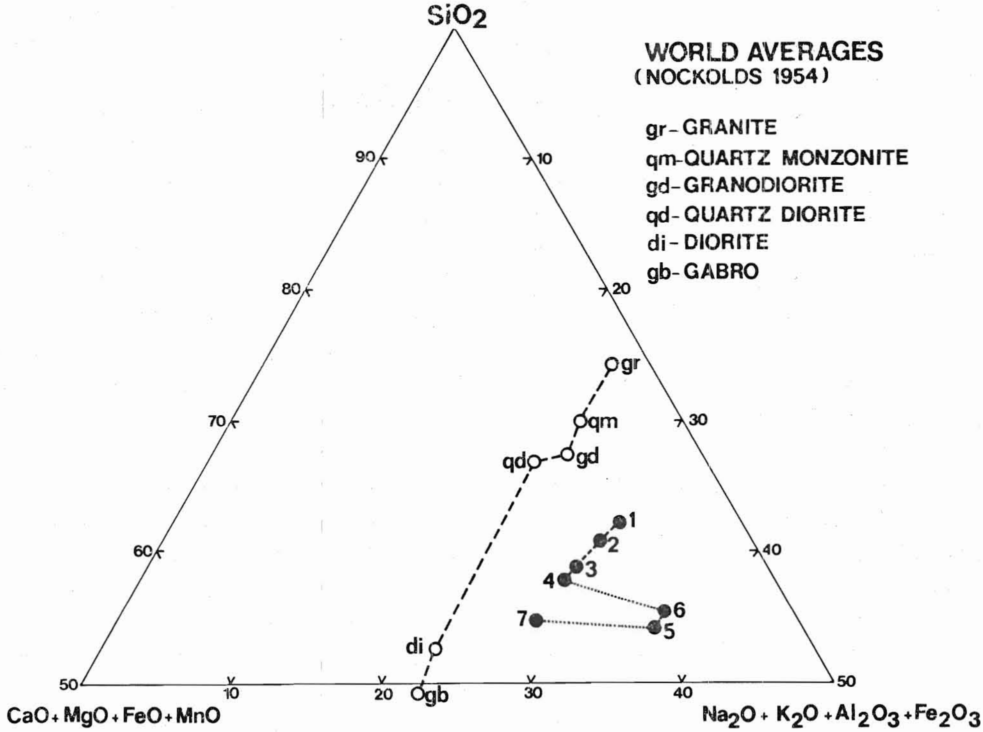

Fig. 26. Compositions of the rocks of the monzonite intrusion and its marginal zone. Nos. 1—7 refer to the analyses in Table 7. The broken line indicates the change in composition of the plutonic rocks from granite to gabbro according to the mean compositions quoted by Nockolds (1954).

nium and ferric iron, and also in part of sodium. In contrast, No. 7, which represents the narrow diorite tongue in the skarn, fits in well as a continuation of the monzonite points, but is exceptional in its high Ca content, quite obviously the consequence of a secondary addition of calcium. Comparison of the composition of the monzonite and diorite indicates that this is not a case of normal magmatic differentiation. Thus the diorite is referred to as a marginal variety of the monzonite intrusion.

The contact between the monzonite and diorite is a sharp one in places and a gentle gradation in others. In addition one often finds at or near the contacts light-coloured varieties, usually several tens of metres thick, with a composition varying from quartz syenite to syenite and albitite. The diorite-dominated rocks at these contacts form an entity in which extensive small-scale variations are found, chiefly due to fluctuations in the amounts of dark minerals and their abundances relative to one another. It is significant, however, that the dominant light mineral, plagioclase, does not vary very much in composition, but has an An value below 30 % even in the darkest types.

The contact between the diorite and the skarns of the Rautuvaara Formation is generally a conformable one and sharp. The diorite frequently contains skarn inclusions near the contact, however. Where it forms veins a certain mixing can be observed in the skarn, causing this to gain narrow, light-coloured diorite streaks or causing the diorite to assume progressively more and more flecks and streaks of skarn. An advanced degree of mixing seems to have taken place between these rocks. It is thus evident that the diorite-dominated rocks at the contact between the monzonite intrusion and the Rautuvaara Formation have arisen through an interaction between the monzonite magma and the sedimentary rocks. These contact phenomena will be dealt with in more detail in the second part of this paper.

Granite and pegmatite

Microcline granite and pegmatite occur in numerous intersecting veins and round-shaped bodies, particularly at the edges of the monzonite intrusion and in the area of the Niesakero—Kuertunturi quartzite complex. The largest individual granite areas are at Kiuaskero, Ulkuvaara and Kihlanki, in the central and northern parts of the study area. Only some of the smaller granite bodies are marked on the bedrock map. The granite varies from homogeneous, even-grained, reddish-coloured types to non-homogeneous pegmatitic types composed almost entirely of microcline and quartz.

RADIOMETRIC AGE DETERMINATIONS

In order to establish the age relations between the rocks of the Rautuvaara area, the author collected in collaboration with the Petrological Department of the Geological Survey of Finland a number of samples for which radiometric age determinations could be carried out. The samples were obtained from the skarn of the Rautuvaara Formation, the mafic pegmatoid which crosses this formation, the margin of the monzonite intrusion, the Saaripudas albitite which cuts across the Kolari Greenstone Formation and the keratophyre of the Siekkijoki Greenstone Formation. The U-Pb analytical data and isotope ages for the zircons and titanites in these samples are listed in Table 9. The results are examined in more detail in the following.

The mafic pegmatoid sample (A 959, Fig. 27) was taken from a narrow, coarse-grained vein cutting across the skarn rock and skarn ore in the Rautuvaara mine and consisting chiefly of plagioclase, hornblende and diopside. The zircon age for this rock, 1748 ± 7 Ma, is the youngest one obtained for the zircons of the Rautuvaara area. This zircon is characterized by a markedly high uranium content and a low common lead content, lead denoting possibly mafic origin. This also departs from all the other samples in having a very low value for ^{208}Pb, suggesting a source in which the ratio U/Th is high.

The same age as for the zircon of the pegmatoid was also obtained for a single crystal of titanite 5 cm in diameter taken from the skarn in the Rautuvaara mine (sample A 949, Fig. 27). One significant feature about this titanite is the low common lead content of its source material, i.e. the exceptionally high 206 Pb/204 Pb ratio for a titanite (Table 9).

The sample of the albititic marginal variety of monzonite (A 958, Fig. 28) was taken from the foot wall of the Sininen ore body in NE-Rautuvaara, from a point close to a contact with the ore at which there is an albititic variety several metres wide. The titanite in this rock is exceptionally poor in lead, in the same manner as the titanite crystal of sam-

Table 9

U-Pb analytical data and isotope ages for zircons and titanites from the Rautuvaara area.

Sample No.	Zircon fraction ($g.cm^{-3}$/grain size, μm)	^{238}U ppm	Radiogenic ^{206}Pb, ppm	$^{206}Pb/^{204}Pb$ (measured)	Isotopic abundance relative to ^{206}Pb (= 100)			Radiometric ages, Ma					
					204	207	208	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±
A840A	d > 4.6, m > 160	337	94.2	5569	.014158	11.609	12.096	1803	± 10	1828	± 5	1857	± 4
A840B	titanite	298	81.4	990	.097239	12.364	45.397	1771	13	1781	10	1794	16
A840C	d > 4.6, m < 70	339	92.8	2812	.030484	11.802	12.938	1774	12	1810	7	1852	4
A840D	4.2 < d < 4.6	539	140.5	2964	.030224	11.759	11.519	1697	11	1765	7	1846	4
A840E	4.0 < d < 4.2, m > 70	878	221.7	2112	.044820	11.935	12.019	1650	11	1736	6	1842	3
A949A	titanite	346	88.7	2385	.037812	11.257	35.118	1671	12	1704	7	1745	6
A958A	titanite	282	76.5	4650	.017351	11.188	59.673	1761	13	1770	8	1782	6
A958B	4.2 < d < 4.6	937	239.2	3646	.023991	11.607	12.412	1666	12	1743	8	1835	5
A958C	d > 4.6	677	169.2	2353	.027184	11.629	17.963	1635	12	1723	9	1832	10
A958D	4.0 < d < 4.2	1202	290.5	3211	.027097	11.628	13.598	1588	50	1696	30	1832	4
A959A	4.0 < d < 4.2, m < 160	2922	711.4	6659	.012640	10.850	2.284	1598	12	1658	8	1735	4
A959B	3.8 < d < 4.0, m < 160	2541	555.9	3798	.022518	10.813	3.070	1452	10	1558	7	1705	6
A959C	3.6 < d < 3.8	3222	496.8	3644	.022164	10.479	2.929	1057	8	1268	7	1646	7
A959D	4.0 < d < 4.2, m > 160	2647	645.4	8473	.008944	10.804	3.637	1600	12	1660	8	1736	5
A959E	3.8 < d < 4.0, m > 160	2988	615.4	7143	.011133	10.666	2.533	1376	10	1511	7	1707	5
A959F	3.8 < d < 4.0, m < 160	2694	563.5	9248	.008725	10.654	2.222	1395	10	1525	6	1711	4
A963A	d > 4,6	388	97.6	1166	.072898	12.005	25.515	1644	13	1709	9	1790	10
A963B	4.2 < d < 4.6	855	213.8	3458	.025572	11.360	20.270	1636	13	1705	8	1791	5
A963D	4.0 < d < 4.2, m < 200	1610	370.1	2945	.030491	11.388	14.197	1518	11	1633	7	1785	4
A963E	titanite	232	63.2	10323	.005814	11.019	37.993	1763	12	1771	7	1780	5
A964A	d > 4.2	200	59.8	4493	.017126	12.549	16.330	1914	14	1952	8	1994	6
A964B	4.0 < d < 4.2, m > 160	275	77.6	6587	.009804	12.271	20.070	1821	15	1890	9	1968	6
A964C	d > 4.6	161	49.3	6524	.007151	12.451	14.922	1951	23	1974	13	1999	7
A964D	4.2 < d < 4.6	220	65.9	4493	.017250	12.610	16.625	1920	15	1960	9	2002	6
A964F	4.2 < d < 4.6	220	64.8	10940	.004535	12.425	16.357	1889	12	1943	7	2000	3
A994aA	d > 4.2	217	66.3	90.7	1.07913	29.812	54.922	1948	14	2206	10	2454	9
A994bB	d > 4.2	193	52.6	197.5	.42252	20.443	47.623	1766	13	2044	21	2337	29
A994aC	titanite	104	25.8	2052	.03827	11.413	19.554	1626	11	1690	7	1771	7
A994bD	titanite	72.6	19.7	4027	.01134	11.206	36.647	1760	11	1778	8	1798	7

The isotope analyses and radiometric age calculations were made at the Geological Survey of Finland. For analytical techniques the reader is referred to Krogh (1973). All ages are calculated with the decay constants given by Jaffey et al. (1971). Least squares regression of $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ data giving upper and lower intercepts with concordia (error: 2 sigma) have been calculated according to York (1966).

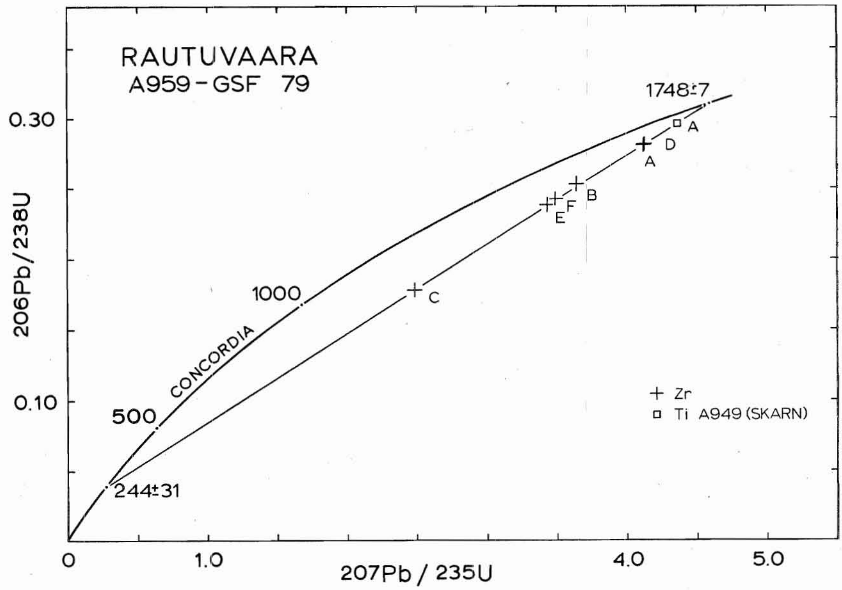

Fig. 27. U-Pb concordia diagram for zircons from the Rautuvaara mafic pegmatoid and a titanite crystal of diameter 5 cm from the Rautuvaara skarn. Letters refer to the analytical data in Table 9.

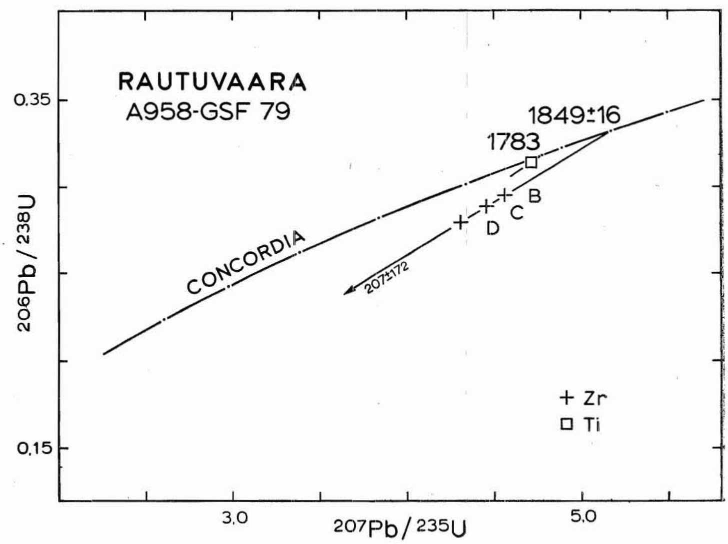

Fig. 28. Concordia plot for zircons and one titanite from the albititic variety of the Rautuvaara monzonite. The zircon fractions lie on a chord which has upper and lower concordia intercepts corresponding to ages of 1849 ± 16 and 207 ± 86 Ma respectively. The off-set and younger age for titanite appears to be a real effect and typical of the Kolari region.

ple A 949. Arguing from the lead ratios, the mafic pegmatoid (A 959) and the albitite (A 958) differ radically in their U/Th ratios. The younger age obtained for the titanite compared with the zircon is a typical feature of the Rautuvaara area.

The monzonite sample (A 840) was taken from the hanging wall of the Kivivuopio ore body and the skarn sample (A 963) from Kuervaara (Fig. 29). These sites are indicated in Fig. 42.

The zircon ages show the monzonite to be much older than the skarn, although the isochron for the monzonite has deviated as a result of metamorphism to intersect that for the younger skarn. Similarly the titanite in

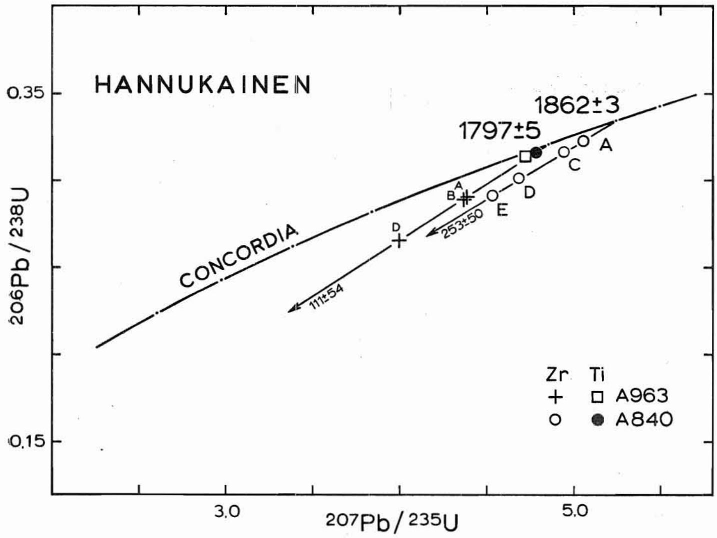

Fig. 29. Concordia diagram for the U-Pb ratios of zircons and titanites from the Hannukainen monzonite (A 840) and skarn (A 963). The lower intercept of 253 Ma for the monzonite zircons as compared with 111 Ma for the skarn minerals indicates episodic loss of lead.

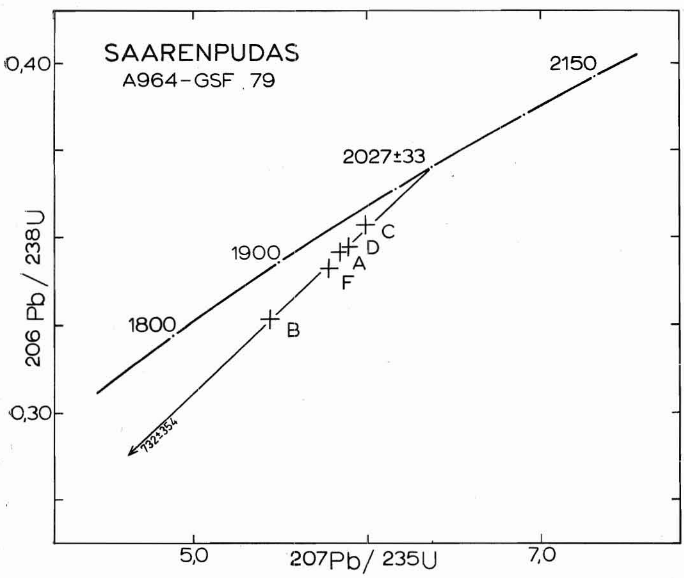

Fig. 30. U-Pb concordia diagram for five zircon fractions from the Saaripudas albitite dike cutting across the *Kolari Greenstone* (A 964). The linear array has an upper intercept age of 2027 ± 33 Ma, corresponding to radiometric age data obtained for younger Karelidic hypabyssial dikes. The lower intercept with concordia at 732 Ma suggests an episodic loss of lead. This is supported by a preliminary age of 1820 Ma for titanite in the same rock sample.

the monzonite is indicative of pronounced recrystallization and its age is the same as that of the skarn minerals, suggesting that the uranium and lead were mobile at the time of metamorphism or close to that time.

The albitite sample (A 964, Fig. 30) was taken from the albititic part of a differentiated vein at the more southerly road cutting at Saaripudas (p. 35). This rock would seem on the basis of the zircon to be very poor in uranium. The source material must have been mafic and poor in lead, judging from the high 206 Pb/204 Pb ratios. The age given is a typical Early Karelidic age, and the preliminary

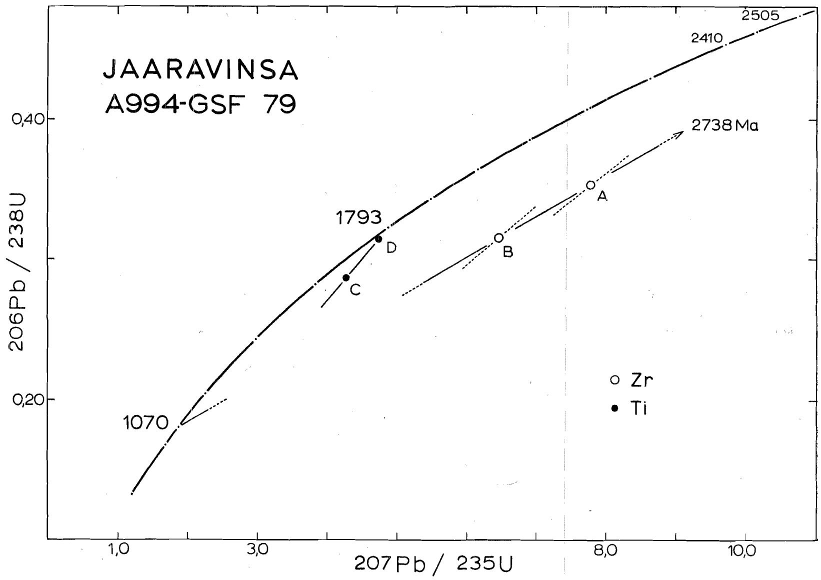

Fig. 31. Concordia diagram and U-Pb isotope ratios for zircon and titanite samples from the Jaaravinsa keratophyre (A 994).

age for the titanite, approx. 1820 Ma, represents the time of metamorphism and indicates pronounced recrystallization.

The keratophyre sample (A 994, Fig. 31) is from the two keratophyre layers in the upper part of the Siekkijoki Greenstone Formation. The sites (A and B) are marked on the section in Fig. 18 and the rock is described on page 38. The titanite results are similar to those of samples A 840, A 958 and A 964, and correspond to diffusion lines of 1787 Ma (C) and 1799 Ma (D). One limitation on the interpretation of the zircon data is that only one fraction from two samples was available (2 mg and 6 mg). A tentative interpretation would be that the two-point chord joining them has an upper intersection equivalent to an age of 2738 Ma, or else that they may not be cogenetic and thus fall on diffusion lines corresponding to ages of 2410 Ma and 2505 Ma. No detailed conclusions can be drawn, but their distribution suggests an Archean age of crystallization close to a minimum age of 2400—2500 Ma, or a maximum estimate of 2738 Ma. Any definitive conclusions would require additional research.

In addition to the above age determinations, the same zircon age has been obtained for the porphyritic quartz diorite of Kiuaskero (p. 46) as for the albititic marginal variety at Rautuvaara (A 958), i.e. approx. 1850 Ma (M. Lehtonen, personal communication). It should be noted that these ages are slightly younger than that obtained for the monzonite, 1862 Ma.

STRUCTURAL INTERPRETATIONS

A detailed description of the structure of the central part of the study area, the area of Rautuvaara itself, has been presented earlier, and the reader is referred to this (Hiltunen and Tontti 1976). Here a general description will simply be provided of the main structural features of the whole area.

Fold structures

The area can be divided into four main parts on the basis of the rock types present, each of these parts having its characteristic fold structure. The eastern part is dominated by the rocks of the Niesakero—Kuertunturi quartzite complex, the central part by the plutonic rocks of the monzonite intrusion, the western part by the metasediments of the Tapojärvi Quartzite Formation and the southern part by the metavolcanites of the Kolari Greenstone Formation. The predominant folding in the area has taken place with respect to a NE-SW axis. This deformation, which also involved the monzonite intrusion, had a profound influence upon the structure of the Rautuvaara area, reworking any structures that had arisen from previous deformations. An apparently younger deformation phase which had a less prominent effect then gave rise to folding with respect to a NW-SE axis mainly in the south-west, which is where the relevant fold axis observations have been made. Similar conclusions can be be reached on the basis of the direction of lineation in the north-east and the tendency for the fold axial plane to link to the NW in that area. The principal fold axial planes, the most important observations of fold axis and lineations are indicated on the tectonic interpretation map in Appendix 2.

The Niesakero—Kuertunturi area

The dominant structural feature in this area is the extensive Niesakero anticlinorium, to the north-west of which is the less distinct Rautuvaara—Kuertunturi anticlinorium. The central part of the intervening Rautuhelukka synclinorium, which opens out to the south-west, is filled by the monzonite intrusion. The fold axis and lineations plunge regularly to the south-west, in the western part of the complex with the dip varying from horizontal at the culmination to 60°, and most commonly lying in the range 20—40°. An axial culmination lies to the north of Niesakero. To the east of this the fold axis and lineations plunge towards the NNE. Here the dip is gentle, usually below 20°.

Folding has been intensive, and the dips of the bedding towards the north-west are suggestive of overturning to the south-east. The sillimanite gneisses in particular have frequently undergone such pronounced small-scale folding that is impossible to make reliable deductions on the stratification. The shearing connected with this folding, together with the axial plane cleavage, has given rise to pronounced lineation, which is particularly clearly reflected in the elongation of the fragments in the Luosujoki volcanic conglomerate in the eastern part of the complex to form rod-like structures. The purer quartzites of the upper part of the complex have behaved in a more peaceful manner under folding although the lineation arising from this is still clearly discernible in the texture.

On account of the low incidence of primary sedimentary structures, conclusions concerning the stratigraphic position and internal stratigraphy of the quartzite complex have to be based to a great extent on structural interpretations. The well-defined shape and structure of the Niesakero anticlinorium suggest that it represents a section deeper than its surroundings. A curving in the bedding to follow the anticline is clearly visible at Niesaselkä, and the position of the Niesaselkä orthoquartzite, overlying the sillimanite quartzite, appears to be clearly in evidence. Internal folding within the anticlinorium nevertheless makes it difficult to obtain a detailed interpretation at many points. The interpretation suggests that the mica gneiss beds of the complex lie either in the synclines, e.g. at Hyyverova, or on the flanks of an anticline, e.g. at Malmivaara.

The dip in the bedding and the coincident dip in the schistosity are both steeper and more clearly concentrated in a north-westerly direction in the area to the south-east of Äkäsjoki than they are in the Kuertunturi area to the north-west, where the bedding slopes in a very gentle manner. The bedding again slopes more steeply towards the north-west in the northernmost part of the complex. Taken as a whole, the Niesakero—Kuertunturi quartzite complex represents an area of intensive deformation in which folding has brought with it pronounced shearing and faults with some overturning towards the south-east.

The area of the monzonite intrusion

The conformability of the contacts involving plutonic rocks of the monzonite intrusion and the coincidence of their foliation with that of the sedimentary rocks are facts which suggest that these rocks were involved in the folding process. Shearing associated with folding is suggested by the pronounced lineation, while the foliation is less well-developed. The same interpretation can also be given to the narrow, lens-like bodies of the intrusive rocks which follow the stratification in the direction of the lineation at Hannukainen.

It is evident that the intrusion of monzonite on top of the Rautuvaara Formation took place in a conformable manner during the early stages of folding, filling the centres of the synclines at Rautuhelukka and Tiuraselkä. The dip of the contact with the intrusive is regularly 20—30° in a westwards direction in the area to the north of Äkäsjoki, whereas the contacts with the metasediments are steep ones to the south of the river. This suggests that folding was more intensive to the south of Äkäsjoki than to the north. More pronounced deformation is seen in the area of the syncline between the monzonite lying south-west of Rautuvaara and the Niesakero quartzite area, and overturning to the south-east has also taken place here. The straight-lined nature and thick overburden of the north-western edge of the quartzite area is indicative of the tectonic character of the contact, which may also involve overthrusting to the south-east. The rocks of both the intrusion and the Rautuvaara Formation in the vicinity of the contact are highly tectonized, as may be seen at Sivakkalehto.

The monzonite intrusion itself has proved more resistant than the surrounding rocks and has folded in a relatively gentle manner. The most pronounced deformation has been concentrated upon the sedimentary rocks of the contact areas. Deformation associated with folding was largely conformable, and thus more plastic, at the eastern contacts of the intrusion than in the west, where sedimentary fragments have sometimes remained inside the intrusive rock, e.g. at Taporova.

The Tapojärvi area

The style of folding seen in the area located at the roof of the monzonite intrusion, composed of sedimentary rocks of the Tapojärvi Formation, differs markedly from the complicated and often small-scale folding of the Niesakero—Kuertunturi quartzite complex. Folding is intensive, but regular and open, and the axes of folding in the well-exposed north-eastern part of the area plunge regularly 20—35° to the south-west. In the case of the poorly exposed south-western part of the area data are only available from the outcrops beside the river Muonionjoki, where the axis of minor folds of the highly tectonized volcanites runs in an ESE direction. The depression in the south-west has been interpreted entirely from the geological and geophysical maps, since no direct observations are available.

The Tapojärvi Formation is dominated by NE—SW-oriented synclines, the mica-rich schists of the upper parts of which show small-scale folding. The axial plane in the western part of this area dips steeply to the south-east, and the folds are thus overturned to the north-west.

The most pronounced deformation has occurred in the south-eastern part of the area, close to the Äkäsjoki fault. The very clear lineation of 30—40° to the south-west is seen best in the hematite-rich schists of Taporova, which form a syncline. The major limestone deposit at Äkäsjoki is interpreted by Lackschewitz (1958) as a syncline, a conclusion which fits in well with the overall structure of the area.

The Kolari greenstone area

Few observations are available on the structure of the Kolari Greenstone Formation in the southern part of the study area on account of the small number of exposures. The area may be interpreted as a broad synclinorium, in which the intensive folding is recognized on the basis of the long, narrow aeromagnetic and electromagnetic anomalies, observed to be regular in pattern. The dips in the bedding and foliation at the Saaripudas outcrops are steep, and there is a pronounced lineation that plunges 25—40° to the WSW. The direction of the fold axis curves gradually westwards from the practically north-south orientation found in the east. It is possible that the Saaripudas and Ristimella greenstone areas may converge on the Swedish side of the border.

Faults

The faults indicated on the geological map are based on both geological observations and interpretations and also interpretations of aerogeophysical and air photograph data. The aim is not to indicate all possible faults, but to limit the material to those that are of obvious significance for the overall geological picture.

The most clearly defined fracture zone with associated faults, and obviously the largest, is the valley of the river Äkäsjoki, which runs across the centre of the area from north-east to south-west. The rocks in the vicinity of this line have undergone pronounced deformation. Folding has been shown to have been less violent to the north than in the intensively folded area to the south, which has also been lifted somewhat in relation to the northern area. This in turn explains the occurrence of the stratigraphically higher Tapojoki Formation in the western part of the area.

The fault is interpreted as continuing in the schist area to the south of Taporova in the form of at least three parallel lines, turning sharply to the south-west at the same time. One of the fault lines links up with the contact with the monzonite intrusion, and mylonitization has taken place at this point. These faults coincide with, or at least come close to, the direction of the fold axial plane.

A fault running in the same direction is to be found to the west of Tapojärvi, where the contact between the Siekkijoki Greenstone Formation and the Tapojärvi Quartzite Formation is interpreted as being tectonic in character. A vertical fault zone running NE—SW at the contact with the quartzite complex is associated with the narrow, compressed syncline at Tiuraselkä, in the north-eastern part of the area. This fault zone has been shown by drilling to be as much as 200 m wide and it has undergone substantial weathering, to a depth of over 100 m in places.

NE—SW-oriented faults are found in association with the contact between the quartzite complex and the Rautuvaara Formation in the area to the south-east of the monzonite intrusion, and the weak, straight-lined electromagnetic anomaly running across the centre of the Niesakero anticlinorium has also been interpreted as a fault. The NE—SW-oriented faults described above are all closely associated with fold structures and represent the general direction of faulting in the area.

A second common direction of faulting is perpendicular to the axial plane, i.e. NW—SE. Faults of this kind cut off the fold structures at Taporova and Hannukainen, for instance. Although more faults of this kind could be quoted than are marked on the maps, they still account for a smaller proportion of the total than do the NE—SW-oriented faults, which are interpreted as predating them.

In addition to the above, one finds some shortish faults running from east to west, of which those passing across the lake Mannajärvi are interpreted as cutting through the northern part of the Äkäsjoki limestone deposit. The most significant fault and fracture zone with a north—south orientation is that running north from Äkäslompolo between the quartzite complex and the Kukastunturi quartzite, in which the rocks are heavily mylonitized. The quartzite complex has been raised above the level of the stratigraphically higher Kukastunturi quartzites, and thus the contact is regarded as a tectonic one.

EXTRA-REGIONAL CORRELATION

In his summary of the stratigraphy of the Kittilä area, Rastas (1980) makes a number of general comparisons which also concern the Rautuvaara area. He compares the sericite quartzites and mica schists of the Kittilä area, which are assigned to the Upper Lapponian Group with the sillimanite—quartzite—mica schist zone of Western Lapland, which also includes amphibolites, carbonate rocks and skarns (op.cit). Rastas is of the opinion that the volcanites of the Kittilä greenstone complex had erupted over the sericite quartzites and mica schists, and could therefore be compared with the metavolcanites of the Rautuvaara area. No volcanite corresponding to the amygdaloidal rock of Kaukonen which underlies the sericite quartzite, and which is attributed to the Lower Lapponian Group, can be identified in the Rautuvaara area. The rocks in the Rautuvaara area corresponding to the sedimentary rocks of the Kumpu Formation deposited on top of the greenstone complex are those of the Tapojärvi Quartzite Formation and the Yllästunturi—Kukastunturi quartzite area, and also the Luosujoki conglomerate, which Rastas (op.cit.) assigns to the Lower Jatulian Group while the quartzites represent the Middle Jatulian. According to the age divisions used by Rastas (op.cit., Fig. 2), the Niesakero—Kuertunturi quartzite complex, the Rautuvaara Formation, the Kolari Greenstone Formation and the Siekkijoki Greenstone Formation would all be Archean in age and the Tapojärvi Quartzite Formation Proterozoic. One piece of evidence in support of this view, although at present insufficient to prove the point, is the Archean age obtained for the zircon in the Siekkijoki keratophyre.

The closest stratigraphic units showing comparability with the formations of the Rautuvaara area are on the Swedish side of the border, where the Kaunisvaara area constitutes a direct south-western extension of the Siekkijoki Greenstone Formation and the Tapojärvi Quartzite Formation. Correlation over an extensive part of Northern Sweden has also been facilitated by the appearance in recent years of a number of geological maps and their explanatory keys concerned with the Norbotten area in which lithostratigraphic aspects are also mentioned. This is true of the works of Eriksson and Hallgren (1975) for the Vittangi area, Padget (1970, 1977) for Tärendö and Pajala, and Ambros (1980) for Lannavaara and Karesuando. These authors come close to one another in their stratigraphic views, the basic outlines of which may be expressed as follows:

The oldest stratigraphic unit deposited on the Archean basement complex is composed of metavolcanites and metasediments. Various names are applied to this unit in different areas, e.g. the Veikkavaara Greenstone Group (Padget 1970), the Vittangi Greenstone Group (Eriksson and Hallgren 1975), and the Kiruna Greenstone Group (Ambros 1980). The lowermost formation within this group in the Vittangi and Lannavaara areas is the Tjärron Quartzite Formation deposited onto granite gneiss (Ambros 1980). This formation may well be comparable in its stratigraphic position with the Niesakero—Kuertunturi quartzite complex in the Rautuvaara area. Two greenstone formations with sedimentary formations between and above them are reported to overlie the Tjärron Quartzite Formation in the Vittangi area (Eriksson and Hallgren 1975), and the rocks of these may well correspond lithologically to the metavolcanites and graphite-rich schists, and also the skarns and carbonate rocks, of the Kolari and Siekkijoki Greenstone Formation and the Rautuvaara Formation.

The skarn iron ore deposits of Northern Sweden, e.g. those of the Kaunisvaara area (Padget 1977) and the Lannavaara—Karesuando area (Ambros 1980), are also included in the Greenstone Group.

The quartzite-dominated stratigraphic unit overlying the uppermost sediments and mafic schists of the Greenstone Group is known by the terms Pahakurkkio Group (Padget 1977, Ambros 1980) or Kilavaara Quartzite Group (Eriksson and Hallgren 1975). Rocks of this group are found above the volcanite group in the Kaunisvaara area, for instance (Padget 1977). A direct connection can be made between these and the rocks of the Tapojärvi Quartzite Formation on the Finnish side of the border.

The sedimentation of the Pahakurkkio Group was followed by folding and intrusion of the plutonic rocks of the Haaparanta suite. These rocks are of an age of 1880 Ma (Welin *et al.* 1970), which corresponds to that of the monzonite of the Rautuvaara area. According to Lundqvist (1979), the supracrustal rocks of eastern Norrbotten, which are older than the plutonic rocks of the Haaparanta suite mainly belong to the Karelian epicontinental facies, and are of an age of 2200—1950 Ma, which coincides with the opinion of Simonen (1980) on the age of the supracrustal formations in Northern Finland.

The intrusion of the plutonic rocks of the Haaparanta suite was followed by an erosion phase, after which the rocks of the Kiruna Porphyry Group were deposited, and also the younger sedimentary rock units, e.g. the Maattavaara Quartzite Group in the Vittangi area (Eriksson and Hallgren 1975).

The above discussion leads us to conclude that the stratigraphy of the Rautuvaara area shows many similarities to the oldest stratigraphic units in Northern Sweden. The description given of the lowermost volcanites, which occur extensively in Sweden, is more detailed than it has been possible to achieve in the case of the poorly exposed volcanites of the Rautuvaara area. No stratigraphic units have been discovered, in the Rautuvaara area, however, which correspond to the younger volcanites of the Porphyry Group, common in Northern Sweden or to the sedimentary rocks younger than these.

PART II: THE GEOLOGY, GEOCHEMISTRY, ORE MINERALOGY AND GENESIS OF THE SKARN IRON ORES OF THE RAUTUVAARA AREA

INTRODUCTION

The aim in this second part of the paper is to discuss in greater detail the skarn iron ore deposits of the Rautuvaara area and the deposits regarded as genetically comparable to these, with the main purpose of providing a general account of the known ore deposits, their relation to the gangue materials and the manner and conditions of formation of the ores. Since this object of study comprises 11 separate deposits, many of which include a number of ore bodies, the main emphasis is placed upon the petrographic description of the principal deposits, although the important role of metasomatic phenomena makes it essential to extend the petrochemical examination to the chemical changes found in the gangue rocks. The previous research carried out on this subject and the methods used for the present purposes are explained on pages 9—11. An account of the trace elements found in the magnetite is to be published later in a separate connection. The work is intended to enable the construction of a general scheme for the ore geology of the Rautuvaara area, for which complementary detailed studies of the mineralogy and geochemistry are required. Some of these are already in progress.

ON THE CONCEPTS OF SKARN AND SKARN ORES

Historical

The term skarn was introduced into the literature by Törnebohm in his work on the mining district of Persberget (1875) and the bedrock of Central Sweden (1880—1882), having been used by the local miners to denote the worthless gangue material found alongside the ore. Törnebohm proposed (1875) at that stage that the word skarn, used of the odd dark rocks occurring in indeterminate layers within felsic volcanite, or eurite, in the manner of carbonate rocks and constituting the true gangue material, should be used as a collective term for all rocks of that kind which deviate from the surrounding bedrock. He also distinguished two type of skarn on the basis of their mineral composition: garnet-rich, or garnet—pyroxene skarn and garnet-free skarn (op.cit.).

Many people studying metamorphic phenomena at contacts involving carbonate rocks at the beginning of this century settled upon the concept of metasomatic changes in contact reactions (Lindgren 1905, Kemp 1907, Goldschmidt 1911). Correspondingly, ore deposits associated with such contacts were referred to by the terms 'contact-metamorphic', 'contact-metasomatic', or 'pyrometasomatic'. Kemp was the first person to draw attention to the wide distribution of andradite as a contact-metamorphic mineral. He, like many others, suggested that it was a hot aqueous solution or steam from the magma that had introduced silica, iron oxide and aluminium into the limestone, together with the sulphides of copper and iron, which are the most common skarn ores (Kemp 1907).

Goldschmidt (1911) defined the alteration in the limestone at a contact as having taken place as a process of metasomatic pneumatolysis in which certain elements were bound to the passing magmatic gases and became enriched at the same time. In his opinion limestone acting as the absorption material caused not only ores but also contact rocks to be formed in this manner. The most common phenomenon of this kind, he claimed, was the formation of skarns, the term being given highly genetic overtones in this way. Even so, not all skarns had been formed from limestone by metasomatic contact metamorphism, although the majority had (op.cit.). In common with most other authors, Goldschmidt assumed that the iron was transported in chloride form. He also noted that skarn deposits were all remarkably similar mineralogically, and distinguished just two main types, andradite skarn and hedenbergite skarn. He assumed magnesium skarns to have arisen from dolomite as the source material. The first mention in a Finnish context is by Eskola (1914), who proposed that the skarn rocks of Orijärvi had been formed from limestone by a process of metasomatic replacement in which Fe, Mg and SiO_2 had been introduced into the rock.

One consequence of the genetic research into skarns was that the term was extended in its usage, gradually gaining new meanings from the differing interpretations. The genetic nonhomogeneity of skarns was emphasized by such authors as Geijer and Magnusson (Geijer and Magnusson 1944, 1952, Geijer 1959, Magnusson 1970) and Watanabe (1960). The former divided skarn ores into two main types:

1. Reaction skarn ores, formed at temperatures sufficiently low as to allow the carbonates of Ca, Mg, Fe and Mn to be in contact with free SiO_2 without the formation of silicates. Skarn formation has then resulted from a later rise in temperature. The original deposits were in some cases chemical-sedimentary and in others hydrothermic-metasomatic.

2. Primary skarn ores, formed at sufficiently high temperatures to allow skarn to form together with the primary ore, usually by contact metasomatism.

These authors note, however, that it may be difficult to draw the line between these two types, since reaction skarn ores can also gain additional elements by metasomatism (Geijer and Magnusson 1944, Geijer 1959). Piirainen and Piispanen (1967) then brought up the idea the primary skarn ores may arise through a reaction between the magma and the carbonate rock, releasing CO_2, which then causes the separation of two immiscible liquids one of iron oxide and the other of silicate.

Watanabe (1960) distinguishes four genetic groups of skarns:

1. Reaction skarn, corresponding to that of Magnusson and Geijer.

2. Recrystallized skarn, which is a hornfels-type product of the thermometamorphism or dynamometamorphism of impure limestone.

3. Primary skarn, which is formed at the contact between an intrusive magma and a carbonate rock.

4. Secondary skarn, which is formed from a carbonate rock by a replacement process caused by high-temperature fluid released from the magma, and is associated in many cases with the occurrence of ore minerals.

The ideas put forward by these authors have attracted relatively little attention in recent decades, during which the skarn research has been concentrated largely in the Soviet Union, where the term has become firmly established to refer to a genetically metasomatic deposit (Zharikov 1970). Among the factors influencing theoretical research into skarns, particular mention should be made of the theories of Korzhinsky (e.g. 1964, 1970) concerning metasomatic processes and their applications to skarn reactions. These start out from a definition of a metasomatosis as any substitution process which alters the chemical composition of a rock, provided that the minerals of the older host rock are dissolved and the new minerals precipitated at practically the same time, so that the rock remains in a solid state throughout. Thus a metasomatosis cannot include a process in which the rock becomes molten or requires a significantly high degree of porosity (Korzhinsky 1964). A second precondition for a metasomatic process is the existence of pore liquids or gases which precipitate some mineral components and remove others.

According to Korzhinsky's theory, a metasomatosis may take place either by diffusion or by infiltration. Diffusive metasomatism involves reactions which require the mediation of a fluid, e.g. as a consequence of a chemical inbalance at the contact between two rocks, so that a series of zonational mineral parageneses is established on account of the differential rate of diffusion as the system moves towards equilibrium. Since diffusion via pore fluids in a mineral material is extremely slow, the transport of mineral elements achieved by it does not extend more than some tens of metres. Thus metasomatic changes in large rock units can take place only on the infiltration principle, i.e. in rocks saturated by flowing mineralized fluids. Replacement reactions will then occur whenever the rock is not in chemical equilibrium with the fluid, giving rise to alterations in the composition of both. The metasomatic minerals that result will depend on the crystallization conditions, the composition of the fluids and the relative activity of the various components. Korzhinsky (1964) presents the following series, in descending order of activity, for contact-metamorphic zones involving limestones and for high-temperature transformation zones generally: H_2O, CO_2, S, K_2O, Na_2O, O_2, MgO, Fe, CaO, SiO_2, P_2O_5, Al_2O_3, TiO_2. The least active in all metasomatic systems are phosphorus, aluminium and especially titanium. According to the infiltration theory, skarns formed close to the contact between silicate and carbonate rocks at times when there was convection of hot fluids. These fluids carried chemical compounds derived from the abyssal magma chamber or the surrounding rocks. Korzhinsky particularly favours the latter source, and discusses contact infiltration skarn formation in the light of this. In this way skarns located entirely within silicates or carbonates can be explained as being due to material entering the fluids in the course of convection (Korzhinsky 1964).

Definition and classification of skarns

With the establishment of the genetic concept of skarn in the Soviet Union, summaries have also appeared in English in which these rocks are defined and attempts are made to classify them (Zharikov 1970, Smirnov 1976, 1977). Zharikov (1970, p. 543) would seem to understand the concept of skarn in the following manner: »Skarns are limy-magnesial-ferruginous metasomatic silicates and aluminosilicates formed in high temperature zones of contact halos of intrusions by interactions implemented by magmatogenic solutions between carbonate rocks and magma or intrusives or other aluminosilicate rocks». He thus emphasizes that skarns are not just any calcium, magnesium or iron silicates, but only those which have associated contact-metasomatic ores formed at high temperatures. The term aposkarn would seem appropriate for rocks formed as the alteration products of skarns at low temperatures (Zharikov 1970). He then divides the skarns on the basis of their mineral composition into limy and magnesian skarns, and according to their mechanism of formation into diffusional and infiltrational skarns. He also defines autoreactional skarns as the products of the calcium metasomatosis of ultrabasites, alkaline ultrabasites and gabbroids.

In the words of Smirnov (1976) »skarns are rocks of a limesilicate composition formed by metasomatism in the contact zone of intrusions into carbonate, and to a lesser degree into silicate rocks». Once valuable mineral elements become concentrated in skarns, we have the formation of skarn mineral deposits. In the case of skarn-like rocks formed from carbonate-bearing rocks with essentially no addition of elements for the formation of skarn minerals Korzhinsky proposes the term »skarnoid» (Smirnov 1976). Smirnov regards as the most rational genetic classification of skarns that which is based on the composition of the host rock:

1. Lime skarns, which are the most common type, are formed by replacement of limestones,

2. Magnesian skarns are formed by replacement of dolomites or dolomitized limestones,

3. Silicate skarns are formed by silicate-rich rocks. The most characteristic feature is the presence of scapolite. In other respects they vary very little in composition from the limestone skarns.

Smirnov regards the concepts of endoskarn, the product of alterations at the margin of an intrusion, and exoskarn, formed further away from the contact, as recognized by Korzhinsky, as unsuitable for forming the basis of a classification, similarly the terms autoskarn and alloskarn of Abdullaev, since these do not represent composition-based classes and may contain rocks with significant mineralogical differences (Smirnov 1976). Skarn deposits may naturally also be classified according to their mineralogical composition, which is the most common method, but is not genetic (op.cit.). With the stadial nature of skarn formation now an accepted fact in Smirnov's opinion, one may also attempt to classify skarns according to the stages at which they were formed. Similarly classifications may be based on the intrusion with which the formation of the skarn is associated.

Very much less work concerned with skarns has been published by western authors in recent decades than by writers in the Soviet Union, nor have the genetic implications of the term emerged so clearly. Although many authors have applied the theories of Korzhinsky to their research into skarns (Tsusue

1961, Perry 1969, Brock 1972, Gustafson 1973, Kerrick 1977, Verkaeren and Bartholome 1979, Morrison 1980), skarns have still not been defined genetically as a clear-cut group of rocks. The definition given in the Glossary of Geology (Bates and Jackson 1980), runs as follows: »*skarn* As used by Fennoscandian geologists, an old Swedish mining term for silicate gangue (amphibole, pyroxene, garnet, etc.) of certain iron ore and sulfide deposits of Archean age, particularly those that have replaced limestone and dolomite. Its meaning has been generally expanded to include lime-bearing silicates, of any geologic age, derived from nearly pure limestone and dolomite with the introduction of large amounts of Si, Al, Fe and Mg».

In the absence of any universally accepted definition, the term is used fairly freely to describe calcium silicate minerals or rocks formed from these, or rocks formed via the replacement of carbonates in general. In referring to ore deposits associated with these, one constantly finds the terms pyrometasomatic, contact-metasomatic, etc. used instead of the term skarn or alongside it. Use of the word has nevertheless been on the increase, and some writers have also tried to give definitions for it. Sangster (1969) and Boyle (1970) propose the term »skarnification» by analogy with fenitization, greisenization, sericitization, etc. This concept includes, according to Sangster (1969), all those processes in which skarn is formed, e.g. contact metamorphism, contact metasomatism, regional metamorphism, etc. The essential feature of the process is the development of silicates of calcium, magnesium, manganese and iron, and also quartz, magnetite and a number of other minerals, in limestones, dolomites or carbonate-bearing schists (Boyle 1970).

Brock (1972) used the term skarn to describe any calcium silicate rock whatsoever which has been formed by the addition of material to a limestone or dolomite. Verkaeren and Bartholome (1979) defined a skarn as a metasedimentary or metavolcanic rock whose main components are calcium-rich silicates.

In the continued absence of an unambiguous genetic definition of skarns, in contrast to the situation in the Soviet Union, it has similarly not proved possible to construct any clear classification on genetic grounds. The most common practice seems, in fact, to be to classify them according to their principal minerals, e.g. into andradite skarns, pyroxene skarns, etc. Some writers have attempted a genetic classification based on their formation in stages (Atkinson and Einaudi 1978, Morrison 1980), but these have been purely local classifications.

It should also be noted that the term tactite has sometimes been used instead of skarn to denote a skarn of contact-metamorphic origin (Sangster 1969), but it has not entered common usage in this sense.

Terminology

The terms connected with skarns are employed in the present paper in the following senses:

Skarnification: the replacement of carbonates in limestones, dolomites or carbonate-rich sedimentary rocks to varying extents by silicates of calcium, magnesium, manganese and iron at high temperatures. The process may be essentially isochemical and involve only the removal of CO_2, but most commonly it brings with it additions of SiO_2, Fe and Mg and the volatiles B, F, Cl and H_2O.

Skarn mineral: a silicate formed by skarnification and containing varying quantities of calcium, magnesium, manganese and iron. Olivine, wollastonite, garnet, pyroxenes, amphiboles and scapolite may be found as skarn minerals.

Skarn, skarn rock: a rock formed via skarnification and containing varying quantities of the silicates of calcium, magnesium, manganese and iron, and possibly also quartz, plagioclase, carbonate and ore minerals.

Skarn ore: an ore formed in skarn rock.

THE HANNUKAINEN MAGNETITE DEPOSIT

General description

The Hannukainen ore body represents the largest known iron ore deposit in the area studied, a deposit which is located beside the river Äkäsjoki, about 7 km north of the Rautuvaara mine. A detailed description of the geology of this deposit is possible by virtue of the intensive research and drilling carried out for inventory purposes. Inventories have been made to date of four ore bodies recognized as belonging to the Hannukainen deposit, those of Kuervaara, Vuopio, Laurinoja and Lauku, which together comprise ore reserves amounting to approx. 68 million tonnes of iron ore. In addition to these, a further blind ore body is known of, i.e. that of Kivivuopio, to the west of Laurinoja, although its dimensions and the quality of the ore have not yet been properly studied. The location of these various ore bodies can be seen on the map in Fig. 32 and the associated geological sections in Figs. 41, 42 and 53.

The Hannukainen ore bodies take the form of plate-like lenses, elongated in the direction of the fold axis, which plunges 10—30° to the south-west, and becoming more tenuous at the edges. They are located in the upper part of the Rautuvaara Formation. The mean dip of the whole formation is 15—20° to the west, ranging from horizontal in places, due to the gentle, open folding, to as much as 50°. The steepest angles of dip are found in the south-eastern part of the Vuopio ore bed. The Rautuvaara Formation overlies conformably the Niesakero—Kuertunturi quartzite complex and is 70—140 m thick. This formation is overlain by the plutonic rocks of the marginal zone of the monzonite intrusion, which also form some conformable, wedge-shaped tongues within the formation itself. It is these tongues that separate the Vuopio and Laurinoja ore bodies and also those of Laurinoja and Kuervaara. The tongues in the northern part of the Hannukainen area divide the Lauku ore body into a number of discrete lenses.

The positioning of the intrusive tongues indicates that they must have entered the rock in conjunction with folding, generally following the bedding, although cross-cutting veins have also been encountered in open-cast mining at Kuervaara. Being more susceptible to weathering and erosion than monzonite or quartzite, the rocks and iron ores of the Rautuvaara Formation, and also the plutonic rocks of the marginal zone of the monzonite intrusion, are covered by a layer of sorted and unsorted surficial deposits generally some 10—25 m in depth.

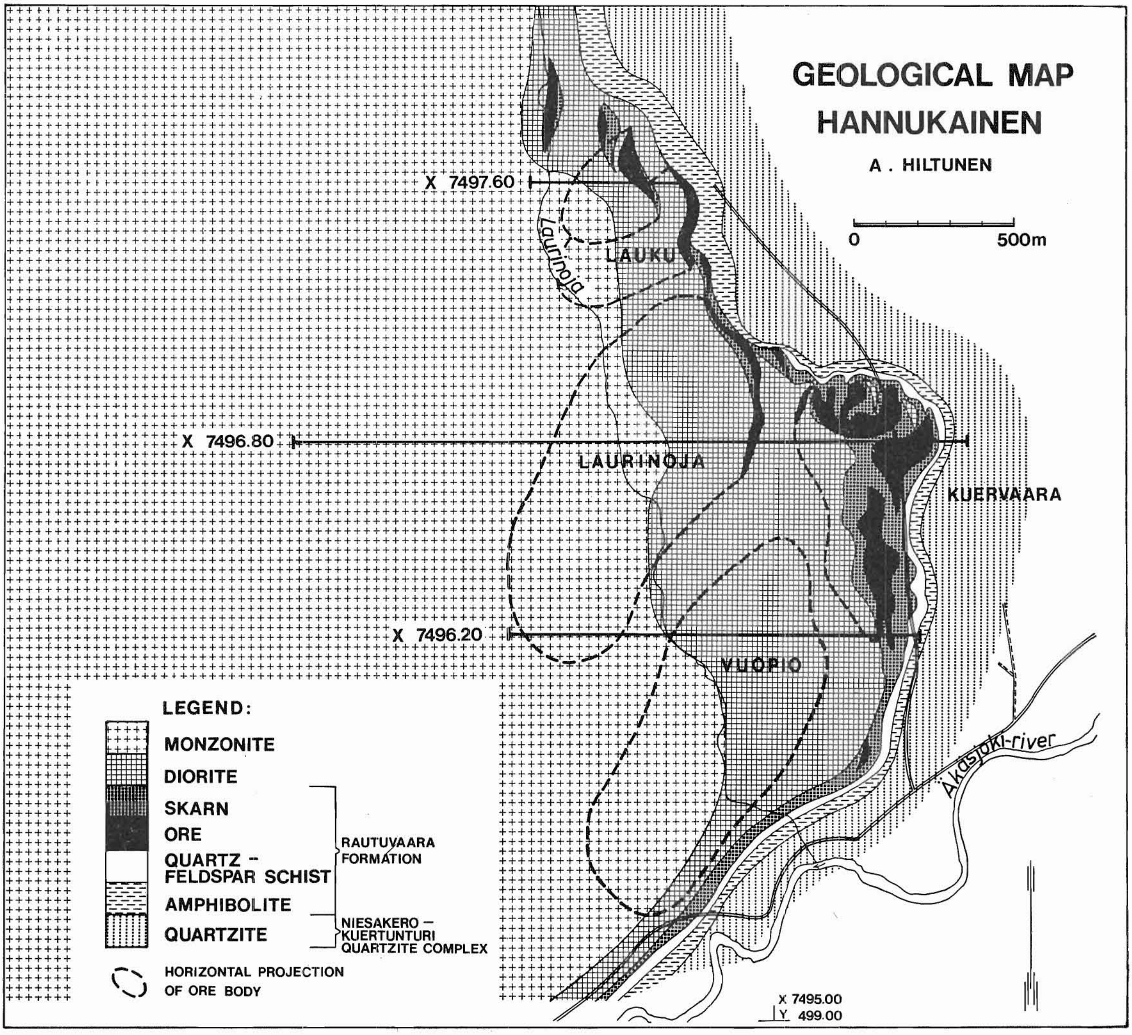

Fig. 32. Geological map of the Hannukainen deposit. Horizontal projections of the inventoried ore bodies are shown with broken lines.

Metasediments surrounding the ore bodies

The sedimentary rocks in the areas immediately surrounding the Hannukainen ore bodies consist of the quartzites and gneisses of the Niesakero—Kuertunturi quartzite complex and the amphibolites, quartz-feldspar schists and skarns of the Rautuvaara Formation. Exposed quartzite occurs at Kuervaara, to the east of the deposit, and the rocks of the Rautuvaara Formation were visible at only one small outcrop prior to excavation work.

The Niesakero—Kuertunturi quartzite complex

The rocks of the quartzite complex lying below the Rautuvaara Formation have been

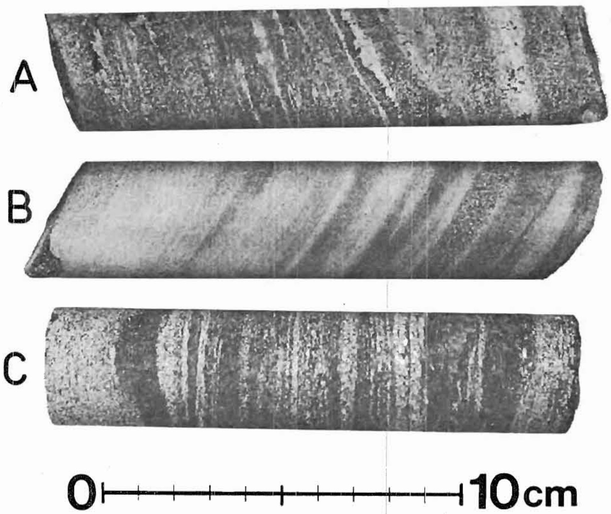

Fig. 33. Drill core samples of rocks from the *Rautuvaara Formation*.
A. Quartz—feldspar schist, Kuervaara, R 35, depth 54.7 m.
B. Cummingtonite amphibolite, Laurinoja, R 82, depth 273.7 m. The light bands are of cummingtonite and plagioclase and the dark bands are rich in hornblende and biotite.
C. Banded amphibolite, Laurinoja, R 78, depth 194.8 m. The dark bands are rich in hornblende and the light bands in plagioclase.

identified at Hannukainen by means of more than ten drillholes, one of which attained a length of 120 m in reaching the quartzite. The rock is a highly recrystallized quartzite typical of the upper part of the complex, containing some purer, more coarse-grained beds and some finer-grained ones richer in feldspar. Sillimanite is only found occasionally as an accessory mineral. The upper part of the quartzite also contains a layer of grey mica gneiss with veins of granite and in places interlayers of quartzite. This gneiss layer varies from a few metres to as much as 20 m in thickness and is overlain by several metres of arkose quartzite in places. The mica gneiss may thus be said to belong to the quartzite complex and to represent its upper part in the Hannukainen area.

The amphibolite of the Rautuvaara Formation

The lowermost rock of the Rautuvaara Formation, the amphibolite, forms a continuous bed some 20—70 m thick upon the quartzite and the mica gneiss of its upper part in the Hannukainen area. This amphibolite bed is thinnest in the east and increases in thickness towards the west. The amphibolite is typically banded with alternate light and dark bands (Fig. 33 C). The most common dark mineral is green hornblende and the light mineral is usually either oligoclase or andesine.

Especially in its upper part, the amphibolite generally contains light-coloured layers composed mainly of cummingtonite and oligoclase, which gives rise to a banded appearance (Fig. 33 B). At its thickest this cummingtonite-dominated amphibolite extends for over 20 m. Being fine-grained and having a clear bedding it bears some macroscopic resemblance to light quartz—feldspar schist, although departing markedly from the latter in its mineral composition.

Both the cummingtonite-dominated and the hornblende-dominated amphibolite feature bands and thicker layers rich in biotite, which further serve (to emphasize) the stratified external appearance of the rock. The upper part of the amphibolite also displays increasing numbers of diopside-rich interlayers near the skarn rocks.

One mineral common to all the types of amphibolite described here is plagioclase,

Table 10

Chemical compositions of the amphibolites and quartz-feldspar schists of the Hannukainen area (% by weight), determined as detailed in Table 1. C was determined gravimetrically.

	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	45.14	45.31	48.37	49.66	51.52	56.73	55.50	52.08
TiO_2	1.20	1.22	1.05	1.03	0.87	0.93	0.70	0.65
Al_2O_3	14.71	15.02	14.15	13.84	15.98	13.67	13.03	13.40
Fe_2O_3	7.04	9.51	11.65	10.50	4.19	7.93	3.40	2.55
FeO	7.00	4.67	4.22	6.45	6.00	2.70	5.50	2.30
MnO	0.08	0.22	0.27	0.12	0.10	0.13	0.12	0.06
MgO	11.40	11.49	6.42	7.72	6.10	7.20	6.23	7.70
CaO	3.18	6.88	9.24	2.80	7.59	3.93	3.64	6.84
Na_2O	3.00	3.56	3.40	2.71	5.47	4.91	2.06	3.02
K_2O	2.81	1.48	1.29	5.25	0.49	0.16	5.40	2.65
P_2O_5	0.09	0.09	0.07	0.07	0.32	0.09	0.16	0.27
CO_2	0.20	0.10	0.00	0.00	0.00	0.00	0.20	0.50
H_2O+	2.70	1.90	1.40	1.60	1.30	1.20	2.00	1.60
H_2O-	1.10	0.00	0.06	0.08	0.12	0.15	0.17	0.16
S	0.07	0.23	0.17	0.02	0.21	0.10	2.25	1.45
Total	99.72	101.68	101.76	101.85	100.26	99.83	100.36	95.23
— O	— 0.04	— 0.12	— 0.08	— 0.01	— 0.10	— 0.05	— 1.12	— 0.72
Total	99.68	101.56	101.68	101.84	100.16	99.78	99.24	94.51
							+ C 0.60	+ C 4.50
							99.84	99.01

1. Amphibolite, with hornblende dominant, Kuervitikko R 161, depth 220 m
2. Amphibolite, with hornblende dominant, Laurinoja R 78, depth 195 m
3. Amphibolite, with hornblende dominant, Laurinoja R 78, depth 213 m
4. Amphibolite, granitized, Laurinoja R 82, depth 243 m
5. Amphibolite, containing diopside, Laurinoja R 79, depth 223 m
6. Cummingtonite-amphibolite, Laurinoja R 82, depth 274 m
7. Quartz-feldspar schist, Kuervaara R 35, depth 55 m
7. Quartz-feldspar schist, Kuervaara R 13, depth 70 m

while their differences arise from variations in the occurrence of the dark minerals hornblende, cummingtonite, diopside and biotite amongst the main constituents. The amphibolites are fine-grained rocks, with a grain size varying in the range 0.2—0.8 mm. The light-coloured cummingtonite amphibolite is finer-grained than the dark hornblende amphibolite, and green hornblende often exists around cummingtonite grains. The accessory minerals are usually magnetite, apatite and titanite, and occasionally scapolite or epidote. Garnet is also found in places in the biotite-rich layers.

In one drillhole (R 61) a light-coloured coarse-grained layer 10 m in thickness was noted at the very top of the amphibolite bed which contained both cummingtonite and orthoamphibole, which conforms in its optical properties to gedrite.

The amphibolite commonly contains veins of pegmatite, and in a few places the rock is coarse and rich in biotite, apparently as a consequence of granitization, including at the same time augens and veins of potassium feldspar.

The chemical compositions (Table 10) correspond to those of the basaltic volcanites, with the exception of the cummingtonite-amphibolite, which corresponds to an andesitic volcanite. In the classification of Middlemost (1972), this rock would correspond most closely to the composition of a subalkaline andesite, while the others, with their higher alkali content, would correspond to alkaline basalts. The alkali content of the highly metamorphosed amphibolite may nevertheless be partly secondary in origin, so that the primary composition may have been subalkaline. Analyses Nos. 5 and 6, with their high Na content, correspond to the composition of the spilites, as reported by Fiala (1974). On the AFM diagram (Fig. 13), the amphibolites of the Hannukainen area lie on the borderline between the subalkaline volcanites of the tholeiite and calcalkaline series, with most of them inclined towards the latter field, as was the case with the metavolcanites of the Kurtakko area.

The chemical composition and stratified structure of the amphibolite suggests that this may well represent a primary mafic tuff or tuffite deposited in water. The gradation towards a quartz—feldspar schist or skarn in the upper part of the bed would be indicative of the increased involvement of clastic and chemical sedimentation as deposition advanced.

The quartz-feldspar schist of the Rautuvaara Formation

The amphibolite is overlain in the eastern part of the Hannukainen area by a bed of less than 20 m thick of fine-grained, clearly stratified schist (Fig. 33 A), which is referred to as quartz—feldspar schist. This rock is granoblastic in texture and varies in grain size in the range 0.1—0.5 mm. It always contains both microcline and plagioclase (oligoclase), in proportions varying up to 40 %. There is usually relatively little quartz, although this again varies in amount up to 30 %. The bedding is seen both in a small variation in grain size and also in an alternation between dark and light minerals. The overall quantity of dark minerals is small, as is seen from the general light colour of the rock. Biotite is generally present in small amounts, as also is colourless or light-green clinoamphibole and in places diopside. Large amounts of graphite are present in some of the layers, but in general there is very little. The accessory minerals are titanite, tourmaline, apatite, chlorite, carbonate, zircon, pyrrhotite and pyrite.

Quartz—feldspar schist is found in a continuous layer beneath the skarns of Kuervaara and Vuopio, but comes to an end in the western part of the Vuopio area. At Laurinoja it is found only beneath the skarn in the eastern part of the ore body. The boundary between the schist and skarn is not usually an abrupt one, but rather the two rocks are found in alternate layers at the contact. It would seem that increasing amounts of carbonate material found their way onto the epiclastic sediment or managed in part to mix with it, this later allowing the formation of skarn minerals.

Two analyses of the quartz—feldspar schist are presented in Table 10 (Nos. 7 and 8). These correspond most closely in composition with graphite-bearing clay-silt schists (Pettijohn 1975, p. 282—285), although they do not differ very much from certain amphibolites. The high Ca and Mg content suggests that the primary sediment may have contained carbonate, this being reflected within the mineral composition in the occurrence of skarn minerals. The Mg content may also have increased metasomatically in connection with the skarn reactions.

The skarn rocks of the Rautuvaara Formation

The skarn rocks with their associated magnetite lenses form a bed ranging in thickness from a few metres up to almost a hundred metres overlying the amphibolite and quartz—feldspar schist. The skarn layer is thicker at

Kuervaara and Vuopio in the south-east of Hannukainen than at Laurinoja and Lauku in the north-west (Figs. 41, 42 and 53). The proportion of the deposit accounted for by the magnetite lenses, on the other hand, is very much higher in the north-west, where there is very little skarn.

The skarns as a whole form a rock unit which is somewhat heterogeneous in its small-scale features, but which when looked on as a larger entity nevertheless presents a highly consistent formation both mineralogically and chemically. The most common type of skarn is a small-grained, banded rock, the banding of which is due to an alternation between darker bands usually of diopside and/or green hornblende, and lighter ones composed of plagioclase (oligoclase—andesine) and/or scapolite and of diopside Scapolitization has been most pronounced in the Kuervaara area, where scapolite is to a great extent the dominant light mineral, especially in the middle and lower parts of the skarn layer. Elsewhere in the Hannukainen area scapolite is found only occasionally, even though there are certainly considerable local variations in the ratio of scapolite to plagioclase.

The quantities and proportions of diopside and hornblende similarly vary, from almost pure massive diopside skarns to hornblende-dominated skarns. Diopside is nevertheless the most abundant of the main minerals in the skarns all told. The skarns are granoblastic, with a grain size normally in the range 0.2—1 mm. A grain size of some centimetres may even be found among the pure diopside skarns.

In addition to the minerals mentioned above, occasionally colourless amphibole, biotite, potassium feldspar, quartz, andradite, epidote, carbonate, chabazite, serpentine and olivine are found as the main constituents. Some minor occurrences of andradite-rich skarn a few metres thick are encountered, mainly in the hanging wall of the northern part of the Laurinoja ore body, and also sporadically at Kuervaara and Vuopio, again in the hanging wall of the ore bodies or as the waste rock within its upper part. Bright green clinopyroxene and quartz are also commonly noted in combination with the andradite at Laurinoja, and quartz-rich, or even quartz-banded skarn is found in places in that same area.

Olivine occurs in places alongside carbonate as rounded, partially serpentinized grains, and chabazite is encountered as a cavity fill in partially altered scapolite and carbonate-bearing skarn in the western part of Kuervaara and in a skarn inclusion in the diorite at Laurinoja. The role of mineral paragenesis will be discussed in more detail in the section dealing with the origins of the skarns and ores.

In addition to titanite and apatite, varying quantities of pyrite, pyrrhotite, chalcopyrite and magnetite, the latter sometimes abundantly, can be found as accessory minerals in skarns. The sulphides are usually scattered throughout the rock, but sometimes form compact, narrow veins, and magnetite is both scattered and in the form of streaks, especially in close proximity to ore lenses. Molybdenite is found occasionally, scattered within the lower part of the skarn layer at Vuopio. A few thin layers of carbonate rock occur as interlayers amongst the skarns at Hannukainen.

The mean chemical compositions of the skarns of Kuervaara, Vuopio and Laurinoja are indicated in Table 11. These figures demonstrate clearly the high CaO content characteristic of skarns. The wide-scale variations in the contents of many elements, however, testify to the heterogeneity of the skarns, even though the silicates of calcium, magnesium and iron, diopside and hornblende are dominant. The division into calcium-rich and magnesium-rich types characteristic of the

Table 11

Mean chemical concentrations in the skarns of the Hannukainen area (% by weight). The mean values are calculated from the analysis results of driill core samples 2—4 m in length taken from typical skarns. Magnetite is determined using the Satmagan apparatus and the others by the x-ray fluorescence method.

	KUERVAARA (8 analyses)			VUOPIO (5 analyses)			LAURINOJA (10 analyses)		
	mean	min	max	mean	min	max	mean	min	max
SiO_2	44.15	40.75	47.14	45.87	40.94	49.39	45.25	37.10	50.24
TiO_2	0.40	0.38	0.75	0.32	0.08	0.70	0.28	0.05	0.50
Al_2O_3	10.71	5.79	13.49	6.93	3.08	13.37	5.91	1.56	9.37
Fe_3O_4	6.37	0.95	10.10	4.33	0.47	12.40	9.88	2.52	15.80
Fe_2O_3	10.77	6.51	14.91	12.92	8.15	19.63	12.97	9.08	18.33
MnO	0.17	0.08	0.32	0.36	0.18	0.50	0.33	0.14	0.49
MgO	5.54	3.98	8.77	8.55	5.66	11.96	6.04	3.55	9.08
CaO	14.04	10.95	18.79	15.95	12.35	19.24	15.91	11.75	22.99
K_2O	0.84	0.24	2.42	0.72	0.36	1.94	0.51	0.06	1.04
P_2O_5	0.27	0.16	0.60	0.16	0.07	0.25	0.27	0.14	0.44
S	1.72	0.71	3.05	1.34	0.24	3.10	1.93	0.27	4.53
Cu	0.20	0.02	0.84	0.04	0.01	0.09	0.26	0.02	0.84

skarn deposits of Central Sweden (Geijer and Magnusson 1944) is not evident at Hannukainen, where the magnesium-rich silicates, olivine, serpentine and phlogopite, are relatively rare and the mean MgO content in the skarns is low.

There are no great differences in the mean composition of the skarns between the areas studied. Perhaps the most significant deviations are found in the Al_2O_3 content, which is very much higher at Kuervaara than at Vuopio or Laurinoja, and in the Fe_2O_3 content, which is correspondingly lower at Kuervaara than at the other two sites. These differences are largely due to the fact that the skarns of Kuervaara are richer in plagioclase and scapolite than the darker Vuopio and Laurinoja skarns. The skarn at Laurinoja, which does not occur in any great abundance, contains more magnetite than that at either Vuopio or Kuervaara, and its low Mn content is also of importance. The concentrations of ore minerals vary considerably, as may be seen from the wide-scale variations in Fe_3O_4, S and Cu content.

The typical banded appearance of the skarns resembles sedimentary stratification, but no features emerge in the texture of these rocks which would lend weight to such an assumption. The light-coloured plagioclase-scapolite bands are admittedly finer-grained than the dark diopside—hornblende bands, presumably due to their metasomatic—metamorphic crystallization into separate coarse stripes rather than to any primary sedimentary structure. On the other hand, even very markedly altered rocks are known to preserve relicts of their primary stratification. These bands are best developed at Kuervaara, where the proportion of light minerals is highest and the conditions are thus most suitable for the formation of such bands. In addition to the pure skarn types, various degrees of mixing occur in connection with veins of other rocks within the skarns, and in these cases the compositions can naturally deviate markedly from those presented for the skarns themselves. The various types of skarn are presented in Fig. 34.

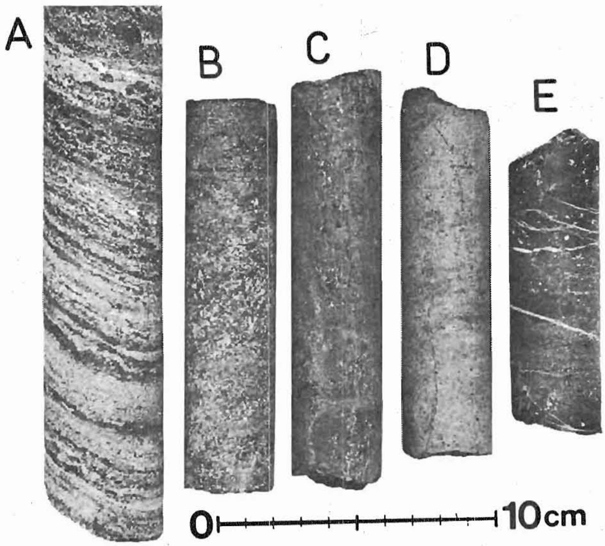

Fig. 34. Drill core samples of skarn rocks at Hannukainen.
A. Banded skarn, R 179, depth 200 m.
The light bands have plagioclase and diopside dominant and the dark bands hornblende.
B. Massive diopside–carbonate skarn, R 194, depth 24.10 m.
C. Andradite–diopside skarn, R 194, depth 34.8 m.
D. Massive diopside skarn, R 194, depth 43.2 m.
E. Serpentine skarn with light-coloured veins of calcite, R 70, depth 248 m.

The monzonite intrusion in the hanging wall of the ore bodies and its marginal zone

The Rautuvaara Formation at Hannukainen is overlain by the rocks of the conformable marginal zone of the monzonite intrusion. These vary in composition, but are predominantly dioritic. This zone, recognized as a marginal variety, varies in thickness from some 30 m to around 150 m. Corresponding rocks to these are also found forming wedge-shaped tongues within the Rautuvaara Formation itself.

The rock type lying above the marginal zone is a typical reddish, gneissose, fairly homogeneous plutonic rock (Fig. 35), with a composition normally corresponding to quartz

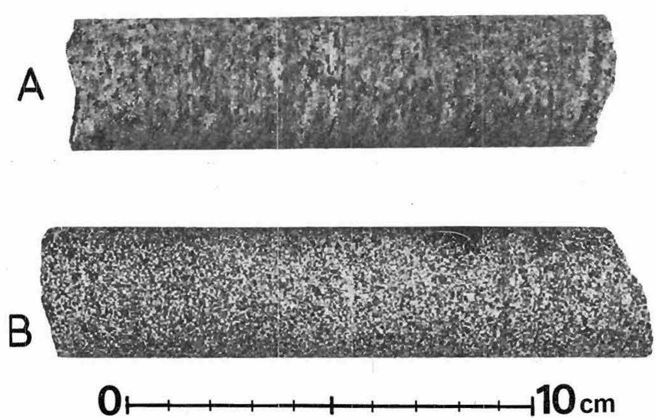

Fig. 35. A. Monzonite, Hannukainen, R 162, depth 384.5 m.
B. Diorite, Hannukainen, R 89, depth 50.4 m.

monzonite (see Table 6, No. 4). A certain nonhomogeneity is introduced into this by veins of red pegmatite ranging in thickness from a few metres to some 40 m. The greatest thickness of monzonite penetrated by drilling is approx. 370 m. This rock retains its composition and external appearance practically unchanged as far as the contact with the above-mentioned marginal zone.

With the beginning of the marginal zone the coarse-grained monzonite usually grades rapidly, and at the most within the space of a few metres, to a fine-grained light-coloured rock with a lower proportion of potassium feldspar in relation to plagioclase, and its composition changes to that of a quartz monzodiorite or monzodiorite. This again grades lower down, usually some 20—30 m from the monzonite contact, either sharply or gradually to a grey diorite.

One regularity seems to be that the thicker the marginal zone is, the more heterogeneous its composition. Thus at Vuopio, where it reaches 160 m in places, one finds small bodies of a number of varieties on a scale from diorite to quartz syenite scattered irregularly especially in the upper part.

In spite of this local heterogeneity, one characteristic feature of the diorite-dominated rocks of the monzonite contact is their clear zonality in both mineral and chemical composition.

Closest to the monzonite is the above-mentioned light-coloured heterogeneous zone some 20—30 m broad, in which the main constituents are plagioclase (An 6—15 %), potassium feldspar and quartz in varying proportions. The dark minerals consist of a small amount of biotite and occasionally some diopside. The mineral compositions are presented in Table 8, Nos. 1—3. This light zone characteristically contains some ore minerals, a feature which distinguishes it from the monzonite. Scattered grains and faint streaks of magnetite and pyrite are found, and in places also a small amount of chalcopyrite. This zone also possesses large numbers of pegmatite veins.

After this light zone, there begins grey, massive diorite, with plagioclase (An 15—30 %) and biotite as its main minerals. This biotite-dominated diorite is usually 30—50 m thick, and although it is relatively homogeneous, some alternation between darker and lighter types is seen depending on fluctuations in the amount of biotite. Scattered amounts of magnetite, pyrite and chalcopyrite are found in the upper part, as in the light zone, and in this sense the boundary of mineralization does not seem to follow the rock type boundary.

The diorite alters in composition towards the skarn bed with a decline in biotite and an increase in hornblende and gradually also diopside. The diorite becomes darker and begins to feature inclusions of skarn. The composition of the plagioclase remains unchanged, however. The change in the mineral composition of the rock is seen well in Table 8 (Nos. 4—6). The contacts between the skarn and diorite are sharp in places and more gradual in others (Fig. 36).

The rocks of the marginal zone are subhypidiomorphic or practically granoblastic in texture, with a grain size of 0.4—0.6 mm. Among the accessory minerals it is worth noting the scarcity of titanite in comparison to monzonite. Other accessory minerals are potassium feldspar, apatite, zircon, epidote, tourmaline, carbonate, scapolite and occasionally also anhydrite and gypsum.

Chemical composition of the marginal zone

The changes in the chemical composition of the rocks of the marginal zone as one moves from the monzonite via the diorite that represents its marginal variety to the skarn deposit are presented in Fig. 37. The

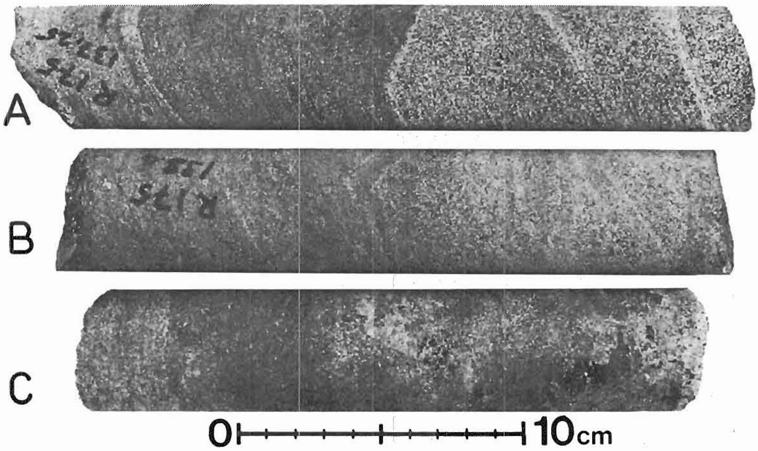

Fig. 36. Contacts between diorite and skarn.
A. Sharp contact, R 175, depth 137.3 m (diorite on the right).
B. Gradual contact, R 175, depth 138.0 m (diorite on the right).
C. Diorite and skarn thoroughly intermixed, R 178, depth 152.2 m.

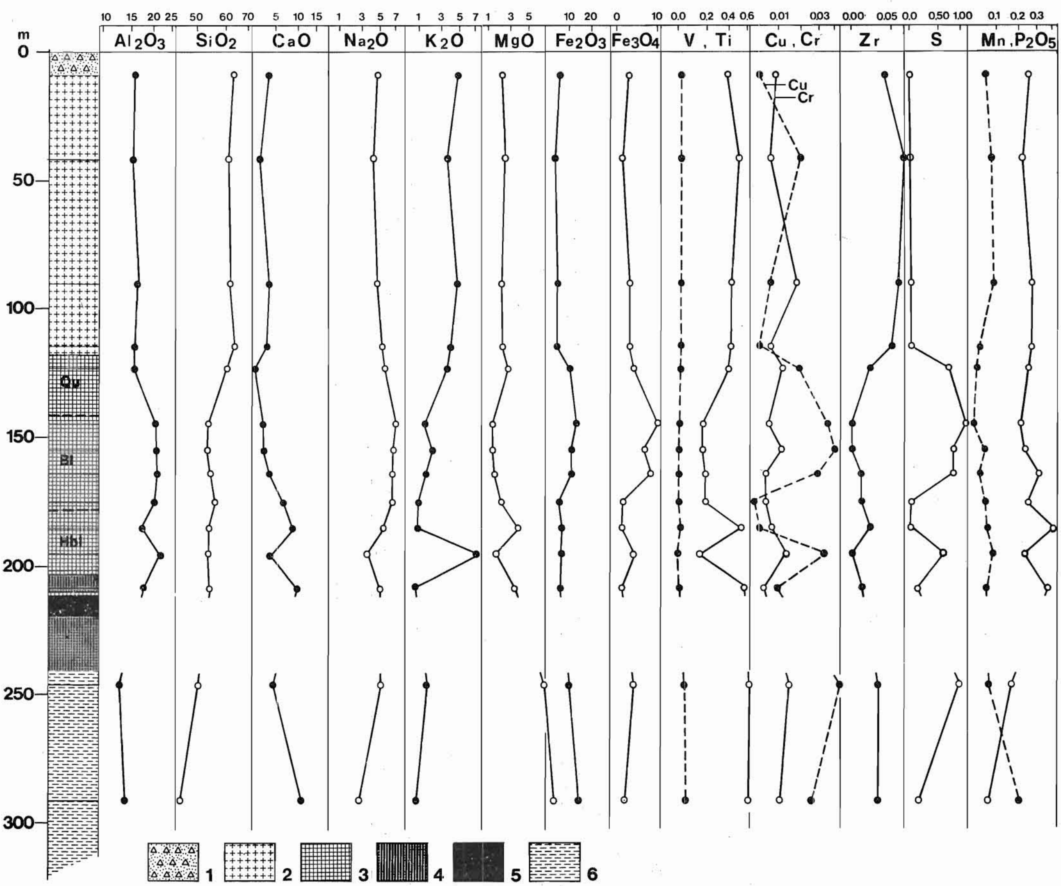

Fig. 37. Variations in chemical composition (% by weight) in the rocks at Laurinoja, drillhole R 72. 1 = overburden; 2 = monzonite; 3 = diorite: Qu — light-coloured zone, largely of quartz monzonite, Bi — diorite with biotite dominant, Hbl — diorite with hornblende and diopside dominant; 4 = skarn; 5 = ore; 6 = amphibolite.

diagram is constructed on the basis of the concentrations of elements determined for samples taken from the drillhole No. 72 at Laurinoja. The concentrations were determined by x-ray fluorescence, except for Na_2O, for which atomic absorption was used. The concentration of magnetite (Fe_3O_4) is determined by the Satmagan apparatus and the remaining iron indicated in terms of Fe_2O_3. Two analyses of the amphibolite lying below this zone are also included for the purpose of comparison.

One outstanding feature when examining the diagram is the evenness of composition of the monzonite, even though a small change in the principal components is observable in the immediate vicinity of the upper part of the diorite, where Na_2O increases and K_2O decreases.

A sharp change in composition occurs as the light-coloured zone of the marginal area is reached, with a decline in the concentrations of SiO_2, CaO, K_2O and Zr and an increase in Na_2O, Fe_2O_3, Fe_3O_4, Cu and S (analysis from 123 m in Fig. 37). Al_2O_3 and MgO remain practically unchanged. The rock is largely quartz monzodiorite, with a scattering of magnetite, pyrite and chalcopyrite as an indication of mineralization.

A change in the same direction is seen on progressing to the biotite-dominated diorite, but it is now steeper in the case of the majority of components. One major change is the abrupt rise in Al_2O_3 content. The central part of the diorite is relatively homogeneous. The next major change is the sudden cessation of the mineralization zone, reflected in a reduction in the concentrations of iron and particularly copper and sulphur. The CaO content begins to increase gradually towards the skarn deposit, and the same trend is also seen in MgO, whereas Al_2O_3 and Na_2O decline. In other words, the composition moves towards that of skarn itself, and the rock lying close to the contact could well be regarded as endoskarn in places, having undergone a metasomatic addition of calcium and magnesium. The last point before the skarn in the diagram, at a depth of 190 m, is exceptional, and represents something approaching monzodiorite in composition, this often being found as an variety a few metres thick in the vicinity of the skarn deposit.

At Vuopio, where the diorite-dominated rocks form a thick, heterogeneous unit, the above regular pattern of changes can naturally not be observed by any means as clearly. The diagram for the analyses carried out on material from drillhole R 74 at Vuopio depicted in Fig. 38 shows the changes to operate in the same direction as at Laurinoja, especially at the diorite-skarn contact. The concentrations of Al_2O_3, SiO_2 and CaO, however, differ at Vuopio from those at Laurinoja in that they are largely of the same order in both the diorite and the monzonite.

The tongues of diorite which follow the banding of the skarn are variable in composition and frequently have an admixture of skarn. The thicker tongues nevertheless demonstrate a clear zonational effect which is comparable to the variation in composition described above for the rocks overlying the skarn. This is most obvious in a tongue of maximum thickness approx. 60 m lying between the ore bodies of Kuervaara and Laurinoja, the upper part of which is usually quartz monzodiorite or monzondiorite in composition, grading downwards to hornblende or diopside-rich diorite. One clear difference with respect to the diorite overlying the skarn is the absence of the most common type of diorite, that with biotite dominant, from these tongues. Some local heterogeneity is also found within the tongues in the form of irregular fluctuations in composition, either sharply defined or more gradual.

The variation in chemical composition may be seen from Fig. 39, which contains two analyses from diorite overlying the skarn and

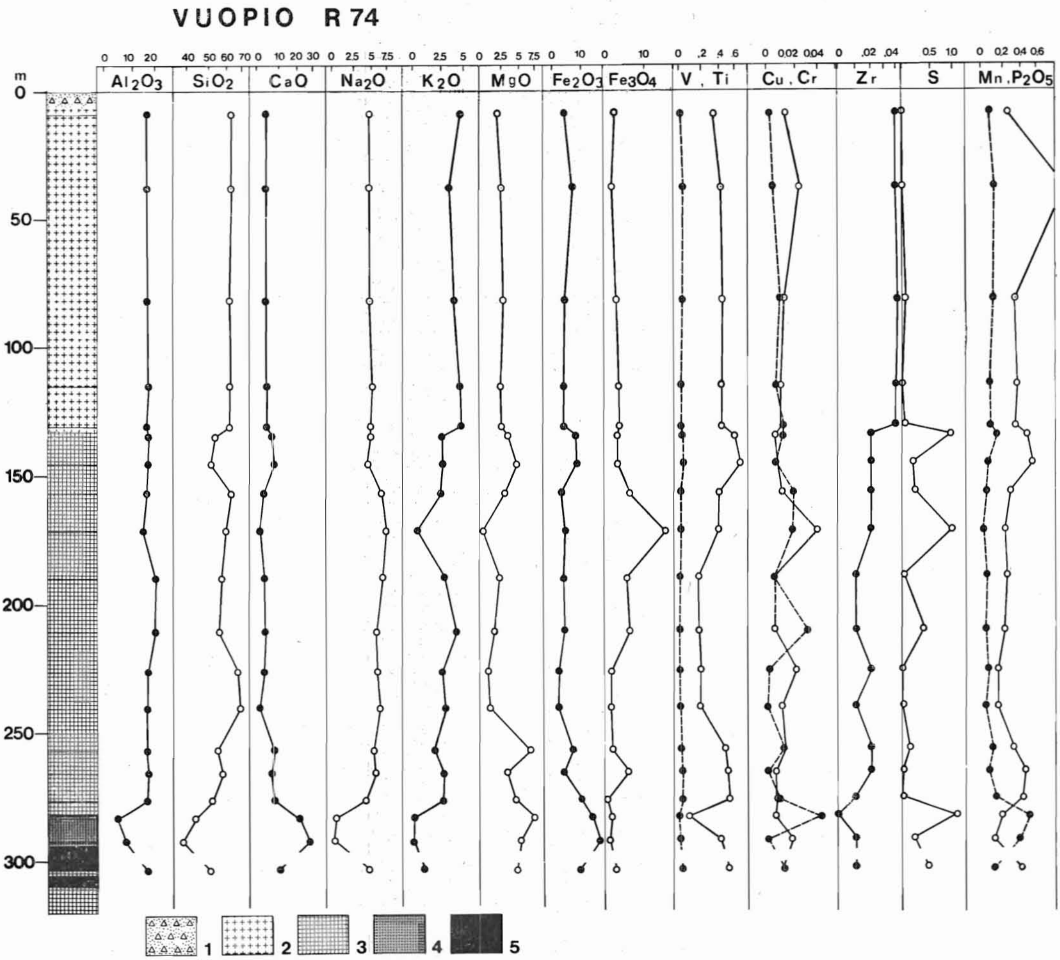

Fig. 38. Variations in chemical composition (% by weight) in the rocks of the Vuopio drillhole, R 74. 1 = overburden; 2 = monzonite; 3 = diorite of the marginal zone; 4 = skarn; 5 = ore.

four from the tongue separating the ore bodies of Laurinoja and Kuervaara. The amounts of magnesium, calcium and silicates of iron increase towards the lower part of the tongue, at the same time as the concentrations of silicon, aluminium and sodium fall.

At Kuervaara, where scapolite-rich skarns are found, scapolite also occurs as a main constituent alongside plagioclase in some places in the diorite tongues. The minerals appear to be in mutual equilibrium, as no replacement phenomena can be detected.

A number of light-coloured, relatively acidic veins of variable composition and at most a few metres in thickness occur in the southern part of the Kuervaara area, one of which clearly cuts through a bed of banded skarn ore (Fig. 40). This vein is composed of granodiorite which resembles the quartz monzodiorite of the upper part of the thick, conformable diorite vein mentioned above both in composition and in external appearance. The relation between these acidic veins and the monzonite intrusion itself is uncertain, but they would seem to be somewhat younger than the intrusion.

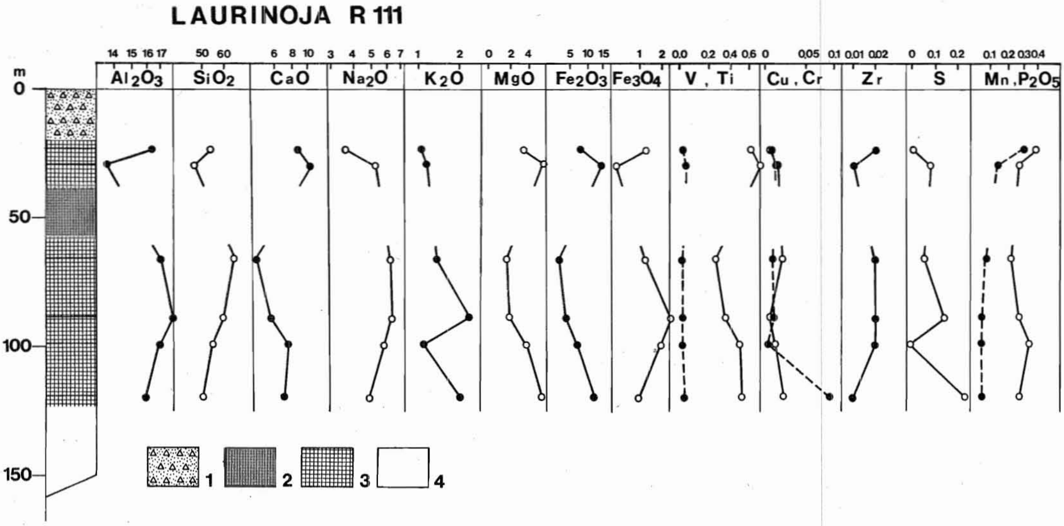

Fig. 39. Variations in chemical composition (% by weight) in the diorite of the hanging wall and footwall of the Laurinoja ore body in the section represented by drillhole R 111. 1 = overburden; 2 = skarn; 3 = diorite; 4 = quartz—feldspar schist.

Origins of the marginal zone

In examining the mode of occurrence and composition of the rock types of the marginal zone of the monzonite intrusion from the observations available, the opinion was put forward (p. 48) on the basis of the triangular graph in Fig. 26 that this cannot be a case of normal magmatic differentiation. Mineralogical and chemical changes are noted both at the upper contact of this zone with the monzonite and at its lower contact with the skarn bed. The occurrence of a marginal zone differing in composition from the main rocks

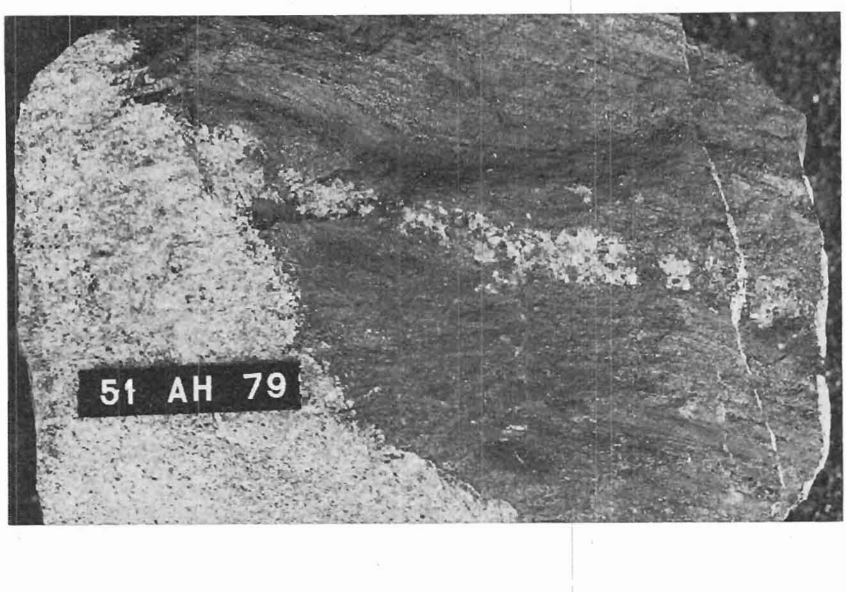

Fig. 40. Granodiorite vein cutting across the skarn iron ore at the opencast site at Kuervaara. The name-plate is 16 cm in length.

of the intrusion would seem to be a fairly common phenomenon at contacts between granitoid and carbonate-rich sedimentary rocks. A number of authors have discussed such cases in works on skarns and skarn ores.

Hotz (1952) assumed the intrusive quartz—oligoclase gneisses associated with the skarn iron ores and metasediments of the Sterling Lake and Ringwood area to have been formed via the partial fusion of metasediments under orogenic pressure. Such an explanation would, in his opinion, be consistent with the grading contacts, the presence of metasediment inclusions and the intrusive behaviour of the gneisses.

According to Kesler (1968) the marginal zone of as much as 200 m in thickness and composed chiefly of syenodiorite and granodiorite found at a contact between quartz monzonite and marble in northern Haiti originated as a product of assimilation between the marble and a plutonic magma. Here he presumes that the dominant process was not the formation of a molten carbonate fluid but instead a dissolving of the marble in the magma. The thickness of the marginal zone may be explained by the contaminated magma flowing along the contact with the limestone, which in turn will also explain why other rock types such as monzonite, diorite, quartz diorite and even a little nepheline syenite occur in the marginal zone as minor variants of the principal rock (op.cit.).

Sangster (1969) notes in his paper on contact-metasomatic iron ores that a number of plutonic rocks may be surrounded by a more mafic phase, perhaps as a product of contamination between the magma and either limestone or volcanite. The contact features in the host rock are most conspicuous in cases where metasomatic deposits have formed. Metasomatic changes are also referred to by many recent workers (Atkinson and Einaudi 1978, Lanier *et al.* 1978, Reid 1978) to explain the changes in plutonic rocks found in connection with the skarns and porphyry copper ores of the Bingham area in Utah.

In discussing the origins of a marginal zone the first question should be at what stage in relation to the intrusion process the changes took place. In other words, did they occur at the magmatic stage, in which case this would involve assimilation, or metasomatically after intrusion, or are both processes implicated?

Even though Korzhinsky (1970) is of the opinion that infiltration metasomatosis can advance over extensive areas and form a sharp contact, the intrusive behaviour of the diorite tongues would favour the notion of some degree of differentiation having taken place at the magmatic stage. The irregular occurrence of rock varieties and the frequently abrupt contacts between these would be further facts pointing in the same direction. The occurrence of diorite-dominated rocks preponderantly in conjunction with skarns confirms the notions of Kesler (1968) and Sangster (1969) concerning the crystallization under altered conditions of a hybrid magma produced by the assimilation of carbonate material by a plutonic magma.

Assimilation and the associated convection of the magma would provide a good explanation for the thickness of the present marginal zone and the intrusive behaviour of its rocks, but would not explain the zonational structure noted between the monzonite and skarn. The formation of endoskarn at the lower diorite contact indicates that the rock became subject to pronounced metasomatic changes subsequent to the intrusion phase. Since these changes are thus linked with the formation of the skarns and ores, the matter will be taken up in more detail in the chapter on the genesis of the ores. It should nevertheless still be noted that the mineralized zone in the upper part of the diorite is quite obviously one product of the metasomatic process of ore formation, and can thus be correlated with the skarn ores. This interpretation gains support from the similarity in S isotope composition between the sulphides of the diorite and the skarn ores (Mäkelä and Mattila, in press).

Petrography and chemical composition of the magnetite ore bodies

The magnetite ore bodies of the Hannukainen area are well-defined, plate-like lenses of varying size, differing to a minor extent in their mineralogical and chemical composition. The greatest degree of similarity is found between those of Kuervaara and Vuopio, in which the dominant sulphide mineral is pyrrhotite. The most significant deposit from an economic point of view is the copper-bearing ore body of Laurinoja. The smallest of the ore bodies, that of Lauku, also constitutes a type of its own, in which the main sulphide mineral is pyrite. Research into the ore body of Kivivuopio is still in progress.

The Kuervaara ore body

The ore body of Kuervaara, some 800 m in length and 200—400 m in breadth, contains three plate-like lenses of ore 10—20 m thick, partly overlapping and partly separated by skarn (Figs. 41 and 42). These ore lenses are located in the central and upper parts of the skarn bed. The gently folded northern part of the ore body is practically horizontal, but the westward dip increases towards the south to reach approx. 35° W at its southern end. In the south the ore is cut across by a vein with the composition of granodiorite (Fig. 40). This ore body, which extends to the bedrock surface at its eastern and northern edges, is overlain throughout by 10—20 m of surficial deposits, with the exception of the southern part, where the ore is exposed in places. Opencast mining has been in progress in this southern area since 1979, producing approx. 200,000 tonnes of ore a year (Fig. 43). The southernmost ore plate is estimated to contain approx. 3 million tonnes and the two

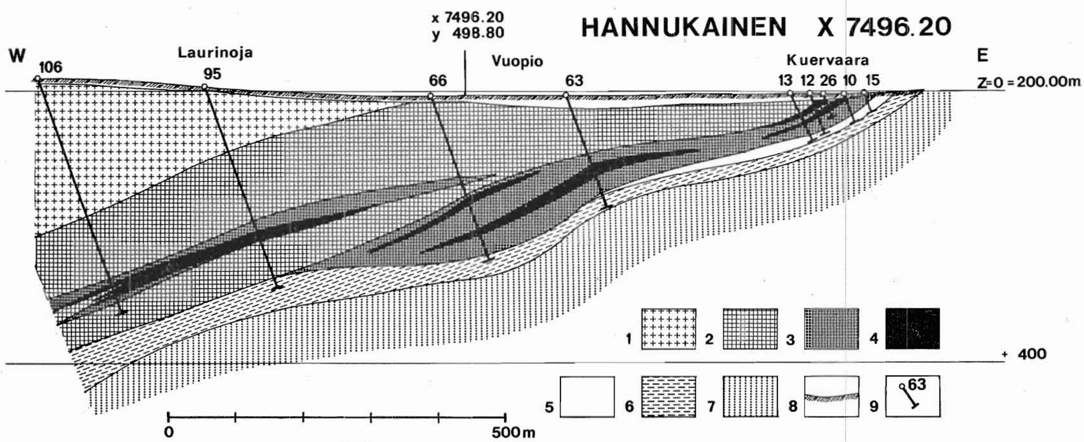

Fig. 41. Geological cross-section from Hannukainen, profile X 7496.20. *Intrusive rocks:* 1 = monzonite; 2 = diorite. *Rautuvaara Formation:* 3 = skarn; 4 = ore; 5 = quartz—feldspar schist; 6 = amphibolite. *Niesakero—Kuertunturi quartzite complex:* 7 = quartzite; 8 = ground surface; 9 = drillhole with number.

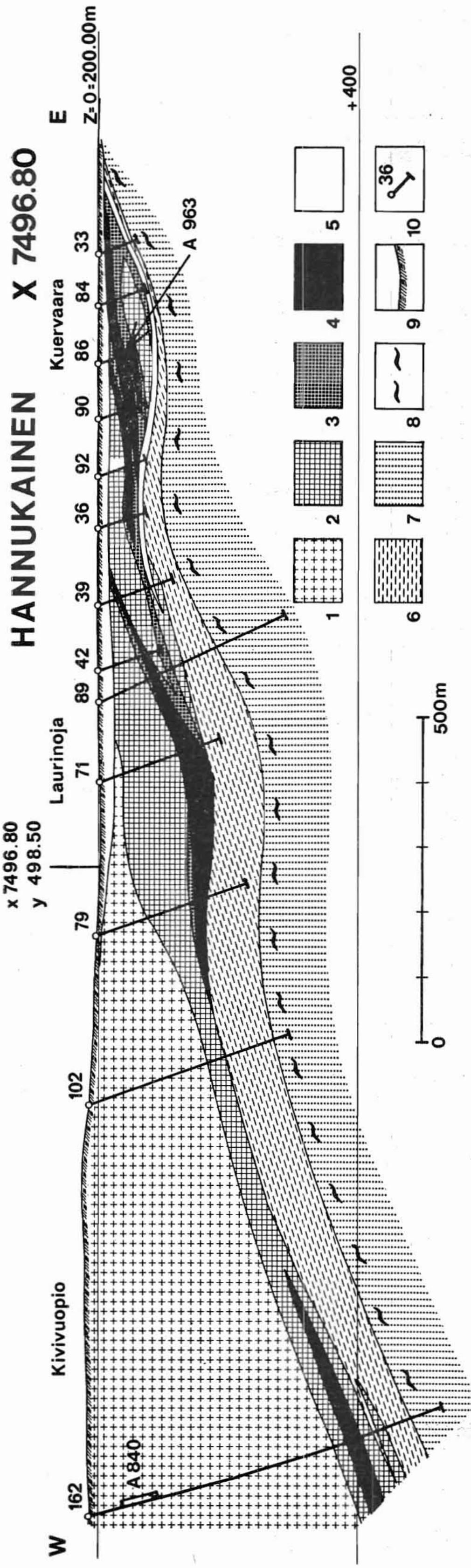

Fig. 42. Geological cross-section from Hannukainen, profile X 7496.80. *Intrusive rocks:* 1 = monzonite; 2 = diorite. *Rautuvaara Formation:* 3 = skarn; 4 = ore; 5 = quartz-feldspar schist; 6 = amphibolite. *Niesakero-Kuertunturi quartzite complex:* 7 = quartzite; 8 = mica gneiss; 9 = ground surface; 10 = drillhole with number. Samples for age determination: A 840, monzonite and A 963, skarn.

further north approx. 4 million tonnes altogether. The mean concentrations in the ores are listed in Table 12, where analysis No. 1 represents the southern lens and No. 2 the two others. Apart from a higher iron content in the southern lens (Fe 41.6 % as compared with 35.1 %) there are no significant differences in composition. The sulphur content is very high, as in the Hannukainen ores generally, but vanadium, manganese, titanium, and phosphorus are low, the manganese content being slightly lower in the Kuervaara ore body than elsewhere at Hannukainen.

The principal ore mineral at Kuervaara, and throughout the Hannukainen area, is magnetite, in addition to which one finds pyrrhotite, pyrite and chalcopyrite. Although the boundaries of the ore lenses can be determined fairly precisely, the magnetite is distributed heterogeneously, with variations in its concentration from points with almost oreless skarn to compact magnetite. Magnetite is also found in scattered grains and streaks within the skarns lying beyond the ore lenses themselves.

The Kuervaara ore has macroscopically a banded appearance, due to an alternation between streaks of magnetite-rich and silicate-rich rock varying in thickness from millimetres to several centimetres. Massive occurrences do also occur, however, and these are usually richer in magnetite, while at other points the rock contains only disseminated ore.

The majority of the magnetite in the banded ores occurs in grains of 0.2—1 mm in size in the magnetite-rich stripes. The intervening silicate-rich stripes contain disseminated finegrained magnetite of grain size 0.01—0.05 mm. The principal gangue minerals, which also make up the silicate stripes, are, in order of importance, diopside, hornblende, scapolite and plagioclase (oligoclase—andesine). Diopside and hornblende are always present, while there is very much less

Fig. 43. Opencast mining at Kuervaara, viewed from the south-east.

of the latter. The hornblende is light and occurs partly around the edges of the diopside grains and in between these, representing an alteration product, although it also appears in thin streaks. The scapolite and plagioclase are often found together, especially in the northern part of the ore body, forming granoblastic stripes in which either may be dominant. Scapolite is also found in the form of largish poikiloblastic grains in places.

In the more massive type of ore the magnetite mainly assumes a more coarse-grained form, although it is also found in lesser amounts as a fine-grained dissemination within gangue minerals. The gangue minerals themselves are the same as in the banded ores. Occasional gangue minerals to appear in all ore types are biotite, phlogopite, andradite, chlorite and carbonate, while titanite, apatite, epidote and serpentine, and in place also zeolite minerals, largely chabazite, occur as accessory minerals.

The magnetite grains are generally roundish in all types, and also subhedral in places. Sometimes the magnetite may contain lamellae of ilmenite, either narrow ones of under 1 μ or broader ones of 0.03 mm, and occasionally also small spinel exsolutions. The number of silicate inclusions, of size 0.005—0.1 mm, varies considerably and sulphide inclusions are few in number.

As seen from the analyses (Table 12), the Kuervaara ore contains over 3.5 % sulphur, the majority of this being bound in the pyrrhotite, and a small proportion in the pyrite and chalcopyrite. Estimated microscopically, the distribution of sulphides in the majority of the Kuervaara ore is approx. 70—80 %

Table 12

Mean chemical concentrations (% by weight) in the Hannukainen iron ores. 1, 2 and 5 are results for combined drill core samples for one ore body in each case, 4 is the mean result from analyses of two combined samples and 3 is the weighted mean of results from analyses on 50 drill core samples. The concentrations are all determined by the x-ray fluorescence method, except for Na_2O, which is determined by AAS.

	1.	2.	3.	4.	5.
Fe	41.6	35.1	43.7	43.0	43.7
Ti	0.15	0.19	0.12	0.10	0.08
V	0.02	0.02	0.07	0.01	0.01
Mn	0.09	0.09	0.14	0.17	0.14
Cu	0.08	0.14	0.14	0.36	0.14
S	3.6	3.7	3.8	2.6	2.7
SiO_2	24.0	26.9	21.2	23.0	23.5
Al_2O_3	4.7	5.6	3.2	4.3	3.5
MgO	7.0	6.4	6.1	6.1	6.3
CaO	7.5	9.2	8.2	6.3	5.4
Na_2O	n.d.*	n.d.	n.d.	n.d.	0.7
K_2O	0.3	0.3	0.3	0.5	0.6
P_2O_5	0.18	0.21	0.14	0.18	0.21

n.d. = not determined

1. Kuervaara S, combined sample, total length approx. 194 m
2. Kuervaara N, combined sample, total length approx. 302 m
3. Vuopio, total length of sample approx. 168 m
4. Laurinoja, combined sample, total length approx. 121 m
5. Lauku, combined sample, total length approx. 121 m

pyrrhotite, 10—20 % pyrite and 5 % chalcopyrite. The proportion of pyrite increases to approx. 30 % in the upper part of the ore body in the north of Kuervaara, however, and that of chalcopyrite to approx. 15 %.

The pyrrhotite occurs in grains of mean size 0.5 mm, although there is considerable variation in this figure, and regularly contains small inclusions of chalcopyrite. Similarly chalcopyrite intergrown with pyrrhotite is frequently found. The crystallization of these two minerals would thus seem to be closely related. Chalcopyrite has also been encountered in the opencast mine at Kuervaara in the form of compact aggregates and narrow veins containing at the same time pyrrhotite, magnetite and calcite.

The pyrrhotite is generally unchanged, and only in the upper part of the ore does one find the edges of the grains beginning to change to fine-grained pyrite. X-ray diffraction analysis suggests a composition of pyrrhotite corresponding to a monoclinic, highly ferromagnetic iron sulphide with a formula $Fe_{0.88}S$.

The majority of the pyrite represents a secondary sulphide which has crystallized in cracks or replaced pyrrhotite close to such cracks. Primary pyrite, which generally occurs in conjunction with pyrrhotite, only exists in any substantial quantity in the upper part of the Kuervaara ore body at its northern end. Magnetite appears to have been the first of the ore minerals to crystallize, mostly doing so after the silicates. The next was pyrite and finally pyrrhotite and chalcopyrite. A gel-textured melnikovite has also crystallized into the cracks in some places in the upper part of the ore body.

The Vuopio ore body

The Vuopio ore body consists of a single plate about 1200 m in length and 500 m broad with its longitudinal axis in a NE—SW direction. The plate is curved in profile, with a dip of 25—50° towards the west. The steepest dip is found in the south-east, where the ore body extends to the bedrock surface. It reaches its thickest, approx. 35 m, in the central part, thinning out towards the edges down to a few metres only. The northern tip lies some 80 m below the bedrock surface and the south-western part about 300 m below. The probable ore reserves are approx. 25 mil. tonnes, estimated from thirteen drill-holes. The mean composition of the ore is given in Table 12, No. 3. The iron and sulphur concentrations are slightly higher than

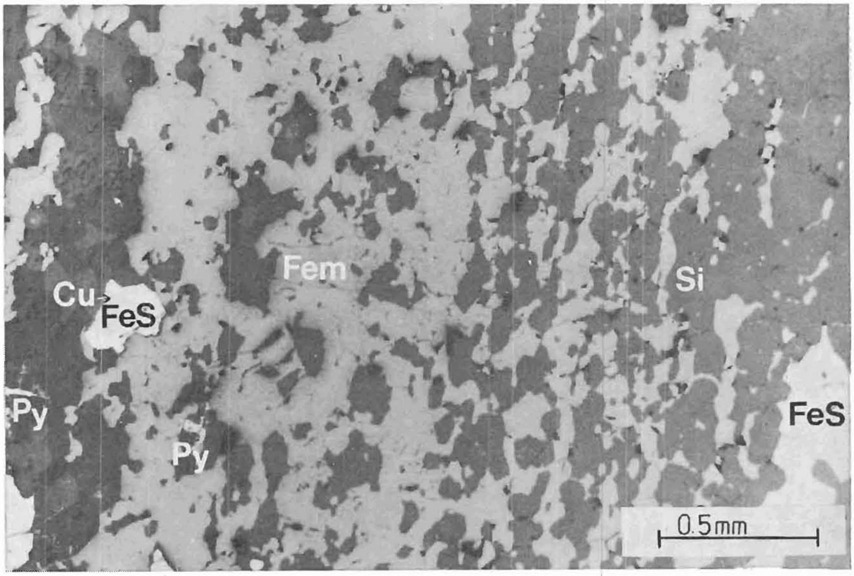

Fig. 44. Banded skarn ore from Vuopio, drillhole R 49, depth 221.2 m. Polished section, without analyser. Fem = magnetite; FeS = pyrrhotite; Cu = chalcopyrite; Py = pyrite; Si = silicate gangue.

at Kuervaara. The vanadium content of the Vuopio ore is also unusually high, although in general the differences in ore composition are relatively minor.

The Vuopio ore body is stratigraphically a south-westerly extension of that at Kuervaara, and is similarly located in the middle or upper part of the skarn layer. A separate ore horizon some 10 m thick was encountered above the ore body proper in one drill core, as denoted in the profile in Fig. 41.

Mineralogically the Vuopio ore is largely of the same kind as that found at Kuervaara. The more or less banded ore (Fig. 44), is composed of alternating magnetite-rich and silicate-rich bands, both of which contain varying amounts of sulphides. The grain size of the magnetite is chiefly 0.3—0.7 mm, with somewhat finer grain sizes occurring among the silicates. No ilmenite has been encountered. The sulphides comprise 85—90 % pyrrhotite, 5—10 % pyrite and 1—5 % chalcopyrite. The majority of the pyrite may be regarded as secondary, having replaced pyrrhotite. Chalcopyrite can usually be found in combination with pyrrhotite, and the larger grains of chalcopyrite often contain inclusions of pyrrhotite.

The main gangue minerals are diopside and amphibole, the latter being very much less common. The diopside is microscopically pale green or almost colourless, often with green, or more rarely colourless, amphibole around the grains. Scapolite, phlogopite, epidote, albite and calcite, with serpentine in conjunction with the latter as an alteration product of olivine, are occasionally found as gangue minerals, while apatite, biotite, titanite, chlorite and zircon occur as accessory minerals.

The Laurinoja ore body

The Laurinoja ore body comprises a single plate of length approx. 1100 m and maximum width approx. 700 m which decreases in thickness towards the edges. Its north-eastern margin extends to the bedrock surface, where it is broken up by veins of diorite and pegmatite, whereas it reaches its maximum depth of 275 m from the bedrock surface at its south-western end.

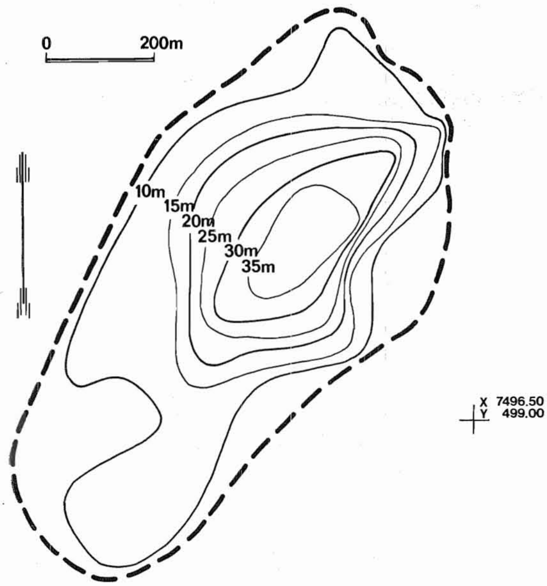

Fig. 45. Thickness of the Laurinoja ore body (in m), as isopleths on the horizontal projection of the ore body.

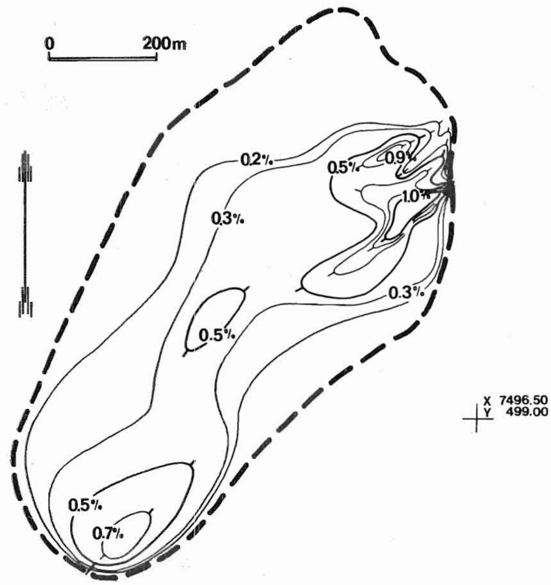

Fig. 46. Distribution of Cu (in %) in the Laurinoja ore body, as isopleths on the horizontal projection of the ore body.

The ore body reaches its maximum thickness of approx. 40 m close to the centre (Fig. 45). Its eastern part shows a dip of about 20°, but it then levels out towards the west to become practically horizontal. The steepest plunge along its longitudinal axis is similarly at the north-eastern end, amounting to approx. 20° to the south-west, while it bends in the central part to reach a horizontal profile. The ore body thus has the shape of a very wide, flattened bowl tilted to the south-west (Fig. 42). It is separated from the Vuopio and Kuervaara ore bodies by a diorite tongue following the stratification and partly running beneath this Laurinoja ore body (Figs. 41 and 42). There is very little skarn associated with this ore body, what is present being found mainly at the eastern edge.

The Laurinoja ore body contains about 33 million tonnes of ore, the main composition of which is shown on the basis of two combined samples in Table 12, No. 4. The total iron content of the ore is of the same order as at Vuopio, 43.0 %, but the sulphur content is very much lower, only 2.6 % S. The principal difference, however, lies in the higher copper content of the Laurinoja ore, 0.36 % Cu. Chalcopyrite can indeed be regarded as a second economically significant ore mineral here alongside magnetite. The Laurinoja ore also contains a little gold, with a mean concentration of 0.15 ppm.

The iron content of the ore body varies in a fairly irregular manner in the range 36—52 % Fe, whereas the distribution of the copper content is more regular. The marginal areas are poorer in copper than the centre, where three peaks in concentration are reached. The richest area for copper is at the north-eastern end of the ore body. The distribution of copper is indicated by an isopleth on the horizontal projection of the ore body in Fig. 46. The poorest area for copper is the north-western margin, where its concentration remains below 0.1 %.

Macroscopically the Laurinoja ore varies

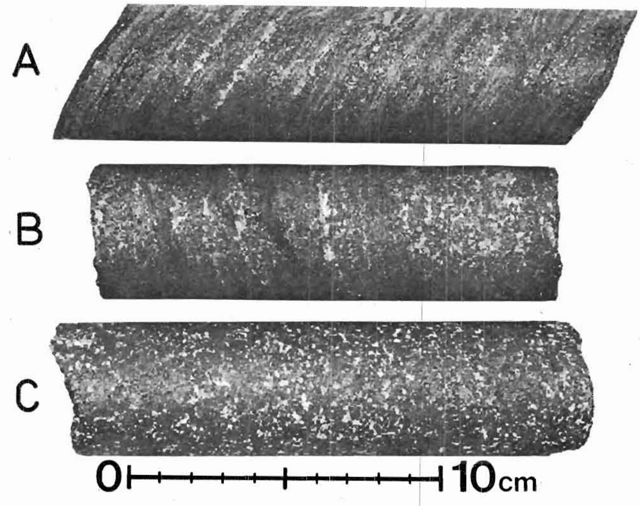

Fig. 47. Types of skarn ore at Laurinoja.
A. Banded ore, R 170, depth 98.1 m. Dark material chiefly magnetite, with some silicate; light material chalcopyrite.
B. Slightly banded ore, R 177, depth 111.8 m. Dark material chiefly magnetite; light material chalcopyrite and calcite.
C. Massive ore, R 170, depth 90.2 m. Dark material magnetite; light material calcite.

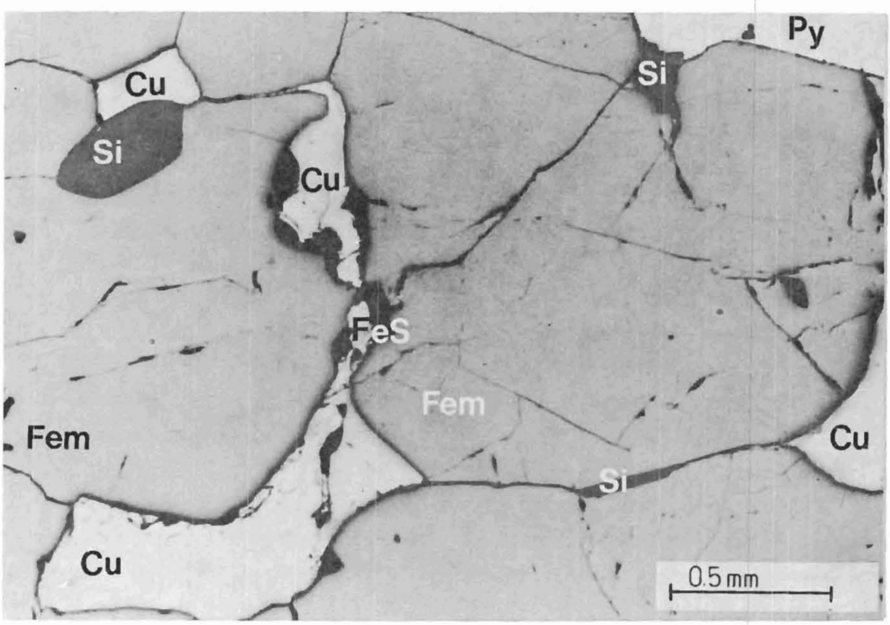

Fig. 48. Magnetite ore from Laurinoja, R 57, depth 48.9 m. Polished section, without analyser. Fem = magnetite; Cu = chalcopyrite; FeS = pyrrhotite; Py = pyrite; Si = silicate.

irregularly from a more or less pronounced banded rock to a massive variety, with the former type the more common (Fig. 47). The streaks in the ore are nevertheless much more poorly developed here than in the Kuervaara ore. As at Kuervaara, however, the effect is due to the presence of alternate stripes of silicate-rich and magnetite-rich rock varying in thickness from a few millimetres to some centimetres. The massive type of ore is richer

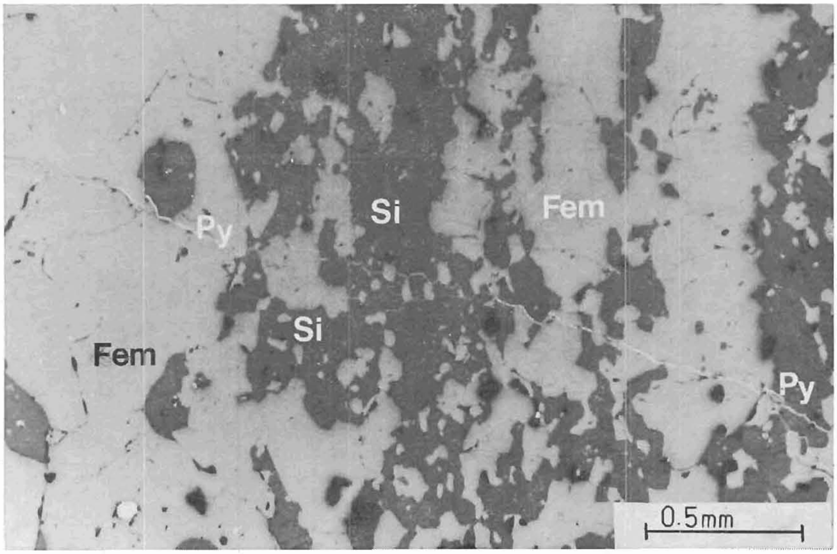

Fig. 49. Magnetite ore from Laurinoja, R 79, depth 170.2 m. Polished section without analyser. Magnetite (Fem) found in coarse-grained stripes and as small grains scattered within the dark silicate stripes (Si). The fissure vein is filled with secondary pyrite (Py).

in magnetite and coarser-grained than the banded type, in which the silicate-rich parts are more fine-grained.

Primary and secondary pyrite and pyrrhotite are present as well as the main minerals, magnetite and chalcopyrite. The ratios between the sulphides vary on a small scale within the ore body, but pyrite still accounts for over a half of all the sulphides. Chalcopyrite and pyrrhotite are broadly speaking equal in occurrence, although the amount of pyrrhotite in particular varies within broad limits.

The magnetite is mostly found in subhedral grains of size 0.5—1.5 mm which are free from inclusions (Fig. 48). It is more coarse-grained than at either Vuopio or Kuervaara. The banded ore contains of a grain size of 0.1—0.02 mm disseminated in its more silicate-rich parts (Fig. 49). The coarsest-grained of all is the massive ore with a carbonate gangue, in which the grains of magnetite can be over 2 mm in size.

The pyrite is found largely in the form of scattered primary, subhedral grains of size 0.2—0.6 mm (Fig. 50), in which there may be small inclusions of chalcopyrite, pyrrhotite and sometimes magnetite. A small proportion of pyrite exists as tiny inclusions (0.01—0.05 mm) within the silicates and even the chalcopyrite. Small amounts of pyrite are found secondarily filling cracks and replacing pyrrhotite, as at Vuopio and Kuervaara. The secondary pyrite was obviously the last sulphide to crystallize in the Hannukainen area (Fig. 51).

The majority of the chalcopyrite consists of independent grains of size 0.2—1.5 mm (Fig. 52), frequently with inclusions of primary pyrite and/or pyrrhotite. Chalcopyrite can also be found as small inclusions within pyrrhotite and pyrite and as intergrowths with these. A small quantity also occurs as inclusions within the silicates and as a recrystallization product in the interspaces of the magnetite and silicates. Some takes the form

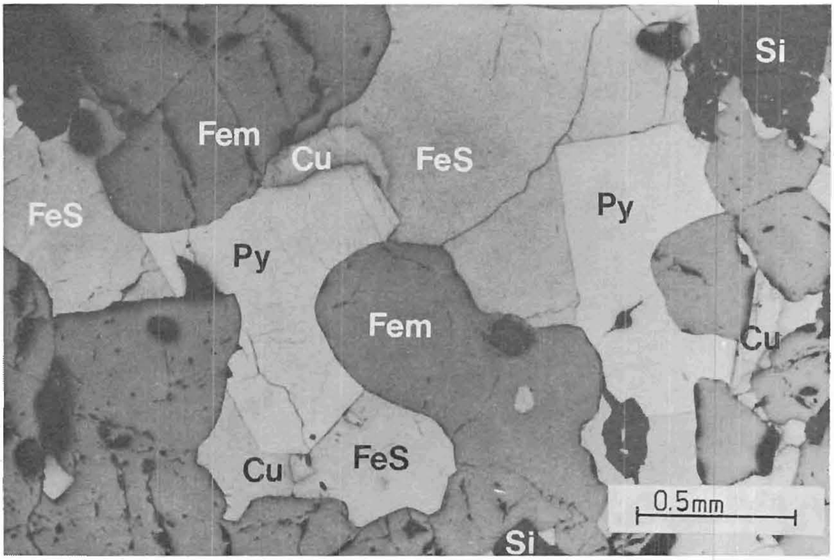

Fig. 50. Sulphide-rich ore from Laurinoja, R 72, depth 212.2 m. Polished section, without analyser. Fem = magnetite, in partly rounded grains; Py = pyrite; FeS = pyrrhotite; Cu = chalcopyrite; Si = silicate.

of compact veins some 5—30 cm thick at most, in which it forms various types of intergrowths with pyrite. This is indicative of simultaneous crystallization of chalcopyrite and pyrite in these veins.

The pyrrhotite occurs in the pyrite-dominated parts mostly as inclusions within chalcopyrite and having a grain size of 0.05—0.1 mm, while in the pyrrhotite-dominated parts the grain size is coarser, with a mean of 0.5 mm. Pyrrhotite and chalcopyrite occur together throughout the Hannukainen area and were crystallized almost simultaneously regardless of their mutual proportions.

Traces of gold have been encountered with minute grains in a few polished sections. The largest grain was of dimensions 0.1 × 0.3 mm. Gold can be found as inclusions in pyrite together with chalcopyrite, in cracks in pyrite and magnetite, as inclusions in chalcopyrite and at contacts between pyrite and chalcopyrite.

As is the case throughout the Hannukainen area, the main gangue minerals are diopside and in lesser amounts hornblende. In addition one also finds large amounts of albite, quartz and microcline, especially close to the diorite tongues. Less common gangue minerals are calcite, serpentine, olivine, epidote, andradite, phlogopite and chlorite. Frequent accessory minerals are apatite and in places titanite and scapolite.

The diopside has a light green or colourless appearance in thin sections. The largest grains often contain large numbers of small magnetite inclusions. The hornblende is highly pleochroic, with α = dark blue-green, β = green, γ = light brownish-green. Colourless amphibole is found as a gangue in places in the north-eastern part of the ore body, in which case chlorite may also be present as an alteration product. Calcite occurs as a gangue in the more massive, coarse-grained ore, together with olivine and its alteration product serpentine, largely in the lower part of the ore lens. Andradite and quartz appear

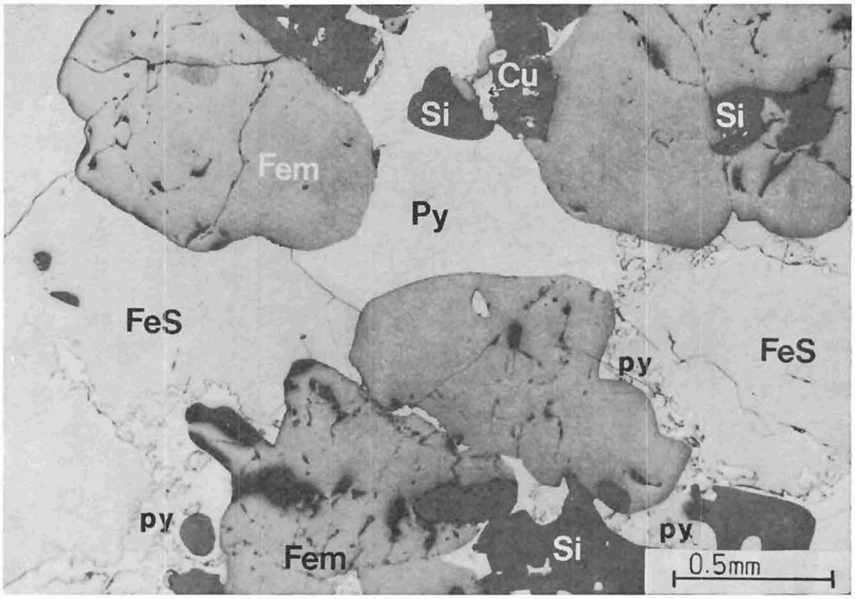

Fig. 51. Secondary pyrite (py) replacing pyrrhotite (FeS) at Laurinoja, R 72, depth 212.2 m. Polished section, without analyzer. The primary pyrite (Py) is brighter than the secondary (py). Cu = chalcopyrite; Fem = magnetite; Si = silicate.

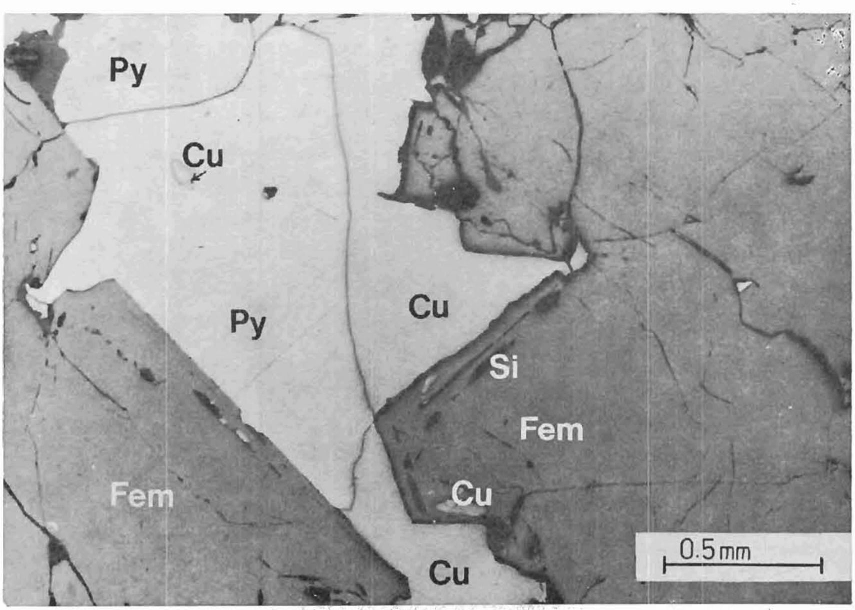

Fig. 52. Chalcopyrite (Cu) and pyrite (Py) in the interspaces of magnetite (Fem) and lamellae of silicate (Si) in the magnetite. Laurinoja, R 45, depth 117.0 m. Polished section, without analyser.

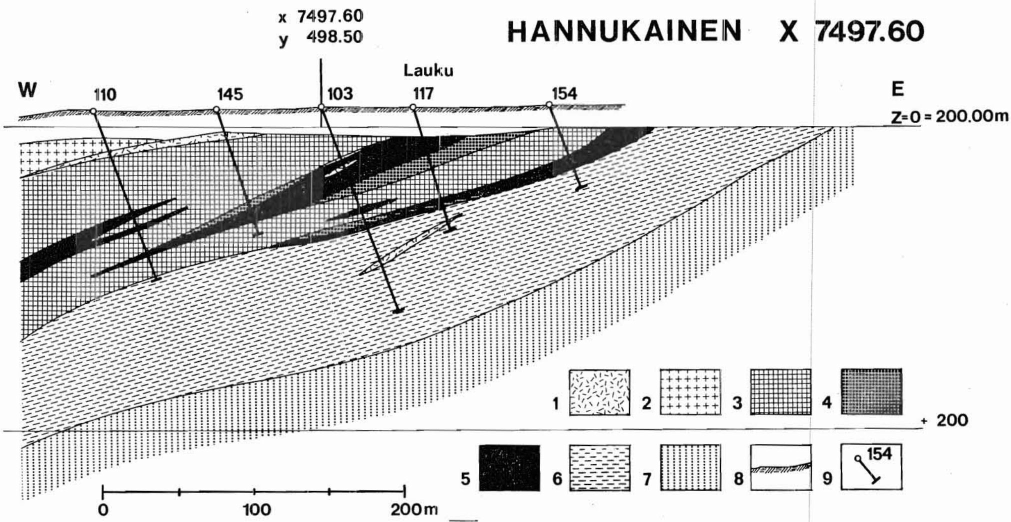

Fig. 53. Geological cross-section from Hannukainen, profile × 7497.60. *Intrusive rocks:* 1 = pegmatite; 2 = monzonite; 3 = diorite. *Rautuvaara Formation:* 4 = skarn; 5 = ore; 6 = amphibolite. *Niesakero—Kuertunturi quartzite complex:* 7 = quartzite; 8 = ground surface; 9 = drillhole with number.

sporadically, either together or separately, in the upper part of the lens at the northern end of the ore body, and are generally accompanied by dark-green clinopyroxene. Quartz can be almost the only gangue mineral in places, in which case the banded type of ore may be referred to as a quartz-banded iron ore. Where this happens the quartz is entirely recrystallized in a vitreous mass of variable grain size with scattered grains and faint streaks of magnetite. It is impossible to say for certain from either the texture or the mineral composition whether or not this is a relict from a primary quartz-banded iron ore. Its position in the upper part of the ore body and close to the contact with the intrusion, in the same area as a skarn containing andradite, would point towards the metamorphic conditions as having led to the abundance of quartz (cf. p. 122).

The Lauku ore body

The Lauku ore body in the northern part of the Hannukainen area comprises two partially overlapping ore lenses of maximum thickness approx. 20 m and thinning at the edges, which each contain more than a million tonnes of ore, together with three separate small lenses, two to the north and one to the south (Fig. 32). The largest of these latter is the northernmost, which has been penetrated in three drillings, showing a maximum thickness of 10 m.

The more southerly of the main lenses overlies the amphibolite bed of the Rautuvaara Formation. The more northerly one is divided from both this and the southern ore lens by a diorite tongue of thickness approx. 20 m following the bedding of the rock (Fig. 53). The edge of the third of the smaller lenses can also be seen in the profile at the western edge, again marked off by diorite. The positioning of the ore lenses *en échelon* with respect to each other may thus be explained by the intrusive behaviour of the diorite. Only a little actual skarn is to be found at Lauku, this occurring in conjunction with the magnetite lenses.

The mean composition of the ores is indicated in Table 12, No. 5. This ore body is comparable chemically with the Vuopio deposit, but differs from this mineralogically in that the main sulphide mineral is pyrite and there is only a little pyrrhotite present.

The ore is for the most part massive in texture, with banded ores, in which stripes of gangue alternate with magnetite, occurring to a lesser extent. Particularly at the edges of the body, the ore contains narrow veins of diorite and pegmatite. The main ore mineral, magnetite, occurs in the form of grains of size 0.3—1.0 mm which are fairly idiomorphic and usually free of inclusions. There are only a small number of silicate and sulphide inclusions present. The silicate gangue also commonly contains a little fine-grained magnetite of grain size 0.1—0.05 mm. The majority of the sulphur is bound to pyrite, with small amounts to the chalcopyrite and pyrrhotite. The distribution of the sulphides disseminated in the ore is highly non-homogeneous, this being true of both pyrite and especially chalcopyrite. Thus pyrite-rich parts alternate with pyrite-free ones with no regular pattern discernible. The pyrite takes the form of subhedral grains of size 0.5—1.2 mm. It is also found in a finer-grained dissemination in the silicates and sometimes the magnetite. The majority of the chalcopyrite can be found as independent grains between the grains of silicate or magnetite, and sometimes as small inclusions in the magnetite or pyrite. Pyrrhotite appears sporadically in conjunction with chalcopyrite.

The gangue minerals are diopside, light-coloured amphibole, plagioclase and occasionally phlogopite, these forming thin stripes in the direction of schistosity in the banded ores.

The Kivivuopio ore body

The blind Kivivuopio ore body is situated about 1 km to the west of Laurinoja, and has been penetrated by four drillholes at a depth of 400—550 m. The edge of the ore body may be seen in Fig. 42, where it forms a continuation of the Laurinoja bed to the south-west. The thicknesses indicated by the drillings are in the approximate range 15—30 m, and the ore corresponds largely to that found at Lauku, with pyrite again as the main sulphide and very little chalcopyrite or pyrrhotite. The hanging wall and footwall of the ore body consist of diorite.

Since research is continuing at this site, it is too early at present to give any estimate of the possible quality or dimensions of this deposit.

Sulphur isotope studies

The sulphur isotope composition of the sulphides in the Hannukainen ore bodies has been studied by Mäkelä and Mattila (in press). This work involved the determination of $\delta^{34}S$ values for one drill core each from Vuopio, Laurinoja and Lauku. A total of 130 determinations was carried out, distributed between the ore bodies as follows: Vuopio 55, Laurinoja 53 and Lauku 22. Some determinations were also carried out on sulphides in the diorite of the hanging wall and the metasediments of the footwall.

The histogram in Fig. 54 shows the distribution of $\delta^{34}S$ values in the diorite, skarn, ore and quartz—feldspar schist. There is apparently no lithological correlation, as the distributions are similar for the various rocks studied, although the scatter in the results is smallest for the diorite. Fig. 55 depicts the distribution of values by ore body, the

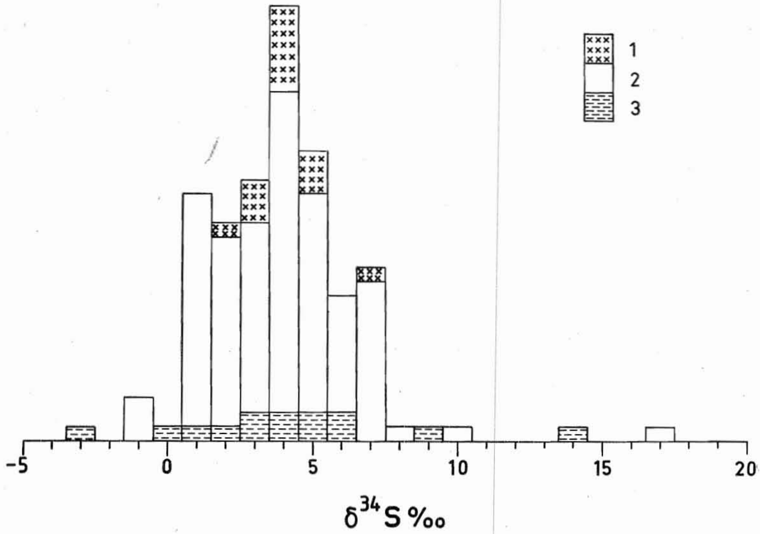

Fig. 54. Histogram of $\delta^{34}S$ values for the Hannukainen sulfides in 1 = diorite; 2 = skarn and ore; 3 = quartz-feldspar schist (Mäkelä & Mattila, in press, Fig. 6).

summary histogram and the pyrite—pyrrhotite distribution of the samples. No major differences in $\delta^{34}S$ values are seen between the ore bodies in spite of the different distribution of sulphides. The histograms for both Lauku and Laurinoja show a maximum value of + 4, while the Vuopio histogram is exceptional in being broad and even, with a maximum of + 1.

In evaluating the significance of the sulphur isotope composition from the point of view of the genesis of the ores, it should be noted that one cannot classify ore deposits or say very much about their genesis from sulphur isotope values alone, since their interpretation presupposes a detailed knowledge of the geology, mineralogy and geochemistry of the deposit (Rye and Ohmoto 1974). Although values close to zero do not necessarily imply a magmatic origin for the sulphur (Ohmoto 1972, Field and Gustafsson 1976), the maximum of + 4 for the Hannukainen ore bodies, together with the fairly narrow range of variation, nevertheless does point to a hypogenic origin for the sulphur present.

Mäkelä and Mattila (in press) note a positive correlation between magnetite concentration and the $\delta^{34}S$ value in one of the ore sections studied, that at Vuopio, the highest magnetite and $\delta^{34}S$ values being recorded in the upper part of the section, where pyrite is dominant in the ore. The Laurinoja ore body shows a weak correlation in this respect and the Lauku ore body none at all.

In considering the significance of the variations in sulphur isotope composition, it should be borne in mind that no firm conclusions can be reached from the direction of changes in $\delta^{34}S$ values and magnetite concentrations in a profile representing a single drilling. Consequently the relationship between this and the primary stratification remains an open question. As noted above (p. 71), although skarns and ores may be characterized by a banded appearance, nothing is known about the relation between this and the primary stratification, except that they are presumably similar in direction.

Under conditions of equilibrium the $\delta^{34}S$ values of hydrothermal minerals are determined by their physico-chemical conditions

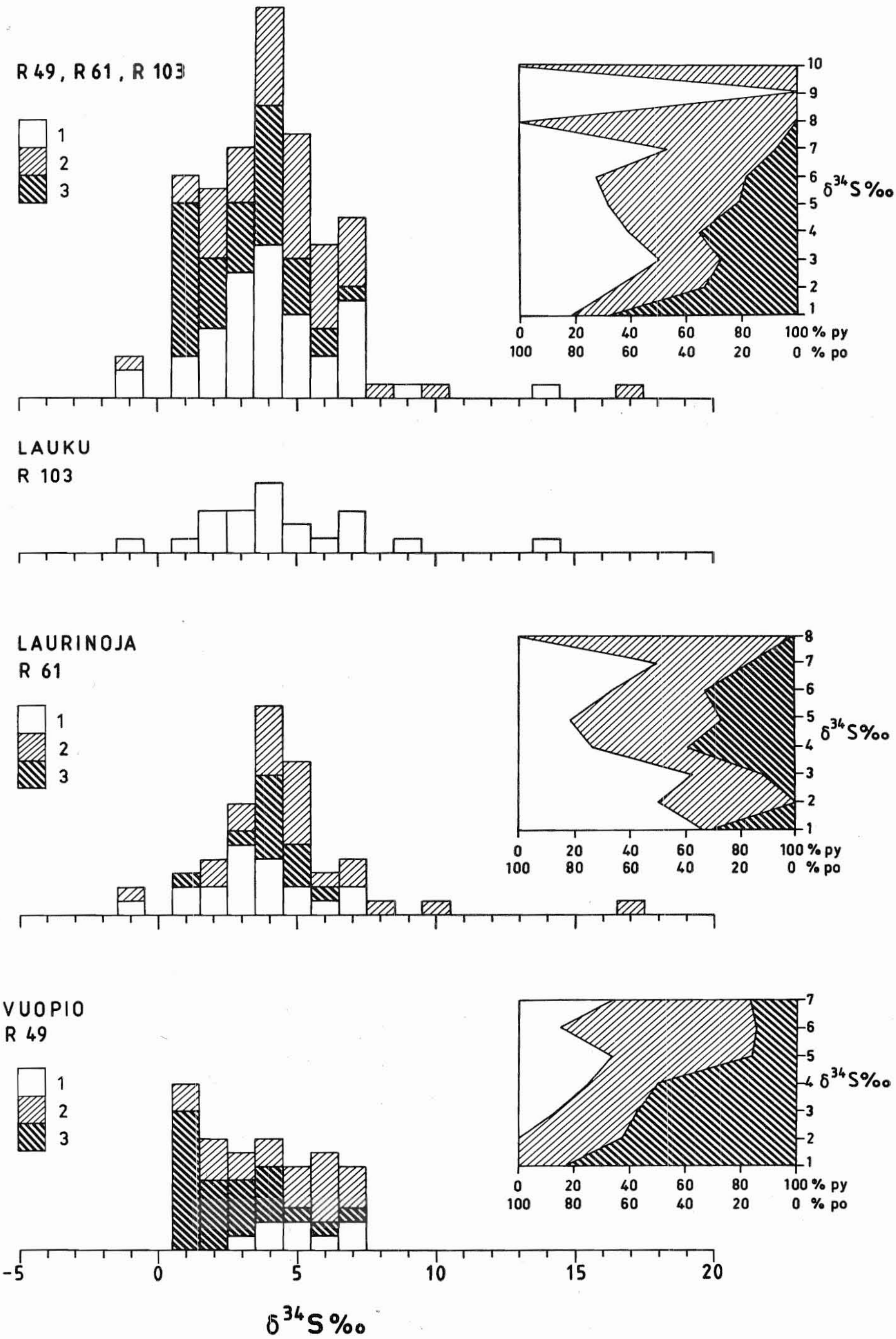

Fig. 55. Relations between $\delta^{34}S$ and sulphide mineral assemblages in the Hannukainen skarn iron ore deposits: 1 = pyrite samples; 2 = pyrite–pyrrhotite samples; 3 = pyrrhotite samples, py - pyrite, po - pyrrhotite (Mäkelä & Mattila, in press, Fig. 7).

(T, pH, f_{O_2}) and the isotope composition of the sulphur in the ore-bearing fluids. On the other hand, differences in the chemical composition of the environment may explain the very widespread variation which can be found in the sulphur isotope compositions of hydrothermal sulphides (Rye and Ohmoto 1974). Under certain conditions even a small rise in pH can cause a marked increase in $\delta^{34}S$ values (Ohmoto 1972), and such a change may well come about when an acidic fluid reacts with a limestone, for instance, in which case magnetite can be precipitated. In an open system such as metasomatic metamorphism, a change of this kind can go on in an apparent state of equilibrium (Korzhinsky 1964), in which case the positive correlation between magnetite content and $\delta^{34}S$ values becomes quite understandable. It is the author's opinion that the relatively minor variations in $\delta^{34}S$ values in the Hannukainen ore bodies can be explained in terms of the composition of the ore-bearing fluids and the physico-chemical factors controlling the formation of ore minerals quite without reference to the origins of the ore material in the fluids. There is then every justification for assuming the sulphur in the sulphides of both the skarn ore and the diorite of the hanging wall of the ore body to be of the same origin in the light of the similarities in mineralogy and $\delta^{34}S$ values.

MAGNETITE DEPOSITS TO THE NORTH OF HANNUKAINEN

A few magnetite deposits are known to exist 3—7 km north of Hannukainen, forming a continuation of the Rautuvaara Formation, but these are of modest dimensions and consequently have not been studied in any detail. The best documented of these is the furthest south, that known as the Kuervitikko deposit. Further north is the Tuohilehto deposit, and between these the most limited of all, the Aavahelukka deposit. The area between these deposits and Hannukainen contains very little skarn, but magnetite and pyrite do exist in greater than usual abundance in the rocks of the monzonite marginal zone. These rocks are also unusually rich in quartz, being further composed of albite and magnetite. Potassium feldspar is also found in places, giving a composition approaching that of granite. The three magnetite deposits mentioned above will be described briefly in the following.

The Kuervitikko magnetite deposit

The Kuervitikko magnetite deposit 3 km north of Hannukainen lies in a tectonically somewhat disturbed area. Interpretations suggest that the Rautuvaara Formation is cut across by a NW—SE-oriented fault just north of this deposit. Four drillholes concentrating on a single profile have provided a detailed section for the deposit, as illustrated in Fig. 56. Three further drillings have been performed to the north of this profile site, and three to the south.

The maximum thickness of the Rautuvaara Formation at this section is approx. 150 m and its dip very gentle, 15° to the west. The overlying surficial deposits are some 20—30 m in thickness, becoming thinner in an even manner towards the area of intrusives in the west. The quartzite of the footwall

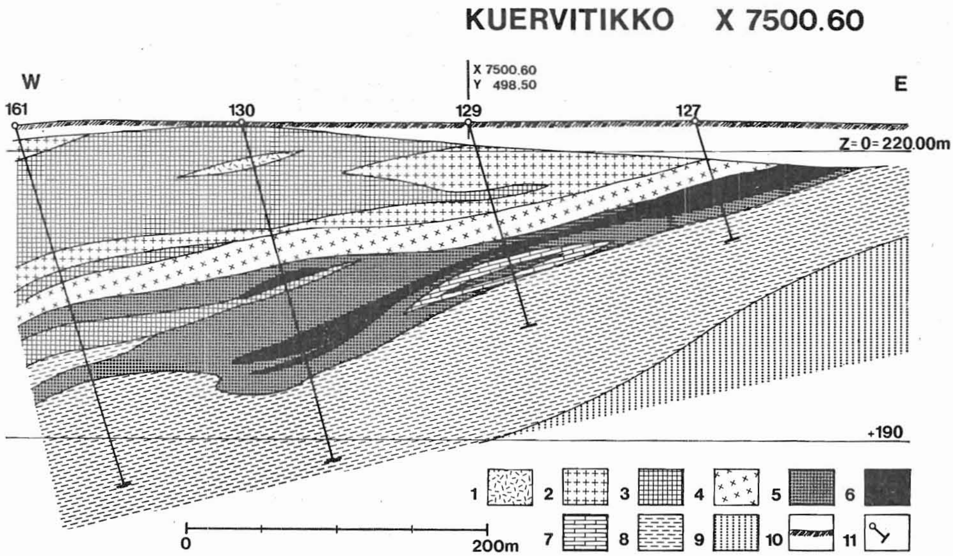

Fig. 56. Geological cross-section from Kuervittikko. *Intrusive rocks:* 1 = pegmatite; 2 = monzonite; 3 = diorite; 4 = albite—quartz rock. *Rautuvaara Formation:* 5 = skarn; 6 = ore; 7 = carbonate; 8 = amphibolite. *Niesakero—Kuertunturi quartzite complex:* 9 = quartzite; 10 = overburden; 11 = drillhole.

has not been reached in the drillings, but a good, representative cross-section has been obtained of the intrusive rocks forming the hanging wall on account of the gently sloping attitude of the strata.

No precise information is available on the thickness of the amphibolite bed in the lower part of the Rautuvaara Formation, although one drillhole passes through some 70 m of this rock. The amphibolite is banded, contains biotite in places, and is partially granitized. Its upper part includes a layer of light-coloured amphibolite with cummingtonite and/or anthophyllite dominant, as at Hannukainen, and this has magnetite, pyrite and a little scattered chalcopyrite associated with it. Some skarn interlayers appear towards the skarn beds themselves.

The amphibolite is overlain by a skarn bed some 80 m thick (at drillhole No. 130), presumably as a consequence of folding. This skarn bed also contains a lens of white carbonate rock approx. 17m thick with patches of skarn inside it. The skarn is principally a banded or massive rock with diopside, amphibole or plagioclase dominant, but also contains some scapolite, epidote and garnet-rich patches. The skarn features amphibolite interlayers and a diorite tongue following the stratification in the western part of the section. The magnetite ore forms a plate of maximum thickness 13 m and gradually thinning out, located in the skarn bed and again following the stratification. A separate small magnetite lens is also found in the upper part of the skarn bed at its thickest point. The longitudinal axis of the ore body plunges obviously towards the south-west, following the general lineation, as has regularly been observed to be the case at Hannukainen. The magnetite ore in the eastern part of the deposit is massive and contains an uneven dissemination of pyrite and chalcopyrite. The gangue mineral is blue-green amphibole. The concentrations of Fe, S, Cu and Au in the best drill cores are of the same order as at Laurinoja.

The ore has a lower iron content in the western part of the section, and is at the same time poorer in sulphur. The copper content is below 0.2 % Cu. The ore here is banded and the gangue mineral is predominantly diopside.

The skarns are overlain by the rocks of the marginal zone of the monzonite intrusion, which differ somewhat in their mode of occurrence from those described at Hannukainen. Closest to the skarns is a zone of about 15—20 m of light-coloured, massive rock composed mainly of albite and containing varying amounts of quartz and occasionally epidote, hornblende and biotite. Its texture is hypidiomorphic-granular, with a grain size of 0.2—0.6 mm. This rock regularly contains scattered grains of magnetite, pyrite and a small amount of chalcopyrite. Susceptibility determinations suggest that the magnetite has become enriched close to the contact with the skarn in the lower part of the albite—quartz rock, and particularly on top of the thicker of the magnetite lenses. This albite—quartz rock thus represents a mineralized contact rock, corresponding closely to the mineralized zone in the upper part of the diorite at Hannukainen.

Above the albite—quartz rock one finds monzonite and diorite, with sharp contacts between them. The monzonite is slightly darker and richer in hornblende than usual and contains red veins of granite and pegmatite, and also sharply defined patches of diorite. The diorite itself is massive in texture, grey and fine-grained, also containing large numbers of veins of granite and pegmatite. As the amount of the dark minerals decreases, it grades to a white albitite-like rock in places. The upper part of the diorite has dark non-homogeneous patches containing diopside in places and with associated streaks and scattered grains of magnetite.

The section presented in Fig. 56 suggests that the diorite at Kuervitikko also penetrated into the monzonite during the later stages of the monzonite movements, and not only in between the monzonite and skarn as at Hannukainen. This exceptional behaviour may be due to the violent movements in the area, associated with the turning of the Rautuvaara Formation towards the north-east to the north of Kuervitikko.

The Aavahelukka magnetite deposit

Two drillholes at Aavahelukka, about 2 km north of Kuervitikko, have encountered a skarn bed of maximum thickness 20 m located on top of striped amphibolite, and one of these drillings also identified a magnetite lens approx. 6 m thick containing 35.3 % Fe, 2.5 % S and 0.07 % Cu. Above this skarn bed are non-homogeneous light-coloured rocks of the monzonite marginal zone with abundant scattered grains of magnetite in places. No actual diorite has been encountered, however.

The Tuohilehto magnetite deposit

The northernmost known skarn iron ore deposit in the area studied here is located at Tuohilehto, at the point where the Rautuvaara Formation bends sharply to the north-west. Small lenses of magnetite are distributed in a scattered manner within a space

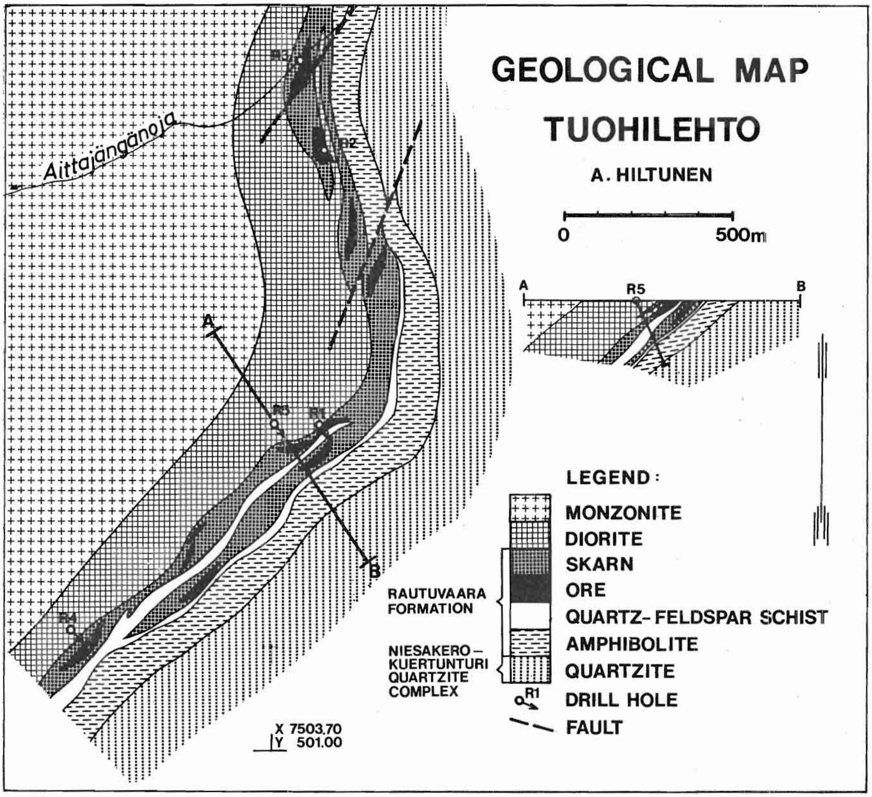

Fig. 57. Geological map of Tuohilehto.

of about 2 km on either side of this point (Fig. 57). The detailed map of this area is based of geophysical interpretations together with results obtained from five drillings, the deepest of which, R 5, penetrated the whole Rautuvaara Formation.

The thickness of the Rautuvaara Formation at the drillhole R 5 is 150 m and its dip 40—45° to the west. Beneath it lies a bed of highly granitized potassium feldspar-rich quartzite, which represents the upper part of the Niesakero—Kuertunturi quartzite complex. On top of the quartzite is approx. 50 m of amphibolite of the streaked, granitized type, rich in biotite in places and with some feldspar augens. The upper part of this amphibolite contains diopside-rich layers and aggregates with a little magnetite in scattered grains in places.

Above the amphibolite is a layer a few metres thick of fine-grained, stratified graphite and pyrrhotite-rich quartz—feldspar schist, and above this the skarn bed, of thickness 90 m. The central part of this bed is occupied by a layer of light-coloured, stratified feldspar-rich schist with a fine-grained dissemination of pyrite and pyrrhotite. The skarn is partly massive in texture and dominated by diopside, and partly streaked, containing hornblende and feldspar, and also garnet in places. In addition to the narrow schist interlayers it also features diorite veins a few metres in width.

The magnetite is located in smallish lenses within the skarn, the thickest of which are over 10 m. The ore is in part clearly banded in texture and in part massive, with diopside as the principal gangue mineral. Others present are carbonate, light-coloured amphibole and garnet. Pyrite, pyrrhotite and occasionally chalcopyrite occur irregularly distributed as scattered grains, aggregates and fissure veins. The drilling results suggest that the concentrations of iron and sulphur in the ore are of the same order as at Hannukainen. The copper content is low.

The magnetite lenses of Tuohilehto are of modest proportions economically, the largest, the two northernmost ones, totalling perhaps 1—2 million tonnes of ore.

The skarn bed is overlain by diorite, which grades from a medium-grained grey rock to a lighter and more fine-grained variety as it approaches the skarn bed. This diorite typically contains a little scattered magnetite. The monzonite which should occur above the diorite has not yet been encountered in the area in either drillings or bedrock outcrops.

THE RAUTUVAARA MAGNETITE DEPOSIT

General description

The Rautuvaara deposit includes three separate ore bodies, NE-Rautuvaara, SW-Rautuvaara and Cu-Rautuvaara, which differ in both their ore and gangue minerals. Only the NE-Rautuvaara ore body represents the true skarn ore type, closely resembling the ores of Kuervaara and Vuopio within the Hannukainen deposits. The Cu-Rautuvaara ore body is of the disseminated type, being composed of albite—antophyllite rock with scattered grains of chalcopyrite and magnetite. The SW-Rautuvaara ore body then represents an intermediate form between these two, charácterized by the iron-rich silicates as gangue minerals. The geological map of the deposit is present in Fig. 58.

The Cu- and SW-Rautuvaara deposits are located about a kilometre apart in the upper part of the Rautuvaara Formation, which occupies its original stratigraphic position between the quartzite complex and the monzonite intrusion. The NE-Rautuvaara ore body is associated with a xenolith of rocks from the Rautuvaara Formation which have become detached from their original position and have remained within the intrusive rocks. Structurally both the Rautuvaara Formation at its contact with the quartzite and the inclusion making up the NE-Rautuvaara ore body show a dip of 70—80° to the south-east. The highly pronounced lineation plunges 30—50° to the south-west, coinciding with the longitudinal axis of the ore lenses.

The rocks of this deposit are described in more detail in connection with the account given of the separate ore bodies. Suffice it at present to note that these rocks are the same as described above at Hannukainen and further north. One special feature is the complex mode of occurrence of the rocks of the monzonite intrusion and its marginal zone, with both sharp and gradual contacts, and frequently overlapping in a wedge-like manner, as may be appreciated from the map. This phenomenon is of the same kind as noted at Kuervitikko (p. 95), but better developed, and may probably be explained by intensive movements during the intrusion stage.

The inventory of the ore reserves of the Rautuvaara deposit prior to the commencement of mining gave a total of approx. 15 million tonnes. Exploitation began at NE-Rautuvaara, where the mine was opened in

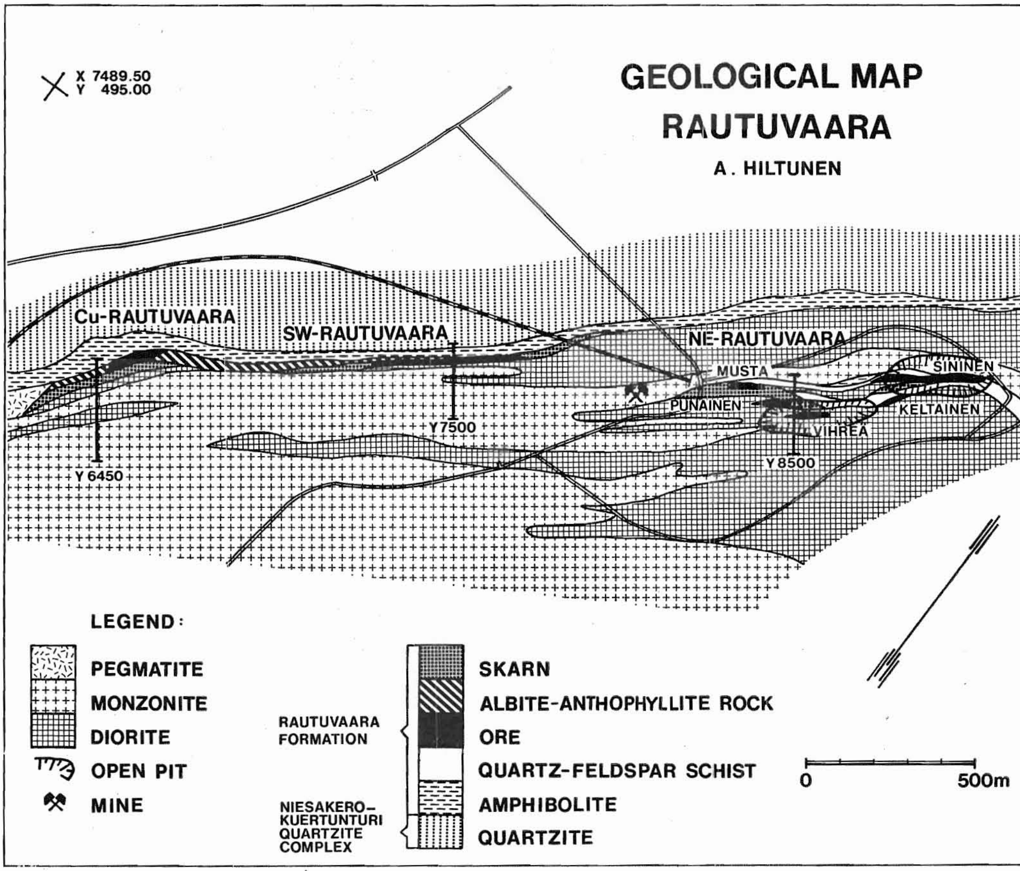

Fig. 58. Geological map of Rautuvaara.

1975. Mining at SW-Rautuvaara began in 1979. A degree dissertation has been produced on the ore bodies of NE-Rautuvaara by Kuivasaari (1980), and his detailed descriptions will be used to complement the author's own observations.

The NE-Rautuvaara ore body

The NE-Rautuvaara ore body (Fig. 58) comprises a number of separate long, narrow, plate-like ore lenses oriented in the direction of the lineation and occurring in a xenolith composed of rocks of the Rautuvaara Formation and located within the intrusive rocks. The formation has a maximum thickness of almost 100 m and a dip of approx. 80° to the south-east at the bedrock surface, levelling off gradually at greater depths. Its cross-section is illustrated in Fig. 59, in which the three largest ore lenses, Sininen, Vihreä and Keltainen are indicated. The lineation is very well developed, and plunges regularly 30—50° to the south-west throughout the area.

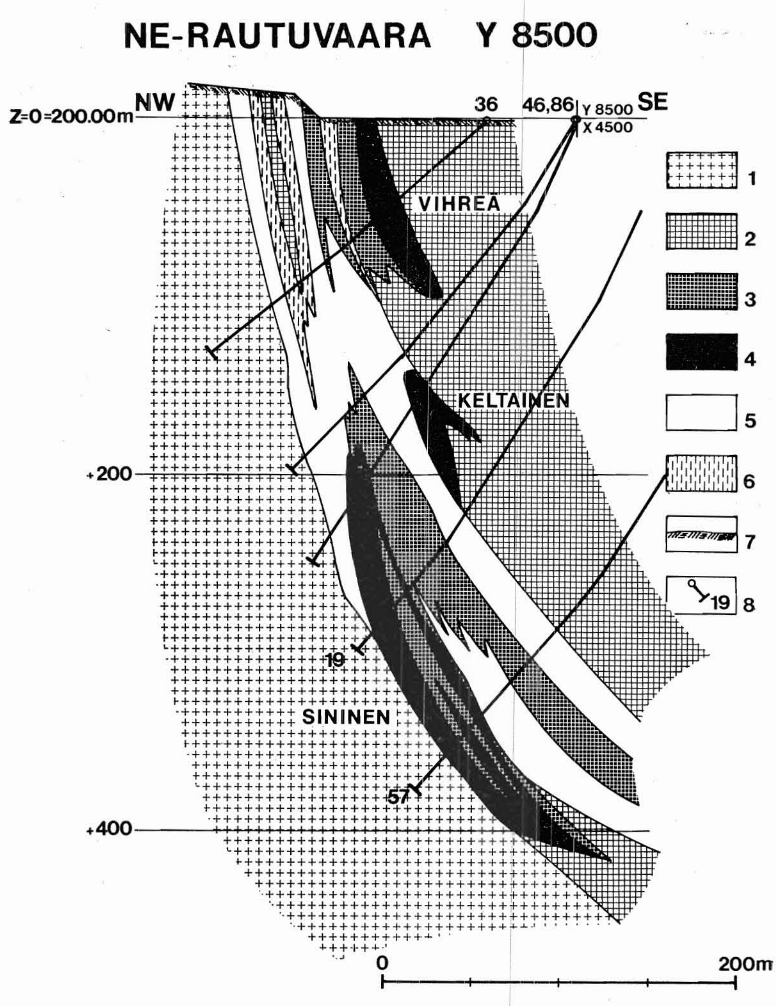

Fig. 59. Geological cross-section of NE-Rautuvaara. *Intrusive rocks:* 1 = monzonite; 2 = diorite. *Rautuvaara Formation:* 3 = skarn; 4 = ore; 5 = quartz-feldspar schist; 6 = amphibolite; 7 = ground surface; 8 = drillhole with number.

Description of the wall rocks

The footwall of the NE-Rautuvaara ore body contains 30—80 m of monzonite (Fig. 59) and then about 50 m of diorite to the NW before the rocks of the Rautuvaara Formation, which represent a continuation of SW-Rautuvaara. The hanging wall is composed largely of diorite-dominated rocks of the monzonite margin, the composition of which varies considerably, as was the case at Hannukainen. Some diorite also exists in conformable tongues within the Rautuvaara Formation. The diorite in the south-western part of NE-Rautuvaara includes tongues of monzonite.

The monzonite found here does not depart appreciably from the types described earlier. The dominant form is a reddish, homogeneous, gneissic rock of medium grain size and with a composition varying from quartz monzonite to monzonite. The footwall of the formation also contains a darker than normal type rich in hornblende in some places and a light-coloured albititic marginal variety in others at the contact with the rocks of the Rautuvaara Formation. The age determination for the albitite of Rautuvaara (p. 51) was based on a sample of this monzonite variety found in the footwall of the formation. The contacts between the monzonite and diorite are either sharp ones or else grade gently over a distance of some metres.

The diorite-dominated rocks of the hanging wall represent a heterogeneous entity encompassing rocks varying in composition from light, albite-rich diorites to dark hornblende diorites, the most common being a homogeneous biotite-bearing type of just the same kind as that found at Hannukainen. The colour varies from light-grey to dark according to the amounts of mafic minerals present. This heterogeneity arises due to greater or lesser admixtures of inclusions consisting of rocks from the Rautuvaara Formation, principally skarns, causing the rock to vary from pure diorite to a mica-rich amphibolite. A mixed zone of this kind is particularly clearly seen in the narrow area marked as diorite which extends southwestwards from NE-Rautuvaara (Fig. 58), which in effect consists of non-homogeneous amphibolite.

Fig. 60 shows a cross-section through the rocks of the hanging wall as represented at drillhole R 65 in profile y 8100 (on the Rautuvaara grid, cf. Fig. 58), and also the variations in chemical composition with respect to the principal components. The diorite is at its most typical largely in the lower part of the section, before the skarn and amphibolite, as seen in particular in the fall in K_2O content. Otherwise the section represents a heterogeneous entity without the clear zonation noted at Hannukainen (Fig. 37). The same general features are to be seen, however, and an increase in both magnesium and also calcium and iron silicates is evident close to the skarn contact. Endoskarn formation is also common at Rautuvaara.

The hanging walls of the ore lenses are frequently composed of several metres of a light-coloured rock, consisting mainly of albite—oligoclase, before the occurrence of darker diorite. The contacts between the lighter and darker types are sharp in places and more gradual in others. The plagioclase of the lighter types is slightly richer in albite than that of the darker types.

The conformable tongues within the Rautuvaara Formation are generally light in colour and would seem to vary in composition from quartz monzodiorite to diorite in the same way as noted at Hannukainen. According to Kuivasaari (1980), the diorite tongue in the hanging wall of the Sininen ore bed grades to scapolite-pyroxene rock, this being reflected not only in a change in mineral composition, but also in the fact that the scapolite becomes dominated by meionite and the pyroxene grades to hedenbergite in the direction of the skarn contact.

The hanging wall of the whole formation in the eastern part of NE-Rautuvaara seems to contain a relatively continuous zone some 50 m thick of a scapolite-dominated amphibolite within the non-homogeneous dark diorite. The main constituents here in addition to scapolite are plagioclase, hornblende, biotite and diopside. The rock also frequently contains cavities, often occupied by chabazite. It would seem likely that this rock represents a highly altered inclusion from the Rautuvaara Formation within the diorite.

All in all, the diorite-dominated rocks of the monzonite marginal zone would seem to represent at Rautuvaara, as elsewhere, a set of hybrid rocks which have also undergone later metasomatic changes. There is thus no question of actual magmatic differentiation.

The most prolific of the rocks of the Rautuvaara Formation in the NE-Rautuvaara area is the quartz—feldspar schist, which is highly rich in graphite in places. This usually bears an obvious stratification (Fig. 10) and corresponds in composition to that described at Hannukainen. An analysis of a typical

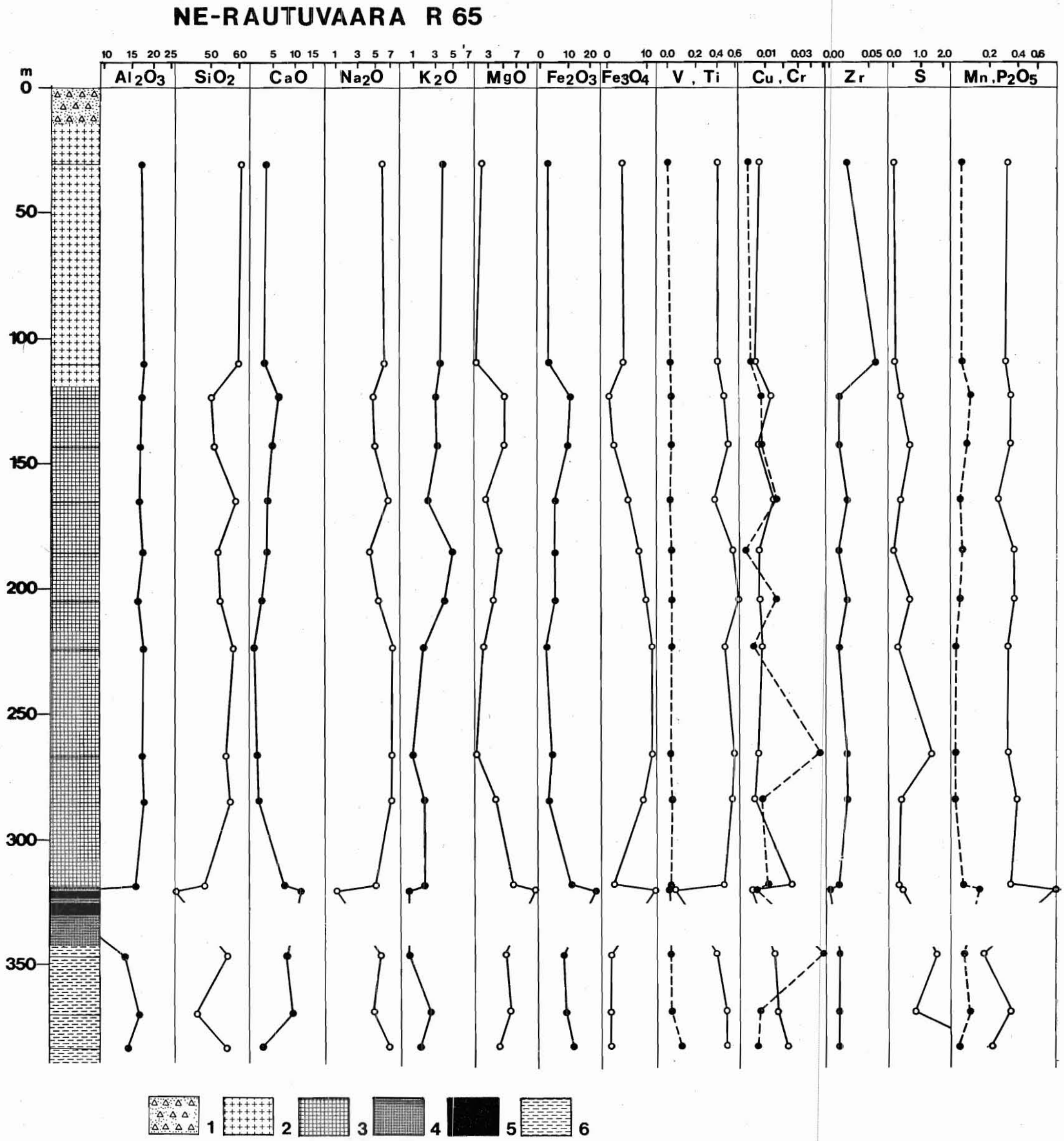

Fig. 60. Variations in chemical composition (⁰/₀ by weight) in the rocks at drillhole R 65 at Rautuvaara. 1 = overburden; 2 = monzonite; 3 = diorite; 4 = skarn; 5 = ore; 6 = amphibolite.

quartz—feldspar schist is given in Table 15, No. 7. This serves to demonstrate the similarity in chemical composition in relation to the corresponding schist at Hannukainen. Gradation forms in the direction of skarn rocks are common, causing the schist to contain substantial proportions of amphibole and diopside on occasions.

Skarns are to be found in connection with the magnetite lenses and within the quartz—feldspar schist, the predominant forms being those bearing diopside and hornblende, with varying quantities of plagioclase and/or scapolite. Other types of skarn occur in small amounts, in which the main minerals may be calcite, serpentine, olivine, hypersthene, phlogopite, garnet or quartz. The gangue in one small ore lens is composed of a hypersthene—serpentine—phlogopite skarn (Kuivasaari 1980) which is poor in calcium. An andradite skarn is found in the upper part of the skarn bed in the hanging wall of the Sininen ore body before the quartz—feldspar schist is reached. The magnetite, pyrite, pyrrhotite and chalcopyrite occurring as accessory minerals have at least for the most part crystallized after the silicate minerals. The diorite tongues and the grading of the skarns to quartz—feldspar schist give rise to a highly heterogeneous entity when examined in detail, and one which corresponds to that described at Hannukainen in the proportions of the rock types.

The banded amphibolite found regularly in the lower part of the Rautuvaara Formation is very little in evidence in the NE-Rautuvaara area, being indentifiable with the greatest certainty in the form of an amphibolite bed a few metres thick in the footwall of the Sininen ore body. A similar amphibolite is also seen in some places in the hanging wall in connection with the quartz—feldspar schist.

The magnetite ore

The iron ores of NE-Rautuvaara are frequently found in plate-like lenses elongated in the general direction of lineation and varying in thickness from a few metres to over 20 m. The maximum lengths of these lenses are around a kilometre and the widths approx. 200 m. The geological section (Fig. 59) suggests that these ore lenses partially overlap and occupy differing stratigraphic positions. It is nevertheless difficult to make reliable stratigraphic observations concerning the rocks of NE-Rautuvaara on account of the violent shear-folding, and thus these conclusions remain tentative. Perhaps the clearest stratigraphic evidence is found at the north-eastern end of the ore body. There the ore contact in the footwall of the Sininen ore body features first quartz—feldspar schist and beneath this streaked amphibolite, corresponding to the order of strata established at Hannukainen. The possibility is that the graphite-rich schists and intrusive tongues may have formed elastic layers during folding, giving rise to slippings and in this way helping to confuse the primary order of strata. Further evidence of this is the fact that the proportion of graphite-bearing schists increases towards the north-east and the schists then continue in the same direction well past the last magnetite lenses. Thus the ore lenses themselves need not necessarily have been formed stratigraphically as discrete units.

The majority of the ore reserves of NE-Rautuvaara are contained in the Sininen ore in the footwall of the Rautuvaara Formation and in the Vihreä ore in the hanging wall. The positions of these may be seen in the geological map (Fig. 58) and the cross-section (Fig. 59). The hanging wall also contains the Keltainen ore, separated from the Vihreä ore by a diorite tongue, and also the small Punainen ore located to the south-west of this. Finally there is the small Musta ore located above the Vihreä ore in the footwall of the formation, which includes a number of small lenses. The total ore reserves of NE-Rautuvaara were approx. 7.7 million tonnes at the time of commencement of extraction in 1974. These ores are to a greater or lesser extent banded, with the richest patches usually representing the more massive types.

The mean compositions of the two principal lenses are presented in Table 13, Nos. 1 and 2. These results suggest that the ores are chemi-

Table 13

Mean chemical concentrations (%) by weight) in the ores of Rautuvaara. 1 and 2 are weighted means of the analyses on the drill cores penetrating the ore lenses concerned, while 3 and 4 are the results of analyses on combined samples representing the ores. The concentrations are determined by the x-ray fluorescence method, except for Na_2O, which is determined by AAS.

	1.	2.	3.	4.
Fe	45.0	44.1	42.7	21.8
Ti	0.14	0.13	0.10	0.44
V	0.01	0.04	0.01	0.03
Mn	0.16	0.07	0.81	0.06
Cu	0.08	0.06	0.15	0.48
S	2.1	2.2	2.5	1.0
SiO_2	21.4	21.3	26.4	44.4
Al_2O_3	4.5	3.9	3.2	14.3
MgO	4.2	6.3	3.2	3.7
CaO	6.4	6.0	2.5	1.0
Na_2O	1.2	1.2	n.d. *	n.d.
K_2O	0.5	0.2	1.1	1.3
P_2O_5	0.19	0.16	0.07	0.07

n.d. = not determined
1. NE Rautuvaara, Sininen ore, 16 samples, total length approx. 264 m
2. NE Rautuvaara, Vihreä ore, 18 samples, total length approx. 307 m
3. SW Rautuvaara, combined sample, total length approx. 57 m
4. Cu Rautuvaara, combined sample, total length approx. 312 m

cally very much alike and are comparable to those of Hannukainen. One significant feature concerns the fairly high CaO and MgO concentrations, typical of skarn ores.

The ore lenses are also similar and comparable with those at Hannukainen, in their mineralogy especially the Vuopio and Kuervaara ore bodies. The main mineral, magnetite, occurs for the most part in grains of 0.2—1 mm, and also to a small extent as a more fine-grained material of 0.1—0.01 mm amongst the silicate. This magnetite regularly features small inclusions or ilmenite and spinel, ilmenite also being found in some coarser lamellae.

The ore of NE-Rautuvaara has a lower sulphur content than that at Hannukainen. The majority of the sulphur, some 90 %, is bound to pyrrhotite, the remainder being in chalcopyrite and secondary pyrite. Melnikovite also occurs sporadically as an alteration product. The mode of occurrence of the sulphides is entirely comparable to that described for Kuervaara. The most common gangue minerals are diopside, which is dominant, and hornblende, in addition to plagioclase, scapolite, calcite, biotite, andradite and quartz.

Quartz-bearing ore occurs only in a few small patches within the pyroxene-bearing ore (Kuivasaari 1980). Where it does occur it is entirely comparable to that of the upper part of the Laurinoja ore body at Hannukainen in its structure and composition, i.e. containing some brightgreen grains of hedenbergite in addition to the quartz. Kuivasaari suspects this ore with quartz of being a relict from a sedimentary quartz-banded ore, but nothing definite can be said on this on the basis of the texture or composition of the rock.

The accessory minerals in this skarn ore are apatite, phlogopite, chlorite, epidote, serpentine, titanite and zircon.

Like the Hannukainen ore, that of NE-Rautuvaara represents a typical pyrite-bearing magnetite mineralization with skarn as its gangue.

The SW-Rautuvaara ore body

The SW-Rautuvaara ore body is located about a kilometre to the south-west of NE-Rautuvaara and lies geologically between an amphibolite footwall and a hanging wall composed of intrusive rocks (Fig. 61). Since a detailed mineralogical study of this ore body is in progress, only its main features will be dealt with here. The amphibolite of the foot-

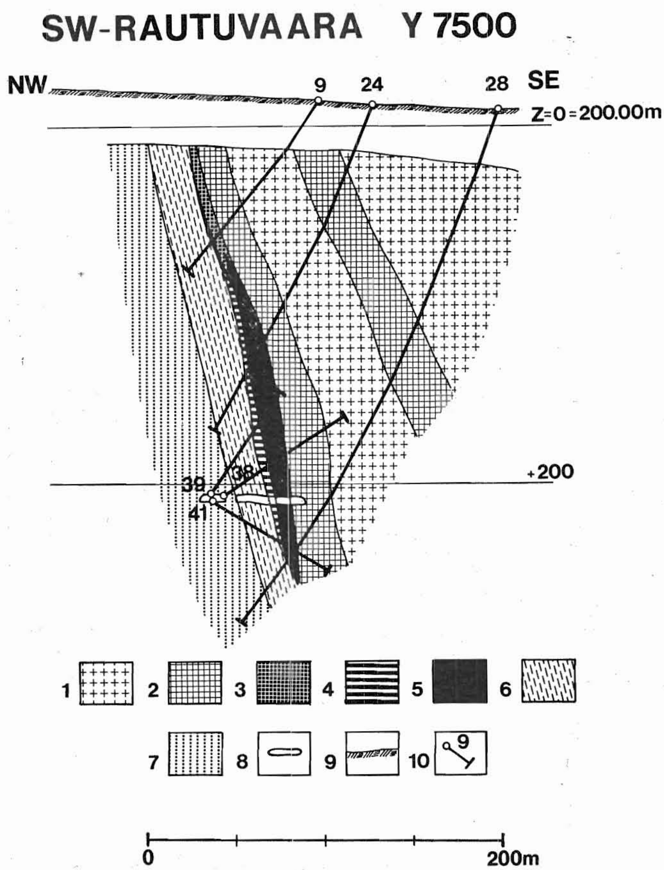

Fig. 61. Geological cross-section of SW-Rautuvaara. *Intrusive rocks:* 1 = monzonite; 2 = diorite. *Rautuvaara Formation:* 3 = skarn; 4 = albite—anthophyllite rock; 5 = ore; 6 = amphibolite. *Niesakero—Kuertunturi quartzite complex:* 7 = quartzite; 8 = drift; 9 = ground surface; 10 = drillhole with number.

wall, which forms a bed some 20 m in thickness, is the usual partly streaked and partly massive type encountered elsewhere in the lower part of the Rautuvaara Formation. Its chemical analysis is given in Table 15, No. 6, and the corresponding point on the AMF diagram (Fig. 13) lies in the calc-alkali field, close to the boundary with the tholeiite field. The upper part of this amphibolite contains a few metres of an albite—amphibole rock with scattered grains of magnetite, resembling the host rock of the Cu-Rautuvaara ore. Below the amphibolite lies a vitreous, partly granitized quartzite. The stratification runs at a steep angle of 80° towards the southeast. Quartz—feldspar schist is found here only in a layer a few metres in thickness at the lower contact of the diorite, and there is very little actual skarn rock at all.

The hanging wall of the deposit comprises 15—25 m of non-homogeneous intrusive rocks varying in composition from quartz monzodiorite to diorite, which then grade to normal monzonite within a few metres at most in the upper part.

The SW-Rautuvaara ore body is structurally simple, comprising a single ore lens at least 800 m long in the direction of lineation, 5—20 m in thickness and 200—300 m in breadth. The inventory of ore reserves amounted to 4.5 million tonnes at the time when mining commenced in 1979. The ore differs considerably from that of NE-Rautuvaara in its chemical composition (Table 13, No. 3), being poorer in calcium, magnesium and phosphorus, but richer in manganese, copper and potassium, and also having a higher SiO_2 content.

Mineralogically this SW-Rautuvaara ore body represents entirely a type of its own. Quartz, diopside, diopside—hedenbergite, (Di_{50}—He_{50}), albite, microcline, hornblende, grünerite, serpentine, calcite and biotite occur as gangue minerals in the upper part, above the + 300 level, the most common gangue paragenesis being quartz + diopside—hedenbergite with varying amounts of biotite, albite and microcline. The paragenesis diopside + hornblende, the most common combination at NE-Rautuvaara and Hannukainen, has been found in only one sample. A further distinctive feature is the gangue mineral paragenesis calcite + serpentine, which occurs in the foot of the ore lens. Above this is a quartz-rich zone, and the roof of the ore lens contains the most skarn-like types.

The following gangue mineral parageneses are encountered in the lower part of the ore body, below the + 300 level:

— quartz + microcline + diopside—hedenbergite + hornblende
— quartz + albite
— diopside—hedenbergite + biotite + hornblende
— albite + microcline + quartz + biotite + eulite
— fayalite + microcline
— eulite

The compositions of the minerals are determined by x-ray diffraction. Chlorite, phlogopite, scapolite, sericite and apatite are found as accessory minerals.

Characteristic of the whole of the SW-Rautuvaara ore body, and in particular of its deeper parts, is the frequent occurrence of iron-rich silicates, fayalite, eulite, hedengergite and alkaline feldspars, and also quartz. There are only small amounts of the calcium silicates, most commonly in the upper part of the ore body. This ore body thus does not represent the true skarn ores, but rather an iron silicate-bearing type of its own, which is closely associated with the skarn ores.

The main constituent is magnetite, which resembles that of NE-Rautuvaara in possessing small exsolutions of ilmenite and spinel. Ilmenite is also found in coarser exsolutions and as individual grains in the deepest parts of the ore body. This ore body has a little higher sulphur content than NE-Rautuvaara (Table 13), and over a half of the sulphur is bound to pyrrhotite. The other major sulphide mineral is chalcopyrite, with pyrite appearing only in the upper part of the ore body. Traces of loellingite, arsenopyrite, cobalt pentlandite and molybdenite are also found.

The Cu-Rautuvaara ore body

Description of the wall rocks

The Cu-Rautuvaara ore body, located about 1 km south-west of SW-Rautuvaara, represents geologically a continuation of the latter, although possessing an ore type of its own. It is not an example of a skarn ore, although it bears an obvious genetic relationship to the skarn ores, and as such provides new clues to possible explanations for the origins of such ores. A cross-section of the ore body is given in Fig. 62.

Stratigraphically the lowermost rock unit at Cu-Rautuvaara is again a vitreous quartzite, which was only reached by one of the drillings performed. This is overlain by an

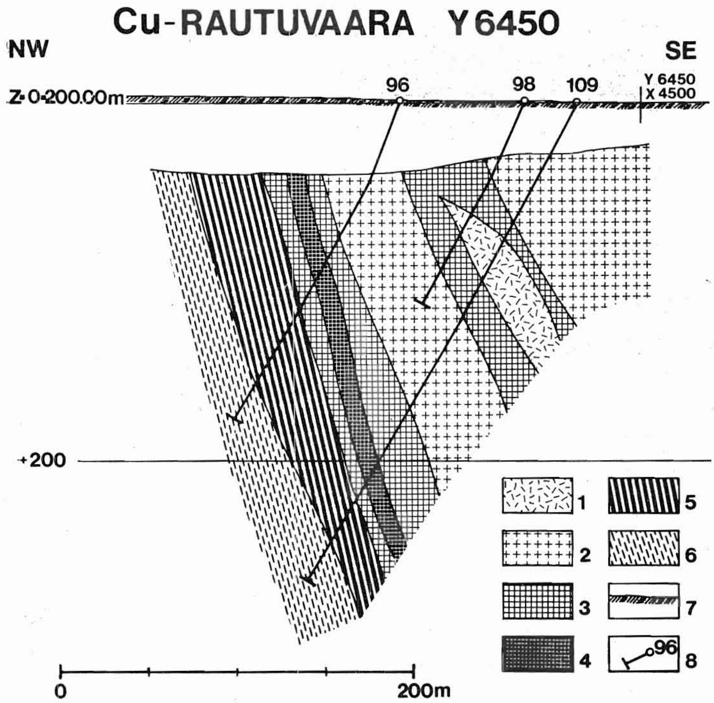

Fig. 62. Geological cross-section of Cu-Rautuvaara. *Intrusive rocks:* 1 = pegmatite; 2 = monzonite; 3 = diorite. *Rautuvaara Formation:* 4 = skarn; 5 = albite—anthophyllite rock; 6 = amphibolite; 7 = ground surface; 8 = drillhole with number.

amphibolite bed of maximum thickness approx. 60 m and gradually becoming thinner in the direction of SW-Rautuvaara to reach approx. 20 m. This is composed of the streaked, or occasionally almost massive, fine-grained hornblende—plagioclase rock typical of the Rautuvaara Formation, which is heavily granitized in places. The dip of the formation is approx. 80° to the south-east.

Above the amphibolite is a bed varying in thickness from a few metres to as much as 50 m comprising an unusual rock composed mainly of albite and anthophyllite and generally also having biotite as a major mineral, and also quartz in places in its upper parts. Occasionally cummingtonite is found instead of the anthophyllite. This rock also contains regularly scattered grains of magnetite and chalcopyrite in varying amounts, so that when these amounts become sufficiently large one can really speak of an ore deposit. Small amounts of scattered grains of pyrrhotite and pyrite are usually also found. The other accessory minerals are zircon, apatite, calcite and serpentine.

The most abundant of the main constituents, albite (An 5—10 %), occurs in unchanged, regularly twinned, subhedral grains of size 0.3—1 mm (Fig. 63), while the anthophyllite takes the form of narrow laths, up to 10 mm in length and usually oriented in the direction of lineation, varying in quantity in the range 5—50 %, and most frequently 10—20 %. There is less anthophyllite, or even none at all, in the types richer in biotite. The amount of quartz, when encountered, is below 10 %. The rock is granoblastic and macroscopically relatively homogeneous, slightly foliated, but otherwise massive. It is light in colour and of an easily recognizable type which also occurs in places elsewhere in the upper part of the amphibolite bed of the Rautuvaara Formation, e.g. at Kuervitikko (p. 94). This rock is closely related to amphibolite,

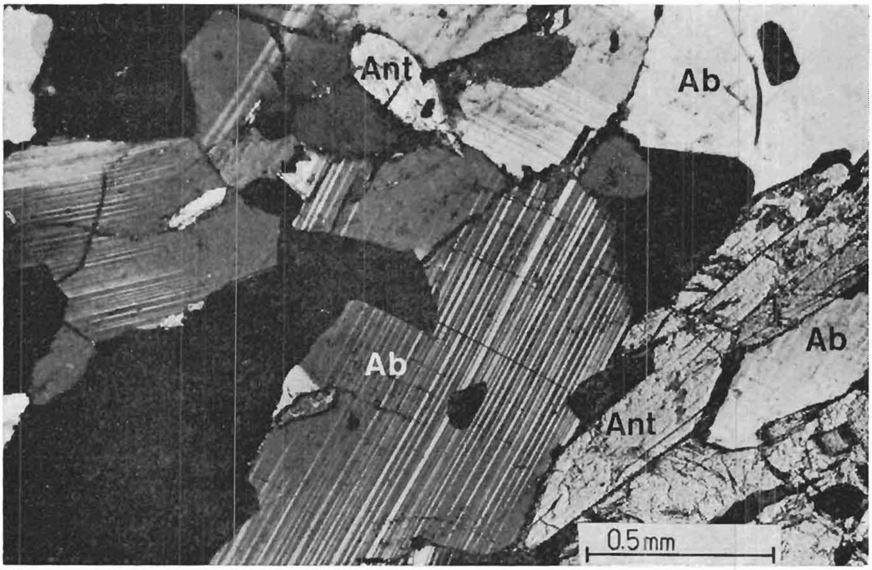

Fig. 63. Albite—anthophyllite rock at Cu-Rautuvaara, R 109, depth 278.6 m. Ab = albite; Ant = anthophyllite. The black consists mainly of magnetite. Thin section, crossed nicols.

and may be a metasomatic alteration product of it. On the other hand, it shows some similarities to certain diorite types, so that one cannot be entirely sure about its origins. Zavaritškij and Kirova (1973) note that the skarnification of volcanic and intrusive rocks always results in albitization or scapolitization of their plagioclase regardless of its original composition. If this were the case, it would explain the common occurrence of albite-dominated rocks in skarn zones.

Above the albite—anthophyllite rock there is usually a non-homogeneous zone some metres in thickness composed of a more or less diorite rock type. This grades to an albite—biotite rock in its lower part, and then to the albite—anthophyllite rock, which in turn extends in a continuous zone from Cu-Rautuvaara to SW-Rautuvaara, becoming thinner at the same time. This has not been detected to the north-east of SW-Rautuvaara.

The hanging wall to the albite—anthophyllite rock and the diorite zone lying above it consists of a skarn layer of maximum thickness approx. 30 m. This skarn is of the normal type, with diopside dominant and usually containing hornblende and possessing aggregates and scattered grains of magnetite in varying amounts, sometimes reaching 30—40 %. Chalcopyrite, pyrrhotite and pyrite are found as unevenly scattered grains and veins, with copper concentration reaching some 0.8 % at its highest. The skarn also contains carbonate layers several metres thick in places and considerable numbers of pegmatite veins and some veins of a variable composition comprising largely diorite. The skarn rock thus forms a heterogeneous mineralized zone at Cu-Rautuvaara in which no actual ore lenses are found. This bed does not continue to the east of Cu-Rautuvaara.

The skarn bed is overlain by plutonic rocks of the marginal zone of the monzonite intrusion, which are similar in their occurrence to those described elsewhere. The marginal zone is some 20—30 m in thickness and varies in composition from quartz monzodiorite to diorite, with the lighter types dominant. In

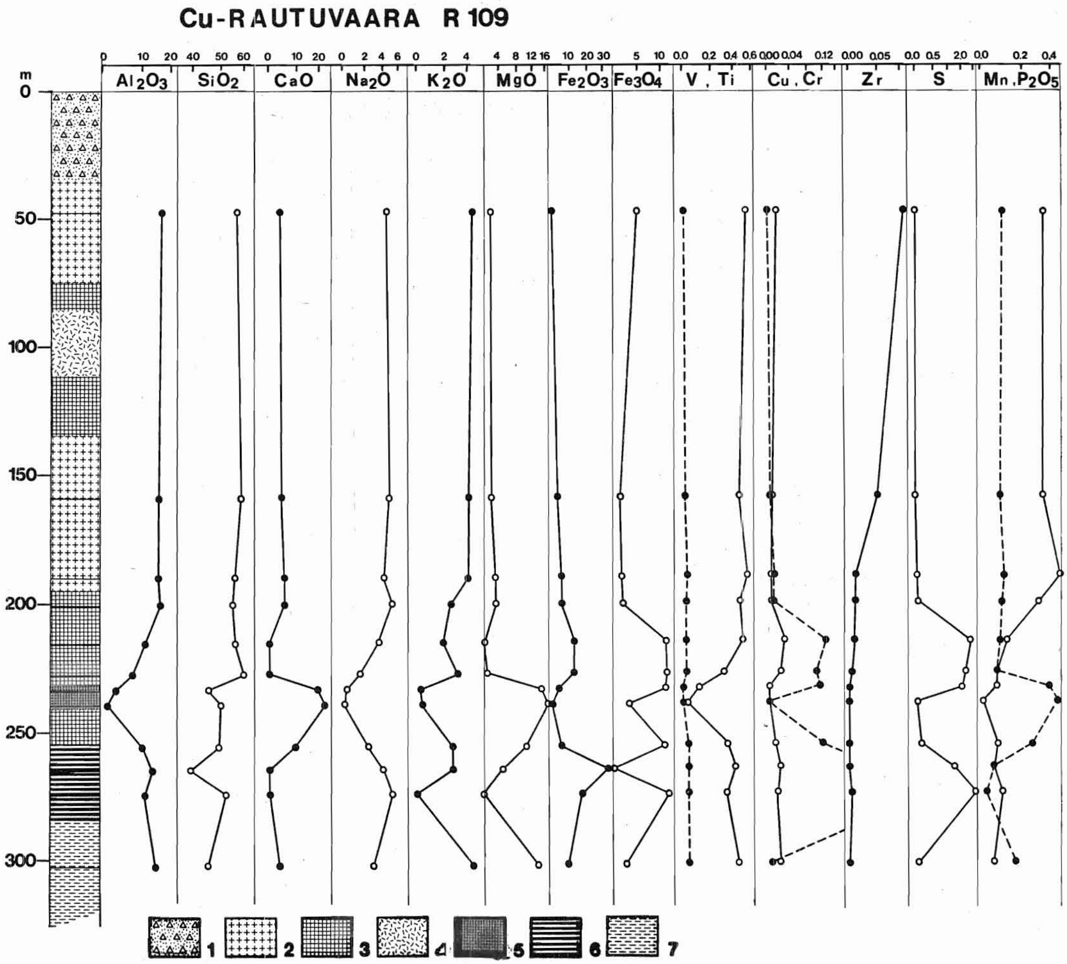

Fig. 64. Variation in chemical composition in the rocks at drillhole R 109 at Cu-Rautuvaara. 1 = overburden; 2 = monzonite; 3 = diorite; 4 = pegmatite; 5 = skarn; 6 = albite—anthophyllite rock; 7 = amphibolite.

places, where it also contains scattered magnetite and sulphides, it comes to resemble closely the albite—biotite/anthophyllite rock described above. The hanging wall of the marginal zone contains firstly about 50 m of normal gneissic monzonite, then a zone of approx. 50 m of non-homogeneous diorite and finally monzonite once again. Fig. 64 depicts a cross-section, represented by drillhole R 109, which indicates the principal rock types and also the chemical compositions of the major components. No analysis is available of the non-homogeneous diorite with veins of pegmatite which constitutes the upper part of the marginal zone. Grading between the skarn, diorite and albite—anthophyllite rock may be seen clearly in the major components, especially as far as aluminium, calcium, sodium and magnesium are concerned. The mineralization of the diorite overlying the skarn rock is reflected in the increased concentrations of magnetite, sulphur and copper. The amphibolite of the lower part can be distinguished from the albite—anthophyllite rock by virtues of its very much higher magnesium content, and also by the absence of any substantial amount of magnetite or sulphides.

The Cu-Fe ore

The Cu-Rautuvaara ore body consists of a clearly-defined shuttle-shaped lens of albite—anthophyllite rock with scattered grains of magnetite and chalcopyrite. This lens is over 200 m in breadth and of a maximum thickness of approx. 45 m. It decreases in thickness towards the south-west to a plate-like lens with the dip of 50° to the south-west.

The ore reserves are estimated at almost 3 million tonnes and the composition of the ore is as stated in Table 13, No. 4. The chemical composition differs markedly from that of the NE-Rautuvaara skarn ore (Nos. 1 and 2), while that of SW-Rautuvaara represents an intermediate form falling closer to the skarn ore in its chemistry. The Cu-Rautuvaara ore is chemically of a distinctive copper-bearing type with a characteristic abundance of alkaline and aluminium silicates and low proportions of iron, calcium and phosphorus.

Mineralogically this ore differs from the skarn ores chiefly in its gangue minerals, since the gangue comprises the main constituents of the host rock, albite, anthophyllite, biotite and quartz. The principal ore minerals are magnetite and chalcopyrite, the latter being of the greater economic significance. Pyrrhotite, pyrite and ilmenite are also common.

The magnetite is chiefly in the form of subhedral scattered grains of size 0.5 mm, containing small lamellae of ilmenite. It is also found in places in thin recrystallized veins between the silicate minerals. Ilmenite occurs both in the exsolution lamellae within the magnetite and also as independent grains, often themselves containing magnetite inclusions.

The majority of the sulphur is bound in the chalcopyrite, which takes the form of xenomorphic anhedral grains of size 0.1—1 mm or else recrystallized veins (Fig. 65). The inclusions in these grains are usually of pyrrhotite and more rarely of magnetite or pyrite. In places chalcopyrite has displaced silicate (Fig. 66). The pyrrhotite is unevenly distributed and usually contains chalcopyrite as inclusions, although small inclusions of pentlandite are also found on occasions. Alterations to pyrite have sometimes taken place at the edges of grains, as found at Hannukainen. Pyrite exists only in small amounts, both as primary and as secondary grains, in the latter case often forming a micro-breccia-like network together with silicates.

In addition to this ore lens, another possibly separate lens of the same ore has been found which acts as a continuation to this and which does not extend to the bedrock surface at any point. Due to its depth of location its limits have not yet been studied precisely. In addition, an albite—anthophyllite rock of the same type as at Cu-Rautuvaara has also been observed in drillings in the amphibolite sequence at Rautuoja, to the north of Cu-Rautuvaara. This has been found to have a lower chalcopyrite and magnetite content than that at Cu-Rautuvaara.

Sulphur isotope studies

The report by Mäkelä and Tammenmaa (1978) contains a summary of sulphur isotope studies for the various ores of the Rautuvaara Formation. This summary is based on the authors' own sulphur isotope determinations, of which 165 were carried out on material from the Rautuvaara Formation. The work has since been complemented with a few

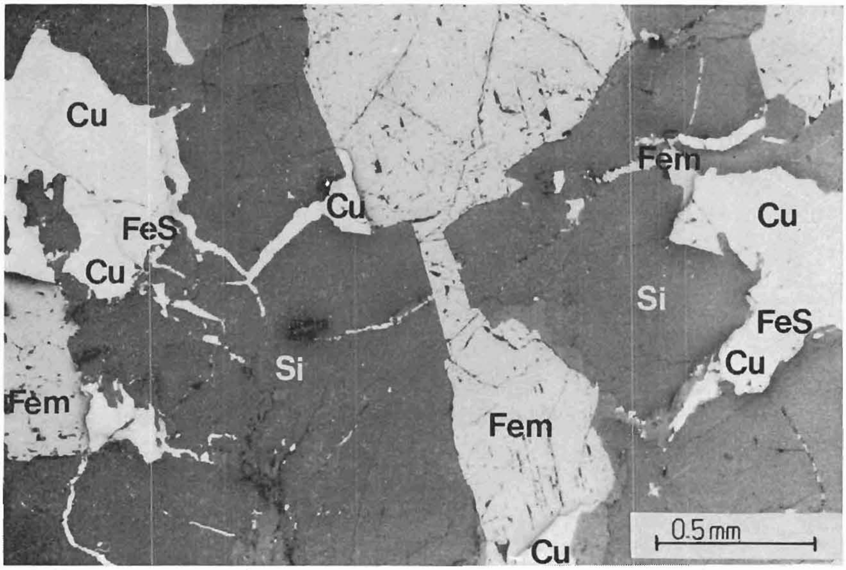

Fig. 65. The disseminated ore at Cu-Rautuvaara, R 109, depth 270.3 m. Polished section without analyser. Fem = magnetite; Cu = chalcopyrite; FeS = pyrrhotite; Si = silicate.

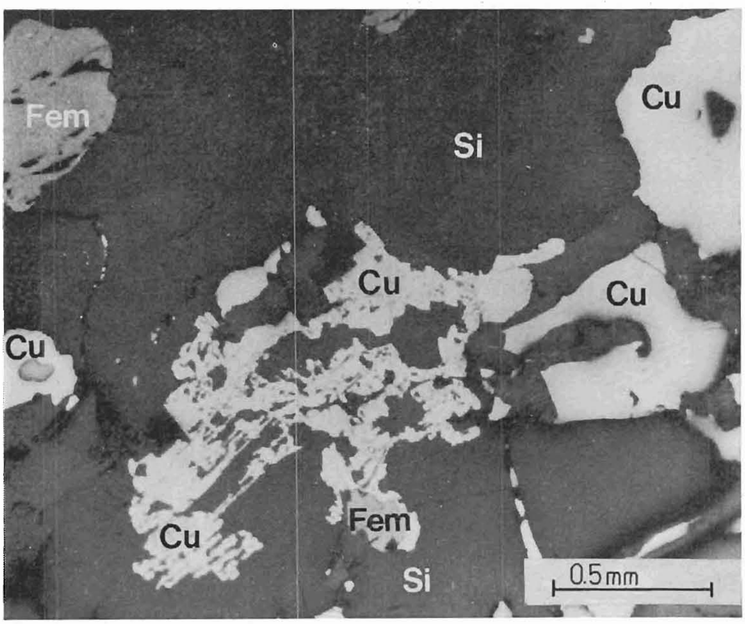

Fig. 66. Chalcopyrite (Cu) replacing silicate at Cu-Rautuvaara, R 109, depth 263.1 m. Polished section without analyser. Fem = magnetite; Si = silicate.

more determinations, so that the present author now has 174 sets of results at his disposal.

Mäkelä and Tammenmaa (1978) point to the existence of two peaks in the $\delta^{34}S$ distribution for the Rautuvaara Formation, at + 12.5 and + 2.5 ‰, and thereby assume the sulphur to be derived from two sources. The sulphur in the sulphides of Cu and SW-Rautuvaara is largely derived from sea water via

Table 14

Mean $\delta^{34}S$ values for the Rautuvaara ore bodies.

Ore body	No. of determinations	Mean $\delta^{34}S$ value	Max.	Min.	S.E.M.
NE Rautuvaara	110	+ 3.01	+ 12.50	— 3.06	1.87
SW Rautuvaara	40	+ 10.92	+ 16.46	— 1.19	2.95
Cu Rautuvaara	24	+ 8.92	+ 17.46	3.70	3.81

sulphate minerals, whereas that in the sulphides of NE-Rautuvaara is predominantly of volcanic origin. They also show that each ore body has its own characteristic mean $\delta^{34}S$ value (Mäkelä and Tammenmaa 1978, Fig. 27), and conclude that this points to precipitation of the ore lenses into different horizons as sedimentation advanced.

The results obtained are examined in more detail below in the light of the original data available. The mean $\delta^{34}S$ values and their standard deviations for the various ore bodies are listed in Table 14. The NE-Rautuvaara ore body has by far the lowest mean $\delta^{34}S$ value and the smallest standard deviation, this mean corresponding to the peak $\delta^{34}S$ figure for the Hannukainen ore bodies as depicted in Fig. 54. In addition to their mineralogical and chemical similarities, these ore bodies have a similar $\delta^{34}S$ composition.

The Cu-Rautuvaara ore body was stated above to involve two types of mineralization, one associated with the skarn rock and the other with the albite—anthophyllite rock. The variations in $\delta^{34}S$ readings in the profile represented by drillhole R 25 are presented in Fig. 67. These results show a clear positive correlation with the rock type, with those for

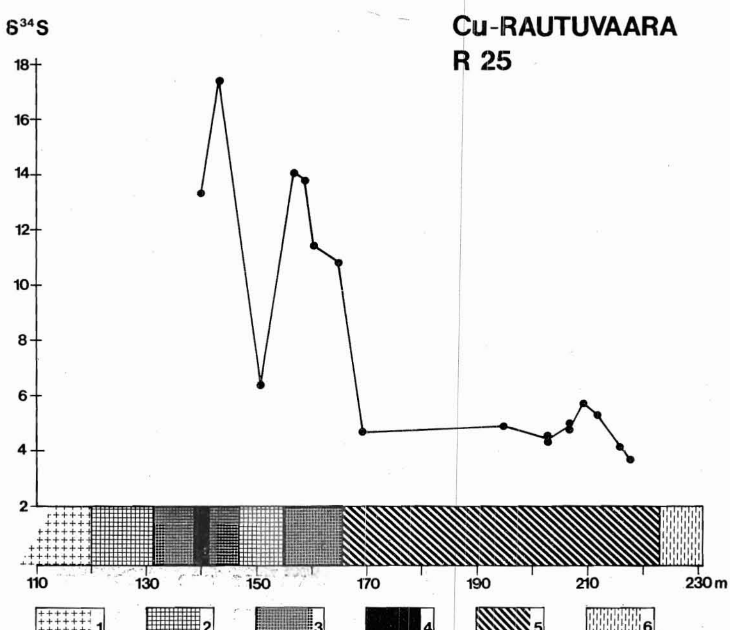

Fig. 67. Variations in $\delta^{34}S$ values in the rocks identified at drillhole R 25 at Cu-Rautuvaara. 1 = monzonite; 2 = diorite; 3 = skarn; 4 = ore; 5 = albite—anthophyllite rock; 6 = amphibolite.

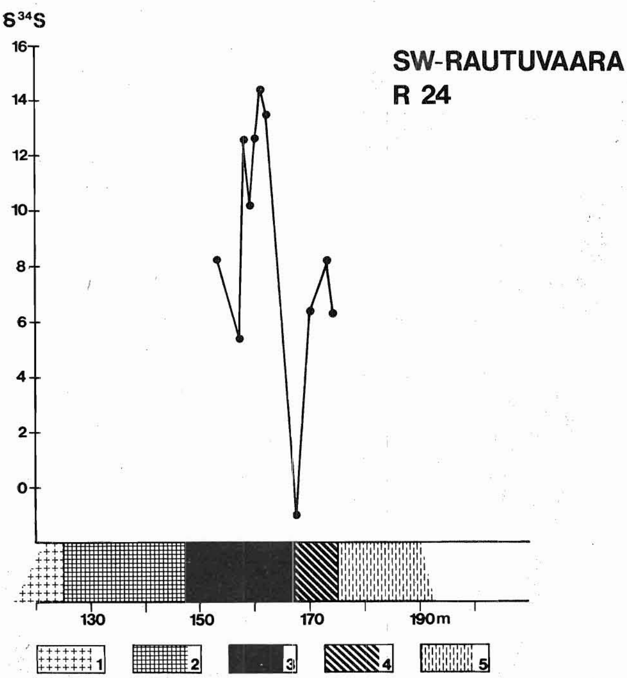

Fig. 68. Variations in $\delta^{34}S$ values in the ore profile represented by drillhole R 24 at SW-Rautuvaara. 1 = monzonite; 2 = diorite; 3 = ore; 4 = albite—anthophyllite rock; 5 = amphibolite.

the sulphides of the albite—anthophyllite rock in the lower part of the profile varying very little and having a maximum value of + 5.77 and a minimum of + 3.70, while the figures for the sulphides in the skarn rocks of the upper part are higher and vary between a maximum of + 17.46 and a minimum of + 10.82. The $\delta^{34}S$ value for the sulphide in the diorite vein within the skarn was + 6.40.

The variation within SW-Rautuvaara, already established as mineralogically and chemically the most complex of the Rautuvaara ore bodies, shows a more complicated pattern.

Fig. 68 shows the variations in $\delta^{34}S$ values in the ore profile represented by drillhole R 24, in which the values for the sulphides of the albite—anthophyllite rock in the footwall of the ore body vary in the range + 4.59 — + 8.74, with the exception of one unusually low reading of — 1.19 from a point right at the ore contact. The highest values are from the foot of the ore body, where the gangue material is dominated by carbonates. The values then decline in the upper part, where the gangue is quartz and/or silicate-dominated. A clear correlation is in evidence at SW-Rautuvaara between the host rock and the $\delta^{34}S$ values obtained for the sulphides.

In summary, it may be noted that although the various ore lenses of the Rautuvaara Formation do indeed have their characteristic mean $\delta^{34}S$ values (Mäkelä 1977, Mäkelä and Tammenmaa 1978), the dominant feature is the broad scale of the local variation in these values following to the composition of the host rock. The most consistent values of all are those found in the NE-Rautuvaara ore body that correspond well with those obtained for the Hannukainen deposit. The figures for the sulphides of the albite—anthophyllite rock of the Cu- and SW-Rautuvaara ore bodies are equal and also of the same order as the corresponding readings for NE-Rautuvaara. The highest values of all are those found in the sulphides of the skarn rocks at Cu-Rautuvaara and the ores with carbonate or silicate gangues at SW-Rautuvaara.

As at Hannukainen, the relatively narrow scope of the variation in $\delta^{34}S$ values for the sulphide sulphur of the NE-Rautuvaara ore body and the mean value of + 3.01 would point to a hypogenic origin for this sulphur, as put forward by Mäkelä and Tammenmaa (1978). The variation encountered at Cu-Rautuvaara and SW-Rautuvaara, on the other hand, may be due either to changing conditions resulting from the composition of the host rocks as the sulphides crystallized. This is backed up by the fact that the $\delta^{34}S$ values are highest in the skarns and ores with carbonate gangue, in which local rises in the pH of the sulphur-bearing fluids may have taken place. The local character of such changes is borne out by the fact that the $\delta^{34}S$ values of the sulphides in the skarns are also lower on a regional scale. One can nevertheless not rule out the possibility that the sulphur in the fluids may itself have been from different sources. It is on this basis that Radtke *et al.* (1980), come to the conclusion that the sulphur of the Carling Gold deposit in Nevada, a deposit interpreted as metasomatic, with $\delta^{34}S$ values in the range + 4.2—16.1, is of sedimentary origin.

THE RAUTUHELUKKA AND RYTIJÄNKÄ MAGNETITE DEPOSITS

Two minor skarn—magnetite deposits are to be found close to the tip of a southwestwards-opening syncline about 3 km northeast of Rautuvaara. That located on the north-western flank of this syncline, which has a dip of 30—40° to the south-east, is known by the name Rautuhelukka, and that on the south-eastern flank as Rytijänkä. The bedding dips approx. 80° to the north-west at the latter flank.

The central part of the syncline, that is the hanging wall of the magnetite deposits, is composed of intrusive rocks varying in composition from monzonite to diorite, as has been described generally for the hanging walls of skarn ore deposits. The scattered grains of magnetite associated with these rocks are seen as a set of extensive weak positive anomalies on the magnetic maps.

The lowermost stratum in the footwall of the deposits is a markedly recrystallized quartzite which has undergone granitization, this being overlain by the rocks of the Rautuvaara Formation. At Rautuhelukka, on the right-hand flank of the syncline, the Rautuvaara Formation reaches a maximum thickness of over 200 m and has an internal structure which resembles that described at NE-Rautuvaara. The uppermost stratum consists of alternate layers of quartz—feldspar schist and skarn with associated magnetite lenses, and the lowermost of alternating quartz—feldspar schist and amphibolite. Here again, it has not been possible to prove with certainty whether the deviant bedding is a primary feature. The depth and discontinuity of the formation, and also its tectonic location, would nevertheless seem to point to an active role for folding processes in determining the internal structure.

At Rytijänkä the bedding is normal, with amphibolite at the bottom, overlain first by quartz—feldspar schist and finally skarn. The quartz—feldspar schist at both sites contains graphite and scattered grains of pyrrhotite, pyrite and also a little chalcopyrite. The skarn bed contains the usual diopside-dominated and hornblende-dominated skarn rocks with scattered grains and aggregates of magnetite and sulphides.

The magnetite lenses within the skarn beds at both Rautuhelukka and Rytijänkä are some 5—10 m in thickness and contain a few hundred thousand tonnes of ore at most. The concentration ranges in the 5 m-thick Rautuhelukka magnetite lens have been shown to be 45—60 % Fe and 0.1—0.5 % S. At Rytijänkä, where the lens is 10 m in thickness, the corresponding figures are 35—45 % Fe and 2—4 % S. These deposits correspond to the skarn iron ores poor in copper found at NE-Rautuvaara and Hannukainen in both their composition and their ore type.

THE SIVAKKALEHTO MAGNETITE DEPOSIT

The Sivakkalehto magnetite deposit, about 3 km south of Rautuvaara, is best known as the cause of the aeromagnetic anomaly of the greatest intensity in the Kolari area, extending for over 2 km in a NE-SW direction. A total of 35 drillholes have been made through this deposit at various times, the deepest extending for 700 m, and as a result of these relatively detailed information is available on the main parts, at least.

Magnetic measurements suggest that the Sivakkalehto deposit has a cross-section over 2 km in length at the ground surface, is 300—500 m broad and constitutes a lens oriented in the direction of lineation at a plunge of 30—50° to the south-west and with a dip of 80—85° to the north-west. The deposit would seem to be entirely surrounded by plutonic rocks, although admittedly only limited information is available on the local bedrock. Its location tectonically in a zone of pronounced shearing would suggest the possibility of a considerable length in the direction of lineation. Geophysical interpretations suggest that the deposit may contain over 200 million tonnes of magnetite, but this is so unevenly distributed that not a single ore lens of economic significance has been discovered.

The rock of Sivakkalehto has been described previously as scapolite amphibolite (Hiltunen and Tontti 1976) with associated varying quantities of magnetite. In the present work, however, a magnetite-bearing lens is singled out as the Sivakkalehto deposit proper and treated as a mineralisation on a par with the skarn ores. The hanging wall of this lens comprises a rock which is predominantly scapolite and has only a little or no magnetite. This is classified among the diorites on the map. Actually both of these are very similar heterogeneous rocks which have undergone pronounced metasomatism, and their origins are difficult to establish with any certainty. Their obvious connection with both skarn ore formation and also the marginal zone of the monzonite intrusion is suggestive of an interaction mainly between the intrusive and the Rautuvaara Formation under the influence of intensive shear movements.

According to Zavaritškij and Kirova (1973) the pyroxenization which occurs first in skarnification is followed by scapolitization rather than albitization in some cases, giving rise to a pyroxene—scapolite rock. Such scapolitized rocks could have primarily been carbonate-bearing tuffs, for example.

The rock forming the hanging wall of the Sivakkalehto deposit is a heterogeneous, usually light-coloured rod-gneiss with some darker amphibolitic patches. The most abundant among the main constituents is scapolite, which frequently accounts for over a half of the minerals in the rock. This takes the form of anhedral grains of size 0.5—1 mm, often

Table 15

Chemical compositions (% by weight) of the rocks of Sivakkalehto and Rautuvaara, determined as detailed in Table 1.

No.	1.	2.	3.	4.	5.	6.	7.
SiO_2	49.00	44.49	55.50	41.89	43.83	56.04	43.00
TiO_2	1.25	0.62	0.63	0.62	0.65	0.67	0.78
Al_2O_3	15.34	12.23	17.50	14.31	12.40	13.73	13.28
Fe_2O_3	1.48	4.09	1.44	8.51	6.11	0.84	4.81
FeO	3.60	5.30	2.60	4.80	8.20	4.60	9.80
MnO	0.03	0.15	0.01	0.01	0.19	0.04	0.30
MgO	8.18	15.50	5.08	6.00	13.10	5.72	7.60
CaO	8.13	7.33	5.35	10.24	6.32	6.52	8.68
Na_2O	5.59	2.67	7.32	5.27	3.08	4.79	3.07
K_2O	3.21	3.08	2.64	2.24	3.45	2.99	3.60
P_2O_5	1.45	0.18	0.07	3.78	0.25	0.18	0.14
CO_2	0.20	0.20	0.20	0.40	0.00	0.30	1.90
H_2O+	1.90	3.50	1.20	1.40	2.20	1.50	2.30
H_2O-	0.10	0.22	0.17	0.04	0.10	0.03	0.09
S	0.11	0.10	0.09	0.20	0.00	1.79	0.07
Cl_2	1.40	0.35	1.51	1.55	0.41	n.d.	0.42
Total	100.97	100.01	101.31	101.26	100.29	99.74	99.84
— O	— 0.37	— 0.13	— 0.39	— 0.45	— 0.09	— 0.89	— 0.13
	100.60	99.88	100.92	100.81	100.20	98.85	99.71

n.d. = not determined

1. Scapolite-hornblende-biotite rock, Sivakkalehto R 30; 23.5 m, hanging wall
2. Hornblende-biotite-scapolite rock, Sivakkalehto R 30; 67.9 m, hanging wall
3. Scapolite-biotite-diopside rock, Sivakkalehto R 30; 119.8 m, hanging wall
4. Scapolite-diopside-magnetite rock, Sivakkalehto R 30; 389.5 m
5. Amphibolite, Sivakkalehto R 30; 672.7 m
6. Amphibolite, SW-Rautuvaara R 38/+ 210 15.6 m; prof. y 7500
7. Quartz-feldspar schist, NE-Rautuvaara R 36/+ 210 48.9 m; prof. y 8400

with inclusions comprising plagioclase relicts. The amounts of plagioclase (albite—oligoclase) vary greatly, and often the feldspar is absent entirely. The dark minerals are hornblende, diopside and biotite, which generally occur as aggregates arranged in the direction of lineation, giving the rock the appearance of rod-gneiss. The rock contains small cavities in places, and these are occupied by idiomorphic crystals of calcite and chabazite. This rock closely resembles the scapolite-dominated rock, also with cavities, found within the diorite of the hanging wall of the NE-Rautuvaara ore body (p. 100). The accessory minerals are apatite, titanite, zircon and potassium feldspar, and a little scattered magnetite and chalcopyrite also occur, one sample representing a few square metres of an exposed surface giving a copper content of 0.78 % Cu.

Chemical compositions for the rock forming the hanging wall of the deposit are given in Table 15, Nos. 1, 2 and 3. Of these analyses, Nos. 1 and 3 represent the most common form, the light-coloured, relatively homogeneous type, which resembles diorite in its composition with the exception of the high chlorine content brought about by scapolitization. Also outstanding is the high P_2O_5 content in analysis No. 1, which is reflected mineralogically by an abundance apatite. Analysis No. 2 applies to a patch of dark amphibolite which is characterized by a low silicon content and high magnesium.

To the north-west of the scapolitized rock of Sivakkalehto itself one finds, after what

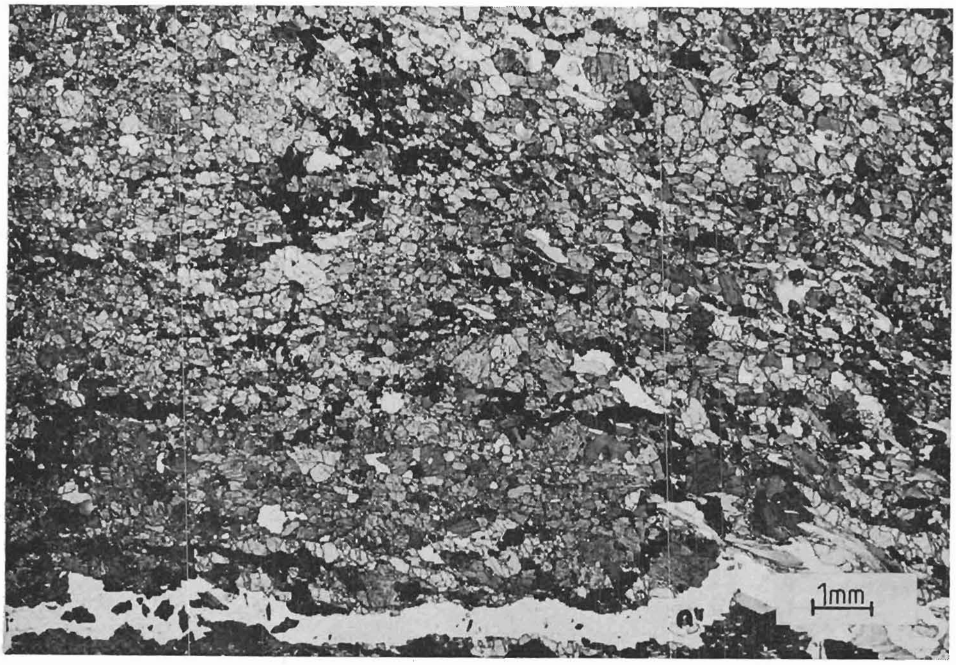

Fig. 69. Diopside skarn at Sivakkalehto, R 30, depth 507.7 m. Between the diopside grains is magnetite (black). A light-coloured vein of apatite runs along the bottom edge. Thin section, without analyzer.

is apparently an abrupt contact, the normal slightly foliated monzonite, which also occurs in a wedge-like vein penetrating between the magnetite deposit and the scapolite rock of the hanging wall. Close to the contact with this vein the scapolitized rock contains some dark, elongated amphibolite fragments in places, which would appear to be relicts from the primary sedimentary rocks of the Rautuvaara Formation.

The rock forming the magnetite-bearing lens of Sivakkalehto resembles that described in the hanging wall in that it contains scapolite, plagioclase (albite—oligoclase), hornblende, diopside and biotite as its main constituents. It is still less homogeneous, however, including within it skarn-like diopside-rich patches (Fig. 69). No clear boundary with the hanging wall can be defined, as the magnetite content increases gradually, but unevenly, outwards from the hanging wall rock itself. At the same time increasing amounts of pink anhydrite aggregates are found, together with green fluorapatite. Zeolite clusters are also found in cavities in the rock. Macroscopically this rock is much like the scapolite-bearing skarns of Kuervaara and Rautuvaara. Analysis No. 4 in Table 5 represents a scapolite—diopside—biotite rock with scattered magnetite grains, which is characterized by a relatively high calcium content and a markedly high phosphorus content, reflected mineralogically in an exceptionally high incidence of apatite. The phosphorus content is usually under 1 %, but the occurrence of apatite is much more common than in the skarn ores of Hannukainen or Rautuvaara.

The magnetite is very unevenly distributed in the form of scattered grains, aggregates and lenses, which may consist of practically compact magnetite. The best drilling result obtained shows an occurrence of 22 m in length with an iron content of 43—67 % Fe. No continuation of this has been found in additional drillings carried out on the same profile, however. It is indeed evident that the largest magnetite ore lenses at Sivakkalehto consist of long, rod-like forms varying in thickness from a few metres to about 20 m and running through the lower part of the deposit in the direction of lineation. No large ore lenses of economic significance appear to be present. The analyses obtained from a sample 60 m in length from one drillhole, R 30, in the part of the deposit richest in magnetite will serve to give some impression of the chemical composition of this mineralization: Fe 30.6 %, S 0.87 %, Cu 0.03 %, Cl 0.24 % and P_2O_5 2.36 %. The phosphorus content is more than ten times that found in the skarn ores of Hannukainen and Rautuvaara.

Mineralogically the deposit may be regarded as comparable with the skarn ores in the quality of its ore minerals. In addition to magnetite, a little pyrite is generally found, and occasionally some chalcopyrite and pyrrhotite. The most common gangue mineral in the compact magnetite occurrences is diopside, in addition to which scapolite, hornblende and biotite are also present, and in places calcite and apatite.

The deepest drillholes at Sivakkalehto have a dark, biotite-bearing, partly scapolized amphibolite as a footwall rock, with a chemical composition as indicated in Table 15 No. 5. The corresponding point on the AFM diagram lies in the calc-alkali field (Fig. 13). This represents the amphibolite of the lower part of the Rautuvaara Formation, which is overlain stratigraphically by the Sivakkalehto deposit.

THE JUVAKAISENMAA AND SAINKANGAS MAGNETITE DEPOSITS

The magnetite deposit at Juvakaisenmaa, about 5 km south-west of Sivakkalehto, is the oldest-known iron ore deposit in the Kolari area. The existence of this ore was known about in the 17th century, and some ore was transported to the smelting furnace at Oravainen around the year 1840 (Borgström 1928). The deposit was studied very thoroughly at the beginning of this century by means of magnetic measurements, excavations and drillings, and it was on the basis of these that Borgström (1928) produced his detailed description of its geology. The most recent research is that carried out for Rautaruukki Oy in the 1970's, when both geophysical measurements and drillings were undertaken.

The Juvakaisenmaa deposit stands out on the magnetic map as a narrow positive anomaly some 1.7 km in length, caused by the magnetite lenses associated with its skarn rocks. It is also exposed at a number of outcrops south of Niesajoki, and it is this that accounts for its early discovery.

The magnetite in the deposit is contained in two lenses of thickness 2—10 m, the more south-westerly of these being about 420 m in length and that to the north-east 250 m. The deposit is almost vertical, and the magnetite lenses are estimated to extend to a depth of about 700 m. The total ore reserves are only approx. 0.8 million tonnes. The best part of the south-western lens, some 200 m in length is, estimated to contain some 100,000 tonnes of ore with a mean composition of 43.7 % Fe, 5.09 % S, 0.030 % Co and 0.10 % Cu at a depth of approx. 20 m. The ore thus has a high sulphur content and a higher than normal cobalt content.

The ore is of the normal skarn ore type, and contains, in addition to the main mineral, magnetite, a relatively large amount of pyrrhotite, some pyrite and a little chalcopyrite. The chief gangue mineral is diopside, in addition to which there may be some scapolite, plagioclase, hornblende and biotite. Skarns containing quartz or garnet are occasionally found. One also sees in connection with the skarn rocks and grading into these, especially in the southern part of Juvakaisenmaa, a quartz—feldspar schist containing diopside and amphibole referred to by Borgström (1928) as leptite or leptitic mica schist. This schist also contains scapolite and tourmaline in places.

The Sainkangas deposit, known from only two drillholes, forms a separate positive magnetic anomaly about a kilometre in length acting as a north-easterly extension to the Juvakaisenmaa deposit. One of these drillholes revealed 11.6 m of skarn ore containing mean values of 53 % Fe, 3.0 % S and 0.12 % Cu, while the other encountered about 10 m of wollastonite-bearing skarn of a type not found elsewhere in the area.

The Juvakaisenmaa and Sainkangas deposits border onto the amphibolite of the Rautuvaara Formation in the south-east and onto diorite which is highly scapolitized in places in the north-west.

THE MANNAKORPI MAGNETITE DEPOSIT

The Mannakorpi magnetite deposit in the south-western part of the Tapojärvi area, is the westernmost of the skarn iron ore deposits in the study area. Its geological association with the upper part of the Siekkijoki Greenstone Formation means that it is the only deposit described here that does not belong to the Rautuvaara Formation. It stands out on the magnetic map as a discrete circular positive anomaly. Since this deposit is not exposed at any outcrop, the available data are based on geophysical interpretations and six diamond drillholes, the longest of which extends to a depth of approx. 700 m.

The deposit is associated with a vertical lens of skarn rock some 200 m thick at its maximum, which lies entirely within a dolomite-dominated carbonate bed. This skarn lens then contains a number of magnetite concentrations located separately, without forming any continuous ore body. Drilling results suggest that there are perhaps five of these lenses, each containing about 1 million tonnes of ore with an iron content of approx. 35 %. These lenses are divided one from another by oreless skarn and veins of albite—hornblende rock varying in thickness from a few metres to around 50 m. The eastern part of the skarn bed, in which the largest amounts of magnetite are found, is estimated to contain about 20 million tonnes of ore with a 25 % Fe content at a depth of 600 m. The mean composition recorded for the best drilling sample, 41.4 m in length in drillhole R 6, will provide an idea of the chemical characteristics of this ore: 33.2 % Fe, 0.06 % Ti, 0.02 % V, 0.07 % Mn, 0.07 % Cu, 3.8 % S, 20.3 % SiO_2, 3.0 % Al_2O_3, 8.3 % CaO, 19.4 % MgO, 0.2 % K_2O, 0.40 % P_2O_5.

These figures come close to the composition of the Kuervaara ore at Hannukainen, with the exception of the magnesium content, which is much higher on account of the presence of dolomite and Mg-rich silicates. Similarly the phosphorus content at Mannakorpi is twice that found at Hannukainen. The main ore mineral is magnetite, and the sulphur is almost entirely bound in pyrite. Pyrrhotite

Table 16

Lithological and mineralogical comparison between the skarn iron ore of Mannakorpi and the skarn ores of the Rautuvaara Formation.

	MANNAKORPI skarn iron ore	RAUTUVAARA FORMATION skarn iron ores
Wall rocks	Dolomite Skarns with tremolite, talc or serpentine dominant Metadiabase	Plutonic rocks of the marginal zone of the monzontite intrusion Skarns with diopside or hornblende dominant
Principal gangue minerals	Dolomite, tremolite talc, serpentine, chlorite	Diopside, hornblende, plagioclase, scapolite
Main ore minerals	Magnetite, pyrite	Magnetite, pyrite, pyrrhotite, chalcopyrite

and chalcopyrite occur occasionally in small quantities.

The principal gangue minerals are dolomite, tremolite, talc, serpentine and chlorite, and the accessory minerals apatite, which is found in relatively large amounts in places, and occasionally biotite and muscovite. Thin veins of anhydrite are also present in the deepest parts of the deposit. The oreless skarn rocks are composed of the gangue minerals listed above, and deviate markedly from the diopside and hornblende-dominated skarns of Hannukainen and Rautuvaara.

The drilling results suggest that the small-grained, massive, homogeneous rock composed of plagioclase (An 10 %) and hornblende which occurs in discontinuous veins within the skarn rock may well represent metadiabase. It is granophyric, and the plagioclase is highly scapolitized in places. The hornblende occurs in needles some 1—3 mm long, with no detectable orientation. The accessory minerals are carbonate, titanite, epidote, apatite, magnetite and pyrites. No such veins have been encountered in the carbonate rock surrounding the skarn.

Carbonate rock more than a hundred metres in thickness is found on either side of the skarn rock. That to the west of the skarn is a light-coloured or pinkish dolomite containing calcite and silicates, while that to the east is grey dolomite. Tremolite is also common in addition to the carbonate, and talc, chlorite, serpentine, plagioclase, quartz, diopside, biotite, titanite and pyrite are found occasionally.

Comparison of the above data on the skarn iron ore of the Mannakorpi deposit with the corresponding ore data for the Rautuvaara Formation shows these to be relatively similar in their chemical composition and proportions of ore minerals. It should be remembered that there are a number of deposits in the Rautuvaara Formation which differ markedly in their proportions of the sulphide minerals which are not indicated in the comparative table (Table 16). At the same time a clear difference appears from the table in respect of the wall rocks and the principal gangue minerals in the ores. The monzonite intrusion and its marginal zone have no counterpart in the case of the Mannakorpi skarn ores, and the degree of metamorphism, in terms of mineral composition, is lower than at the skarn ore deposits of the Rautuvaara Formation.

According to Lindroos (1974), the iron ores of Kaunisvaara are located stratigraphically on top of the greenstone formation. Although no direct observations are available on the stratigraphic position of the Mannakorpi deposit, it would seem to be comparable in location to that of Kaunisvaara, which it also resembles mineralogically.

CONDITIONS FOR SKARN AND ORE MINERAL FORMATION AND THE ROLE OF FLUIDS

Skarn rocks were defined on p. 63 as rocks formed from calcium, magnesium, manganese and iron silicates by skarnification, i.e. by the replacement of carbonates at high temperatures under the influence of fluids containing water. The compositions of the mineral parageneses produced will have been determined by the prevailing pressure and temperature conditions and by the compositions of the fluids and host rocks. The mineralogical study of the skarn rocks of the Rautuvaara area and their associated ores carried out here has not been sufficiently detailed as to allow any exact determination of the conditions under which these rocks were formed, although it is possible to set limits of variation for these conditions with reasonable accuracy.

Pressure

It is always difficult to estimate accurately the pressure conditions prevailing at the crystallization of skarn minerals, since these minerals are usually not particularly sensitive indicators of pressure. Most investigators settle for a pressure of 1—3 kb, which would correspond to the conditions for a contact-metamorphic hornblende-hornfels facies (Turner and Verhoogen 1960, p. 520) and would thus deviate considerably from those of an amphibolite facies of regional metamorphism. Under conditions of high-temperature metamorphism the load of the overlying rock mass gives rise to a confining pressure which may be assumed to be close to that of the pore fluid.

The most widespread minerals in the skarns of the Rautuvaara area are diopside and hornblende, both of which may be regarded as primary skarn minerals. The frequent occurrence of water-bearing silicates may well be due to the relatively high partial pressure of water in the fluid. The total pressure may be assumed to have varied largely in the range 2—3 kb during the formation of the Rautuvaara skarns.

Temperature

In estimating the temperature one can set out from the assumption that the skarn rocks must have crystallized after the monzonite intrusion and close to its marginal zone. The upper limit may therefore be set at 700—750°C, at which granite will begin to melt if the water pressure is sufficient (Turner and Verhoogen 1960, p. 458), the temperature of the intrusion itself having evidently been around 900°C (Winkler 1979, p. 99). The highest formation temperatures amongst the mineral parageneses would seem to be represented by the rocks of the deeper parts of SW-Rautuvaara, which contain Fe-rich silicates, fayalite and eulite.

The estimation of formation temperatures in the case of the skarn rocks on the basis of the mineral parageneses is hampered by the complexity of the fluids which promoted the formation of these minerals. Apart from water, the CO_2 content of the fluid may also be of considerable importance, as may other components (Weeks 1956). No component in a solution can have a partial pressure in excess of that of the pure component under the same conditions, and a mixture of two or more components in a gaseous facies will have the effect of reducing the reaction temperature at any pressure whatsoever. For this reason all formation temperatures for minerals obtained from experimentally determined or calculated equilibrium curves should be taken as maximum estimates (Sangster 1969).

The experiments of Slaughter, Kerrick and Wall (1975, Fig. 9) with the system CaO-MgO-SiO_2-H_2O-CO_2 indicate that diopside is stable in the presence of H_2O and CO_2 above 500°C at a pressure of 2 kb, while X_{CO2} is 0.3, whereas a stable paragenesis at a temperature below 500°C would be tremolite + calcite + quartz. An increase in the molar proportion of CO_2 will raise the equilibrium temperature in the same way as will an increase in the total pressure. In any case, 500°C may be regarded as the lower boundary for the majority of the Rautuvaara skarn, as tremolite is not usually found as a primary skarn mineral. The one exception is the Mannakorpi deposit, where it occupies this position alongside talc, serpentine and chlorite. The temperature upon formation of the skarn at Mannakorpi was thus apparently below 500°C, and the crystallization conditions will have largely corresponded to those for a greenschist facies.

The common occurrence of small amounts of secondary amphibole in the skarns of the Rautuvaara area is apparently a consequence of the commencement of retrograde metamorphism as the temperature fell following the main skarn formation stage. The local occurrences of serpentine and chlorite elsewhere than at Mannakorpi also point towards the same conclusion. Mineral formation at a still lower temperature is indicated by the relative abundance of the Ca-Al zeolite chabazite at Sivakkalehto and sporadically at other sites. This represents a much later event than skarn formation, however, the prevailing temperature being below 350°C (Stringham 1952).

The ore minerals have been shown to have crystallized for the most part after the primary silicate minerals, and with magnetite being the first to do so, followed, apparently with some overlap, by pyrite, and lastly pyrrhotite and chalcopyrite. Thus the magnetite can be assumed to have crystallized at a slightly lower temperature than the silicates, and the sulphides at lower temperatures than the magnetite. The occurrence of ilmenite lamellae within the magnetite is suggestive of crystallization at a relatively high temperature, since virtually no exsolution of such lamellae takes place at temperatures below 500°C (Buddington and Lindsley 1964). The magnetite must thus have crystallized at around 500—650°C. As far as the sulphides are concerned, one can only assume that they must have crystallized at 450—550°C, as attempts to determine the crystallization temperature from the composition of the pyrrhotite in equilibrium with the pyrite by the method of Arnold (1962) failed when the pyrrhotite proved to be a monoclinic variant. Determinations carried out by Arnold for ten hydrothermal ore deposits gave temperature values in the range 425—

520°C (Arnold 1962). In summary, crystallization of the skarn minerals in the Rautuvaara area may be stated to have taken place at temperatures around 750—500°C, that of the magnetite at approx. 650—500°C and that of the sulphides at approx. 550—450°C.

Oxygen fugacity

The f_{O_2} values of the fluids promoting crystallization are of considerable importance in the formation of both the skarn silicates and the ore minerals. Under the assumed temperature conditions of 650—500°C, magnetite is stable at $f_{O_2} = 10^{-14}$—10^{-28} atm (Holland 1959). It is this broad area of stability that has led to the widespread occurrence of magnetite as the iron-bearing mineral in skarns. At values for f_{O_2} greater than 10^{-14} atm the stable mineral at a temperature of 650°C would be hematite.

According to Gustafson (1974) the pure component, andradite, is stable in the presence of quartz and magnetite at a fluid pressure of 2 kb and a temperature of 500°C at f_{O_2} values of 10^{-18}—10^{-23} atm. Once the f_{O_2} value is greater than 10^{-18} atm the stable iron-bearing mineral is hematite, and when it is less than 10^{-23} atm hedenbergite. Although the impurity of the components in practice would extend these areas of stability somewhat, the rarity of the paragenesis andradite—quartz—magnetite in the Rautuvaara area suggests that the oxygen fugacity remained relatively low during the period of skarn formation, perhaps in the range $f_{O_2} = 10^{-18}$—10^{-28} atm. The occasional occurrences of andradite skarn would then be indicative of local increases in oxygen fugacity. Similarly the predominance of pyrite in the Lauku ore body, for example, could be attributed in part to a higher level of oxygen fugacity. On the other hand, the occurrence of the fayalite—quartz—magnetite paragenesis at SW-Rautuvaara would denote a lower than normal oxygen fugacity (Klein 1973, Frisch and Bridgewater 1976). The sporadic appearance of anhydrite, particularly at Sivakkalehto, although admittedly a later crystallization product, could also be explained, following Krauskopf (1957), as being due simply to a somewhat more oxidizing gas than normal.

The fluids

The fluids involved in skarnification and the formation of skarn ores functioned both to transport the material and to regulate the conditions for the crystallization of new minerals. In view of the many stages involved in the metasomatic processes, these fluids were also subject to constant change. Thus their composition can only be discussed in terms of certain generalized qualitative estimates.

According to existing theories, metals are transported in hot, acidic, water-bearing fluids, largely in the form of halogenides, and are precipitated as the temperature falls or alkalinity increases. Krauskopf (1957, 1964) has shown that of all the volatile compounds, it is the chlorides of the majority of metals that are the most important transport media at high temperatures. Arguing from experimental research and theoretical descriptions concerning supercritical chloride solutions, Chou and Eugster (1977), Eugster and Chou (1979) propose that it would certainly be possible for the considerable quantities of material required for the formation of magnetite and pyrite to be transported via such solutions. These would, in their opinion, be capable of dissolving, and thus concentrating, iron from any compounds containing this metal.

When acidic, and evidently supercritical, fluids enter a contact involving a carbonate rock, neutralization sets in and skarns begin to form, these reactions being largely regulated by the partial pressures of the principal components in the fluid, H_2O and CO_2, these two also being the most mobile components in the fluids in skarn reactions (Korzhinskiy 1964, Zharikov 1970). Replacement of the carbonate minerals by silicates can continue only if the system is open with respect to CO_2, as is usually the case in skarnification. If it is a closed system there is no decomposition of the carbonates even if SiO_2 is available. Such a situation is frequently encountered in the regional metamorphism of sedimentary iron formations, where the activity of CO_2 can show appreciable local variations (Klein 1966, 1973, 1978).

The mineral composition can be affected by even quite small changes in the partial pressures of CO_2 and H_2O, so that the replacement of diopside by tremolite, calcite and quartz can be occasioned not only by a drop in temperature, but also by a rise in the partial pressure of CO_2 in relation to that of H_2O (Slaughter *et al.* 1975). In the case of the Rautuvaara skarns both H_2O and CO_2 would seem to have been entirely mobile in the crystallization reactions, since the quartz—carbonate parageneses occurring in connection with the skarns are explicable as products of these reactions.

The formation of the skarns of the Rautuvaara area appears to have involved the carbonate-bearing rocks being penetrated by fluids carrying at least iron, magnesium, aluminium, silicon, sulphur and chlorine, while at the contacts between the skarns and the intrusives, largely diorite, calcium, magnesium and iron entered the rock in amounts which obviously increased towards the contact itself. Another notable feature is the high activity of Cl in places, as reflected in the pronounced scapolitization noted at Sivakkalehto in particular.

Of the ore metals, copper and small amounts of gold were transported by the fluids in addition to the iron. The occurrence of gold in connection with skarn magnetite deposits containing copper is a fairly common phenomenon, and the crystallization of this metal is associated with a late stage in mineralization (Entin 1975, Boyle 1979, Shimazaki 1980). Alongside the concentration of the materials and the oxygen fugacity, the pH of the fluids is obviously of great importance in the crystallization of ore minerals, and in particular the sulphides. According to Rye and Ohmoto (1974), the replacement of pyrite at the quartz monzonite contact in the Darwin deposit in California by a pyrite—pyrrhotite—magnetite paragenesis was due to an increase in the pH of the fluid with extending distance from the contact and into the limestone rock. Thus the pH may have been lower during the formation of the pyrite-dominated ore at Lauku in the Hannukainen deposit than at the time of the crystallization of the pyrrhotite-dominated ores of Vuopio and Kuervaara, although this may also have been influenced by the increase in oxygen fugacity at Lauku. The important role of pH in determining the sulphur isotope composition of crystallizing sulphides has already been noted in connection with the description of the Hannukainen and Rautuvaara deposits.

GENETIC SURVEY OF THE ORES

Any account of the genesis of the skarn ores should provide answers to two questions:

— the mode of formation of the ores
— the origins of their ore material.

An answer to the first of these can be sought by studying the concrete product of the formation process, the ore deposit and its surroundings, and the achieving of such an answer may also help in resolving the second question at the same time. In the case of epigenetic ores, as represented by these metasomatic skarn ores, it may nevertheless prove difficult to find an answer to the second question, and the matter may remain to a greater or lesser extent dependent upon guesswork. The ore material may be derived from one source or from several sources, so that a detailed study not only of the deposit itself, but also of a broad sector of the surroundings may be required, and even then the question may remain unsettled.

Since there is no general unambiguous genetic definition of the concept of skarn rock, the deposits described by different authors as skarn ores cover a variety of types, at least as far as the origins of the ore material are concerned. One feature common to practically all such accounts, however, is that the ore is located in contacts between intermediate granitoids, such as granodiorite, quartz diorite or monzonite, and rocks containing carbonate, or at least close to contacts with intrusions. Skarn ores are not normally found in the area of a contact with a mafic intrusions, perhaps due to the excessively low volatile content of such rocks for the transportation of ore materials (Stanton 1972, p. 616). The most numerous references in the literature concern skarn iron ore deposits interpreted as purely contact-metasomatic in which the ore material is assumed to be derived from intrusives. Such cases have been described in the U.S.A. (Postel 1952, Hotz 1952, Lamey 1961, Bennet 1962, Leonard and Buddington 1964, Mackin 1968, Morgan 1975 and Kerrik 1977), Canada (Stevenson and Jeffery 1964) and Japan (Tsusue 1961). Skarn iron ores interpreted as contact-metasomatic are also frequently found in connection with porphyry copper ores, as described at least in the U.S.A. (Perry 1969, Atkinson and Einaudi 1978, Reid 1978) and New Guinea (Bamford 1972, Arnold and Griffin 1978).

More and more opinions are being put forward to the effect that the ore materials and even the fluids transporting them may be derived from primary sedimentary and volcanic rocks which had then reached a sufficiently high temperature, e.g. under the influence of an intrusion (Belevtsev 1970, Boyle 1970), and these interpretations have found support from certain recent experimental investigations on supercritical chloride solutions (Althaus and Johannes 1969, Eugster and Chou 1979). Thus Eastwood (1965) and Sangster (1969) interpret certain skarn iron ores in Canada as having been formed metasomatically under the influence of intrusive fluids, the iron being derived from the underlying volcanites. Hagner *et al.* (1963) and Brock (1972) in the U.S.A., Leo (1972) in Turkey, Verkaeren and Bartholome (1979) in Italy and Morrison (1980) in Canada have all interpreted skarn iron ores as having been formed metamorphically from sedimentary rocks under the influence of metasomatic processes, while Collins (1969) in the U.S.A. explains similar ores as originating from ankeritic marble purely by metamorphic recrystallization.

Conflicting genetic interpretations have been provided for the many skarn iron ores found in Sweden. The skarn ores of Central Sweden, which contain manganese in places, have mainly been interpreted as primary sedimentary rocks deposited together with quartz and limestone or dolomite which have then undergone regional metamorphism under the influence of Sveco-fennidic granites to form a reaction skarn (Geijer and Magnusson 1944, 1952, Geijer 1959, Magnusson 1970). The sulphides occurring in these skarns are regarded by the above authors as having entered the rock later as impregnations in connection with magnesium metasomatism. A smaller proportion of the skarn iron ores are held to be of contact-metasomatic origin (Geijer 1959, Magnusson 1970), and the skarn ores of Northern Sweden are interpreted as pyrometasomatic (Geijer 1931, 1959, Geijer and Magnusson 1952).

Frietsch (1967, 1970, 1973, 1977, 1980) regards skarn iron ores as syngenetic volcanic-sedimentary deposits and explains the formation of skarn silicates as due to reactions within the formation stimulated by regional metamorphism. Opinions in support of these views have been expressed by Lindroos (1974) and Eriksson and Hallgren (1975) on evidence from skarn iron ores in Northern Sweden.

Few papers have been published in Finland concerned with skarn iron ores. Mikkola A. (1947) interpreted the iron ore of Vähäjoki as a sedimentary reaction skarn ore, adhering to the views of Magnusson, while the skarn iron ores of the Rautuvaara area have been viewed as contact-metasomatic in origin (Borgström 1928), sedimentary (Mikkola T. 1960, Mäkelä and Tammenmaa 1978, Mäkelä and Mattila in press) and even magmatic (Shaikh 1964).

It is now possible within the framework of the present study to approach a genetic examination of the ore deposits of the Rautuvaara area from the standpoint of the following observations:

1. The deposits are of the strata-bound type and the ore lenses are located principally in the skarn rocks of the upper part of the Rautuvaara Formation.
2. With only one exception, the Mannakorpi deposit, the deposits are associated with a contact zone involving the monzonite intrusion.
3. Mineralization has taken place both in the skarn rocks and in the rocks of the hanging wall and footwall. Mineralization in the hanging wall is most clearly discernible in the diorite at Hannukainen, where it forms a zone of ore mineral-bearing rock. North of Hannukainen this mineralization has taken place along the marginal zone of the monzonite, even where no skarn is found. One good example of mineralization in the footwall is the albite—anthophyllite rock of Cu-Rautuvaara, and a similar type is also noted at Kuervitikko, north of Hannukainen. Both the hanging wall and the footwall ore-bearing zones are of the disseminated type.
4. The ore lenses are elongated in the direction of regional lineation. Especially at Rautuvaara, where shear movement has been pronounced, they have been »stretched out» into long rod-like conformations.
5. The principal ore mineral in all the ore lenses and the mineralized areas of the hanging wall and footwall rocks is magnetite, alongside which one finds pyrite and pyrrhotite in varying proportions.
6. All the deposits contain at least a small amount of chalcopyrite, but a few ore bodies have significant quantities (i.e. Laurinoja, Cu-Rautuvaara, SW-Rautuvaara). Concentrations of copper are also found in both the hanging wall and footwall rocks in places (i.e. Cu-Rautuvaara, Kuervitikko).
7. The skarn silicate crystallized before the ore minerals. The order of crystallization of the ore minerals is usually: magnetite (first), pyrite, pyrrhotite, chalcopyrite.

8. Where the intrusive rocks form the hanging wall to the skarn bed, these very commonly show a gradual increase in Ca, Fe and Mg content towards the contact with the skarn.
9. Zircon age determinations gave results of 1860 Ma for the monzonite, 1849 Ma for the albitite of the monzonite margin and 1797 Ma for the skarn. The youngest zircon age obtained, 1748 Ma, applies to a hornblende-rich pegmatoid vein cutting the skarn. The titanite age determinations regularly give younger ages but the order is the same.

The ore deposits of the Rautuvaara Formation may be said to have been formed as a consequence of the following geological processes.

— During the early stage of the main folding movements, the monzonite intruded conformably upon the basic volcanites, schists and carbonate-bearing rocks of the Rautuvaara Formation and less frequently between these, in which case parts of the formation were left within the intrusion (as at NE-Rautuvaara).

— The hybridic diorite-dominated rocks of the marginal zone then intruded in between the cooled edge of the monzonite and the sedimentary rocks and became partly mixed with these. The intrusive rocks of the marginal zone were probably themselves formed at a deeper level, as a product of assimilation between the monzonite magma and the surrounding rocks.

— The fluids created in the areas adjacent to the edge of the plutonic rocks after the intrusion gave rise to extensive metasomatic changes in the rocks of the contact zone.

— The first stage of metasomatic reactions would seem to have consisted of diffusion reactions between the carbonate and silicate rocks. This may be the reason for the general banded appearance of the skarns. The great extent of the metasomatic changes nevertheless indicates that infiltration metasomatism was the dominant process in the formation of both the skarns and the ores.

— The first stage of the replacement reactions involved the formation of skarn silicates, chiefly diopside and hornblende, from the carbonate-bearing sedimentary rocks under the influence of the fluids, while the silicate-bearing rocks gave rise to albite—anthophyllite rocks in some places and scapolite-dominated rocks in others. Endoskarn was formed at the edges of the plutonic rocks.

— The ore minerals crystallized as the temperature gradually fell, displacing the silicates and carbonates. The first to crystallize were magnetite and pyrite, and the last pyrrhotite, chalcopyrite and small amounts of gold. Partial retrograde metamorphism occurred in the skarn silicates.

— The majority of the ore minerals crystallized in the skarns and carbonate rocks, which are the most susceptible to replacement reactions, but some crystallized in the diorites of the marginal zone and the metasomatic albite—anthophyllite and scapolite rocks.

— Movement of the fluids was promoted by tectonic movements, which also stimulated the metasomatic reactions. This explains the marked tectonic control reflected in the ore lenses.

There are not many clues available to the origin of the ore material and the fluids which transported it. It has been shown that these materials were in all probability transported in acidic supercritical chloride solutions, these being capable of solubilizing and transporting material from a variety of sources. In addition to the monzonite intrusion, the volcanites and sedimentary rocks of the Rautuvaara Formation may also be regarded as potential sources of ore metals in the Rautuvaara area. The sulphur isotope composition of the sulphide minerals is indicative of a possible hypogenic source of sulphur at the majority of sites, but part of the sulphur may still be of sedimentary origin.

The origin of the fluids which transported the ore material is equally obscure, since they could have been released either from the monzonite intrusion or from the surrounding rocks by a heat effect, or perhaps most plausibly from both. More information on this subject could be furnished by the study of trace elements in the ore minerals and an extension of the work on the stable oxygen and sulphur isotope compositions of both the surrounding rocks and the ore deposits.

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