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Evolution of the Precambrian volcanic complex in the Kiuruvesi area, Finland

by Erkki Marttila

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EVOLUTION OF THE PRECAMBRIAN VOLCANIC COMPLEX IN THE KIURUVESI AREA, FINLAND

BY
ERKKI MARTTILA

WITH 32 FIGURES, 11 TABLES IN THE TEXT AND TWO APPENDICES

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The Kiuruvesi area is located in a fracture zone that trends southeast to northwest across central Finland and forms a structural division between the Svecofennian rocks to the south and the Karelian rocks to the north.

The volcanic complex in the area includes metamorphosed basic lavas and agglomerates as well as basic and acid tuffs and tuffites. These were erupted into a marine eugeosyncline directly on top of the basal gneiss complex. The volcanic rocks grade into sedimentogeneous mica and hornblende gneisses stratigraphically overlying the volcanites.

The orogeny involved block movements that gave rise to a central block, which is conspicuously different from its environment in metamorphic facies. The rocks within the block — hypersthene-bearing dioritic and granitic rocks — derive from anatectically melted volcanic-sedimentary rocks of the basement under conditions of the pyroxene gabbro-granulite facies. The rocks outside the block — amphibolites and gneisses — were formed under conditions of the amphibolite facies. Cordierite-bearing rocks are encountered in narrow marginal and shear zones. The cordierite-garnet-anthophyllite (hypersthene) rocks were formed from basic volcanites that underwent partial anatectic melting in association with contact and dislocation metamorphism. The cordierite-garnet-biotite rocks appear to derive from pelites with some volcanic components.

The formation of sulphide mineralisation in the area seems to be associated genetically with volcanism and the occurrence of cordierite-bearing rocks.

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PREFACE

Geological investigation in the Kiuruvesi area got underway after an ore deposit was discovered at Pyhäjärvi, in the county of Oulu, at the end of the 1950s. Outokumpu Oy started mining operations at Pyhäsalmi, and the Exploration Department of that company began local investigations at sites favourable for the occurrence of ore. Initially, mapping was restricted to these sites and their environment, but year by year the area covered was extended.

In 1967—1972 I was commissioned by the Outokumpu Exploration Department to carry out geologic mapping and revise the earlier maps on the basis of aerial photos, aerial photo maps and 1:20 000 topographical maps published by the National Board of Survey. In compiling maps for the present study I made good use of rock type and tectonic observations made in the field as well as results from geophysical surveys and maps of the area.

As research assistant of the Academy of Finland in 1972—1975, I was in a position to analyse the material gathered and draw the pertinent conclusions.

The tenors of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, P_2O_5, H_2O+ and H_2O-, and of the trace elements Cu, Zn, Ni, Pb and S were determined by Mrs. Irja Rautiainen of the Outokumpu Exploration Department. The S abundances were determined with a Leco DB-64 titrator, relative accuracy $\pm$ 3 percent. I am personally responsible for the MgO, CaO, Na_2O and K_2O assays, which I did with a model 290 Perkin-Elmer Atomic Absorption Spectrophotometer.

The petrological map compiled for the present investigation (Appendix 1) is soon to be published by the Geological Survey as map sheet 3323 Kiuruvesi.

Turku, October 1975.

Erkki Marttila

INTRODUCTION

The Kiuruvesi area is located in central Finland, in the northern part of the province of Savo, on the structurally interesting Raahe — Lake Ladoga line, which roughly divides the so-called Svecofennian rocks in the south from the Karelian rocks in the north (Fig. 1).

The most ancient Prekarelian bedrock in Finland occurs mainly in the eastern and northern parts of the country. In central Finland in the Savo area the basement gneiss bulges up in several mantled domes, especially around Kuopio (Wilkman 1923, 1938; Preston 1954). The granite gneiss complex of Iisalmi has also been likened to the basement gneiss complex of eastern and northeastern Finland. There is no conclusive evidence of Presvecofennian basement in central Pohjanmaa northwest of the Raahe — Ladoga line. It has been presumed that the depositional basement of the so-called Bothnian schists, which form part of the Svecofennian fold area, has been melted and metamorphosed with the result that the overlying volcanic series is now the oldest known formation in the area.

On the map sheet of Kajaani (scale 1: 400 000) by Wilkman (1929, 1931) the area marks the confluence of the granite gneisses of eastern Finland and the Kalevian formations associated with them as well as the plutonic rocks of Pohjanmaa including their effusive associates and schists (Wilkman 1931, p. 12). The boundary continues southwards onto the Kuopio map sheet area (scale 1: 400 000), also by Wilkman (1935, 1938). An interesting feature is that the division drawn by Wilkman between the granite gneiss complex (basal gneiss formation) and the Bothnian (Svecofennian) and the younger rock types passes through the Kiuruvesi area. Even earlier, in the geologic map of central Pohjanmaa compiled by Mäkinen in 1916, the boundary between the Bothnian and older rocks (Mäkinen's orthogneisses) had been drawn along the line Kiuruvesi — Pyhäjärvi — Kärsämäki.

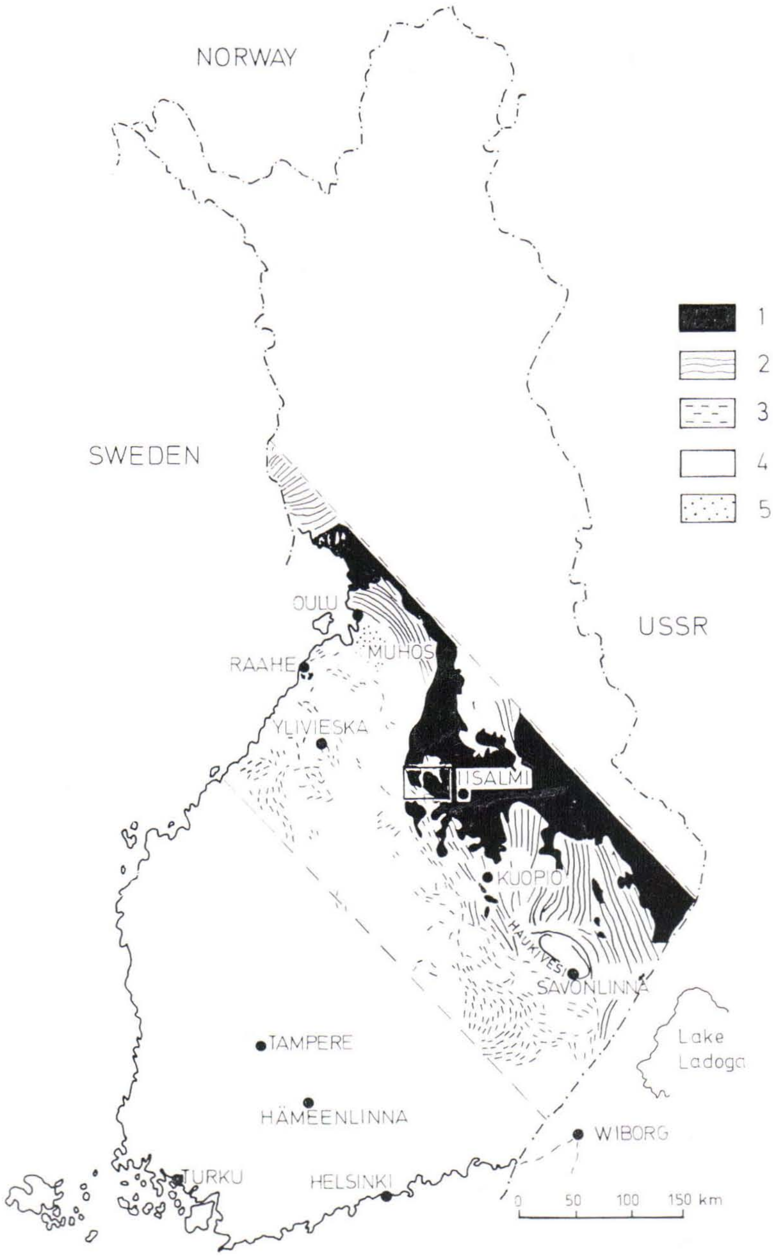

Fig. 1. Structural elements of the Finnish rock crust in the Lake Ladoga — Raahe zone after Simonen (1971, p. 1411). 1. Presvecokarelidic ortho- and paragneisses. Svecokarelidic structural elements: 2. Karelidic schist belt, 3. Svecofennidic schist belt, 4. orogenic plutonic rocks. Later Precambrian: 5. anorogenic Jotnian sediments. The location of the Kiuruvesi study area is marked by the rectangle west of Iisalmi.

THE BASEMENT COMPLEX

In the Kiuruvesi area the basement gneiss complex is composed of para- and orthogneisses that are difficult to distinguish owing to the extent of alteration. The paragneisses consist of amphibolites, hornblende gneisses and mica gneisses. Banding is marked and commonly accompanied by appreciable folding and bending. Migmatisation and conspicuous granitisation are present. The paragneisses often also contain ghost-like darker inclusions suggesting that the rock was once partly molten. This makes it very difficult, even impossible, to identify the type of the original rock. Paragneisses are more common than orthogneisses. The orthogneisses of the basement complex are mainly gneissose quartz diorites, granodiorites and granites. In the present context the granites may be entitled gneiss granites; they exhibit distinct orientation that is partly a consequence of compression and is revealed in thin section by bent plagioclase twinning lamellae and biotite scales. The gneiss granites in the area are generally grey in colour, but east of the Vieremä—Haajainen conglomerate the rock is pink and aplitic, with intense orientation due to faulting when in contact with conglomerates. They are medium-grained (2 to 5 mm) rocks, but under the influence of the younger granites, feldspar augen are also visible.

Northwest of Lake Haapajärvi there are occurrences of medium- and even-grained grey granodiorite with very little or no orientation and local ghost-like breccia remnants of older gneiss. It seems that this granodiorite once formed part of the basement gneiss formation, but it has been remobilised and its structure is now that of orthogneiss, as is also suggested by the shape of the zircon crystals. According to the age of the zircons, determined by O. Kouvo of the Geological Survey, and presented in Table 4, the granodiorite represents the late orogenic stage of Svecokarelian folding.

The basement gneiss complex includes dome-like forms. The basement east of the lakes Kiuruvesi and Valkeisjärvi consists of two successive dome-like ridges with an intensely granitic core in which feldspar exhibits faintly developed porphyritic texture (cf. biotite-granite). The margins of the domes and the intervening spaces are granodioritic and quartz dioritic. Another faintly dome-like form occurs at the western edge of the map sheet in the Niinimäki region. Here the granitic core is distinctly porphyritic and somewhat elevated above its environment. The composition of the margins is variable, being, however, granodioritic and quartz dioritic. In structure it is a fine- and medium-grained rock with distinct orientation. There is a third basement dome, Liittovuori, but only its southern end extends to the northwestern corner of the investigation area. The core of this dome is microporphyritic granite and the margin is oriented medium-grained granodiorite and quartz diorite. The basement complex, including both para- and orthogneisses, is cut by pegmatite, aplite and granite dykes, and by diabase dykes trending in several directions. These dykes are well displayed in road cuts between Pyhäsalmi and Iisalmi.

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THE SUPRACRUSTAL COVER

The basement formation is overlain by the metamorphosed volcanogeneous and sedimentogeneous rock types that constitute the greater part of the bedrock in the Kiuruvesi area. In composition the volcanites are largely basic and intermediary, whereas the sedimentogeneous rocks are mostly clastic sediments interbedded by some pyroclastic tephra. The Vieremä—Haajainen conglomerate-schist zone in the eastern part of the area forms a separate depositional series composed of clastic sediments.

Volcanogeneous rocks

Well-preserved volcanogeneous rocks are encountered throughout the area as fragmented zones less than a kilometre in width. Their rock types include basic lava rocks, agglomerates, basic and intermediate tuffaceous schists (amphibolites, uralite porphyrites and plagioclase porphyrites) as well as acid tuffaceous and tuffite schists (leptites).

Basic lava rocks

In the investigation area there are only two outcrops of originally basic lavas. These are in the northwestern section of the area, at Vantunmäki and Äyhynkorpi.

At Vantunmäki the bottom layer of a volcanic series consists of a lava bed that was deformed together with the overlying tuffaceous bed (Fig. 2). The lava bed exhibits a fragmentary structure with light green pillow-like fragments from 5 to 50 cm in size. The fragments are basic in composition, containing abundant diopside, hornblende and epidote, as well as some plagioclase and carbonate. The accessories are appreciable titanite and a little quartz. The agglomerate in the tuffaceous beds displays bombs of fragmentary lava suggestive of the pillow lava-like and fragmentary lavas described by Laitala (1973) from the Pellinge region. It has been proposed that this structure is the outcome of an eruption of lava

Fig. 2. The structure of fragmentary lava. Kiuruvesi, Honkaperä, Vantunmäki.

into water (Laitala 1973, p. 24). The sample of fragmentary lava taken for chemical analysis contained material of pillow-like lava and tuff. The composition, which is given in Table 1, analysis 1, does not differ essentially from that of the basic tuffaceous schists, given in the same table (analyses 3—5).

At Äyhynkorpi there are occurrences of fine-grained and massive lava rock with a pale yellowish green weathering surface in which it is just possible to distinguish flow features revealing elongated lenses of darker minerals. Thin section examination showed that the rock contains abundant diopside ($c \wedge z =$ 37—40°), epidote and plagioclase (An_{59-60}) as well as rounded clusters and individual wedge-shaped crystals of titanite and opaque sulphide and oxide mineral. The chemical composition of the rock, presented in Table 1, analysis 2, indicates a high CaO and MgO content, and a low alkali and aluminium content compared with the other volcanites.

Northeast of the lava rock outcrop there is agglomerate that grades eastwards into acid tuffaceous schist, whereas west of it there is gneiss granite that is obviously part of the basement formation. No contact between the rocks is discernible.

About 3.5 km north of the northwestern corner of the map an outcrop has been noted by the road at Lohva in which pillow lava structures are visible in dark hornblende amphibolite. The rocks is cut by a fine-grained diabase dyke about 10 cm wide. Its structure is suggestive of subaqueous eruption.

Agglomerates

According to Fisher (1961, p. 1412), "agglomerate is a rock aggregate composed mainly of large (> 64 mm) pyroclastic fragments rounded by volcanic processes". Agglomerates of the investigation area consistent with this definition and associated with the acid and basic volcanites have been encountered at Äyhynkorpi, Vantunmäki and 3 km southwest of the village of Kiuruvesi.

The Äyhynkorpi agglomerate (Fig. 3) is associated with the acid tuffaceous schists (leptites) east of it; immediately to the southwest these is an occurence of basic lava rock.

The agglomerate contains rounded and subangular fragments of acid and intermediate leptite, from 1 to 7 cm in size, in a pyroclastic matrix (Fig. 4). The fragments and matrix are composed of plagioclase ($An_{c.31}$), quartz, chloritised biotite and hornblende. The plagioclase and quartz have rough edges, and the quartz is also intensely deformed. Tattered scales of biotite and laths of hornblende occur in greater abundance in the matrix than in the fragments. Accessories in both matrix and fragments are epidote, pistacite, apatite and some grains of opaques. By and large the rock is basic in composition and was obviously intensely deformed during later tectonic movements.

The agglomerate about 3 km southwest of the village of Kiuruvesi is at the boundary of the basic tuffaceous schist (amphibolite) and the mica gneiss. The fragments of agglomerate, which are elongated flattened rods 1 to 10 cm long

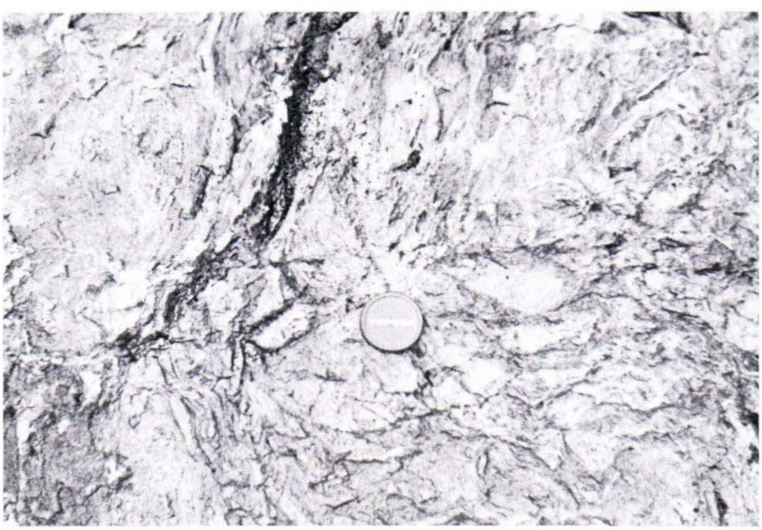

Fig. 3. Agglomerate. Pyhäjärvi (county of Oulu), Äyhynkorpi, map sheet 3323 03 7068.56/460.35.

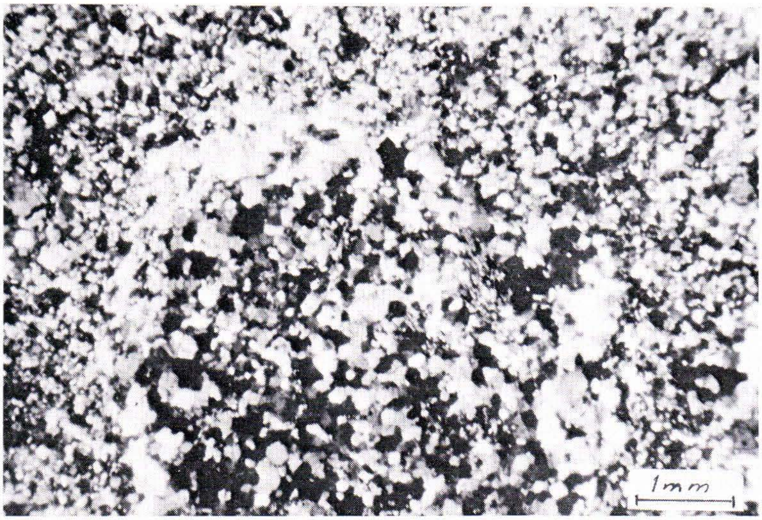

Fig. 4. A fragment of agglomerate. Photomicrograph, nicols crossed. Pyhäjärvi (county of Oulu), Äyhynkorpi, map sheet 3323 03 7068.56/460.35.

in the direction of schistosity, form layers 5 to 10 cm thick in the amphibolite. The main rock types represented by the fragments are light-coloured leptites with some amphibolitic inclusions.

The Vantunmäki agglomerate (Fig. 5) is associated with the fragmentary lava to the west; eastwards it grades into tuffaceous schist. The bombs of agglomerate vary in mineral composition and size, the largest being about 15 cm long. The light-coloured fragments with slightly greenish margins contain abundant plagioclase whose An content increases from An_{36} at the centre of the fragments to An_{43} at the edges; in the basic matrix the An content is as high as An_{50}. The plagioclase is partly intensely sericitised and the edges of the fragments contain abundant diopside and epidote. Titanite occurs as twinned wedges. In the most basic bombs the plagioclase crystals are interspersed with diopside; the plagioclase is then labradoritic An_{60} in composition. It displays streaky zoning and includes such minerals as twinned pleochroic titanite wedges, carbonate and local light-coloured tremolitic amphibolite laths. Minor amounts of carbonate are present here and there in the bombs.

The Kiuruvesi agglomerates occur in much the same associations as do those in the Tampere and Hämeenlinna areas. In the former, in the immediate vicinity of both basic and acid lava rock beds, apparent "bombs" of both types of lava rocks are sometimes met with in tuffitic layers (Seitsaari 1951, p. 21). Near the town of Hämeenlinna an intermediate agglomerate is associated with a stratified tuffitic rock (Simonen 1948, p. 18 and 1949, p. 12).

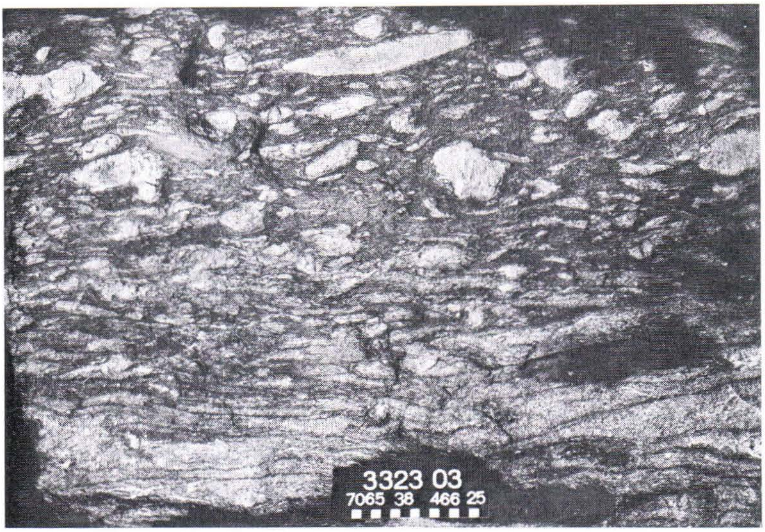

Fig. 5. Agglomerate. Kiuruvesi, Honkaperä, Vantunmäki.

Basic and intermediate tuffaceous schists

Basic tuffaceous schists (amphibolites)

Basic tuffaceous schists are encountered as minor deposits throughout the area, usually in close association and alternately with more acid tuffaceous and tuffitic schists (leptites). Other rocks with which they have affinity are hornblende gneisses and mica gneisses as well as cordierite-garnet-anthophyllite rocks.

Skarn-banded amphibolite can be traced west-northwest from north of Vaaksjärvi. It is associated with a cordierite-garnet-anthophyllite rock that shows some thin bands of leptite with a minor sulphide dissemination. A second zone containing metamorphosed basic volcanites starts north of Honkaperä, continues east-southeast as narrow ribbon-like deposits to Niemisjärvi and from there proceeds to Hautajärvi. At Honkaperä this zone includes metamorphosed basic lavas and agglomerates in association with tuffaceous schists, whereas in the environment of Niemisjärvi the prevailing rocks are cordierite-garnet-anthophyllite rocks and hornblende gneisses in association with amphibolites. North of Lake Hautajärvi, there is a fairly broad hornblende-diopside-banded amphibolite zone that south of the lake also contains cordierite-garnet-anthophyllite rocks and some mineralisations. The amphibolite follows the margin of the pyroxene granite-granodiorite massif until it separates to go on to Majoonjärvi, where it once more includes cordierite-garnet-anthophyllite rocks.

Northwest of Kalliojärvi amphibolite occurs as a fairly broad zone and as bands and inclusions in association with migmatitic gneiss granite and mica gneiss. Characteristic of this area are the bands and beds of amphibolite in the cordierite-garnet-anthophyllite rock.

Table 1

Chemical compositions of intermediate and basic volcanites. Analyses 1—9 are from the Kiuruvesi investigation area.

	1.	2.	3.	4.	5.	6.	7.	8.		9.	10.
SiO_2	53.66	50.18	51.04	50.09	47.49	53.74	48.76	51.96		54.93	48.99
TiO_2	0.40	0.28	1.58	0.48	1.28	0.66	0.56	0.41		1.53	1.47
Al_2O_3 ...	15.20	10.03	14.20	15.40	15.03	17.92	17.59	14.87		14.43	14.26
Fe_2O_3 ...	1.36	0.99	0.90	1.84	1.02	2.02	1.26	1.60		7.11	1.56
FeO	6.51	8.07	12.80	7.82	11.34	6.62	9.50	7.26		7.83	10.48
MnO	0.23	0.15	0.20	0.17	0.19	0.15	0.19	0.19		0.20	0.31
MgO	7.26	8.29	5.41	8.52	7.59	3.68	7.48	7.36		4.91	5.77
CaO	10.51	18.85	8.46	10.00	11.03	7.69	10.64	11.03		5.50	12.64
Na_2O ...	3.52	0.94	2.94	3.77	2.70	4.97	2.73	3.64		3.03	1.69
K_2O	0.44	0.29	0.20	0.17	0.26	0.55	1.08	0.53		0.02	0.41
P_2O_5	0.09	0.14	0.16	0.11	0.11	0.22	0.10	0.08		0.13	0.66
H_2O+ ..	0.82	0.84	1.42	1.54	1.68	1.14	1.42	1.52		0.34	1.52
H_2O- ..	0.06	0.07	0.17	0.07	0.21	0.18	0.19	0.12		0.01	0.14
	100.06	99.12	99.48	99.98	99.93	99.54	101.50	100.57			99.90
Cu ppm	61	110	81	42	137	87	62	2	CO_2	0.0	
Zn ppm	148	90	127	80	108	78	98	82	F	0.06	
Ni ppm	78	346	82	71	135	15	95	79	Cl	0.01	
Pb ppm	69	74	45	44	34	38	74	37		100.04	
S ppm	160	12 034	3 982	355	1 240	572	399	104	—O	0.03	
										100.01	

The samples and their location on the map

1. Basic tuff lava (fragmentary lava). Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.38/466.24.
2. Basic lava rock. Pyhäjärvi (county of Oulu), Äyhynkorpi, map sheet 3323 03 7068.56/460.35.
3. Basic tuffaceous schist (amphibolite). Kiuruvesi, south of Lake Hautajärvi, map sheet 3323 08 7053.28/482.46.
4. Basic tuffaceous schist (amphibolite). Kiuruvesi, northwest of Lake Kalliojärvi, map sheet 3323 02 7054.30/469.81.
5. Basic tuffaceous schist (amphibolite). Kiuruvesi, 2.5 km southwest of church, map sheet 3323 08 7059.60/480.10.
6. Intermediate tuffaceous schist. Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.38/466.25.
7. Uralite tuffaceous schist (uralite porphyrite). Kiuruvesi, Laukkala, map sheet 3323 01 7041.38/467.70.
8. Plagioclase tuffaceous schist (plagioclase porphyrite). Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.38/466.32.
9. Quartz-bearing amphibolite. Kiuruvesi, Toiviaiskylä, Lake Juurikka, point 4, anal. A. Heikkinen (Savolahti 1966, p. 350, Table 1).
10. Uralite porphyrite. 1 km west of the town of Hämeenlinna, anal. A. Simonen (Simonen 1948, p. 22, Table II, 1).

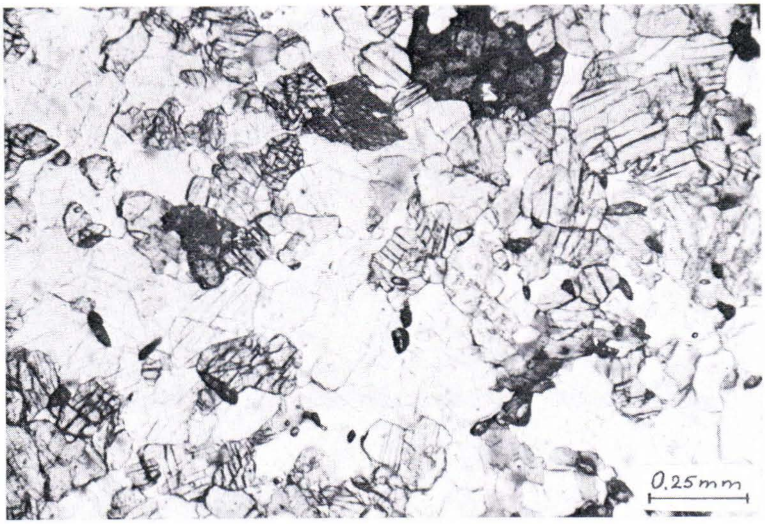

Fig. 6. A light green band of amphibolite with abundant diopside. Photomicrograph, nicols not crossed. Kiuruvesi, Sulkava, map sheet 3323 07 7042.72/487.72.

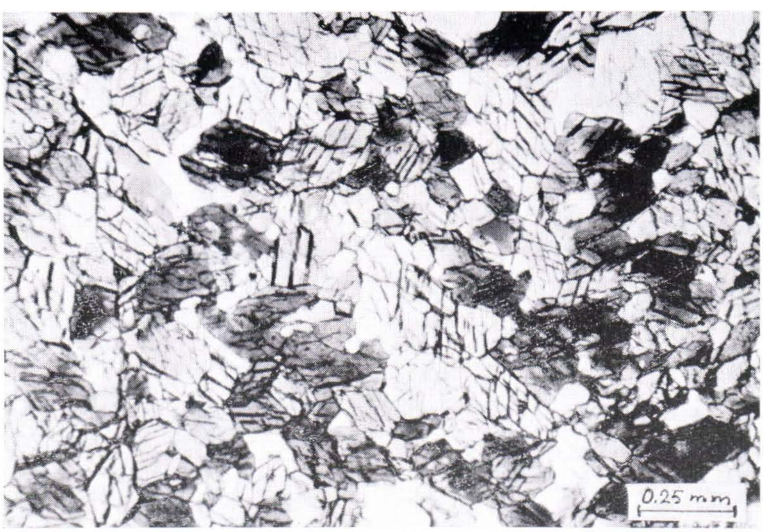

Fig. 7. A dark band of amphibolite composed mainly of hornblende. Photomicrograph, nicols not crossed. Kiuruvesi, Sulkava, map sheet 3323 07 7042.72/487.72.

Amphibolite has been encountered northwest of Lake Koivujärvi and in a zone about 2 km north of the northern shore of the lake. In both localities the amphibolite is a hornblende diopside variety, but northwest of the lake it contains hornblende gneissose and gabbroic features. The other amphibolite mentioned is a banded, rather dark and folded hornblende diopside variety that in its eastern portion exhibits some narrow bands of uralite porphyrite and minor mineralisation. West of the lake there are a few schlierens of amphibolite in migmatitic mica gneiss.

Banded hornblende-diopside amphibolite occurs east of Lake Luupuvesi, where it seems to form a fold with an axial plunge of 30—40° WSW. This zone continues to the north.

At Tuomijoki and around Juurikkajärvi small schlieren of amphibolite are found in cordierite-garnet-anthophyllite rock, leptite, pyroxene diorite and pyroxene quartz diorite.

The basic amphibolitic tuffaceous schists are fine-grained, distinctly oriented, black green rocks with lighter-coloured bands. The light green bands contain abundant diopside (Fig. 6) and the dark bands hornblende (Fig. 7). There are no marked boundaries between the bands, whose average width is from 3 to 5 cm. Light-coloured bands of leptite with quartz, plagioclase and cummingtonite are often met with in association with the amphibolites. The banding of the leptites and amphibolites is more conspicuous and of more varied width than that of the other rocks mentioned.

Table 2

Mineral composition of amphibolites by volume percent.

	1.	2.	3.	4.	5.	6.	7.
Plagioclase	28.5	21.1	10.2	56.0	39.3	25.6	45.6
Hornblende	62.5	72.1	5.0	5.2	6.4	61.5	49.7
Diopside	0.7	—	59.0	32.0	51.5	—	—
Quartz	1.4	—	—	—	—	—	1.3
Cummingtonite					—	7.5	
Epidote	—	—	11.4	—			
Opaques	5.8	4.5	3.7	2.7	2.8	5.4	2.1
Titanite	—	0.9	6.2	1.2			
Apatite	—	0.9	0.7	0.6			
Carbonate	—	—	3.0	—			
Other minerals	1.1	0.5	0.8	2.3			1.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1—4. Diopside amphibolite: hornblende-rich band (1 and 2), diopside-rich band (3), and plagioclase-rich band (4). North of Lake Hautajärvi, Kiuruvesi (Savolahti and Marjonen 1966, p. 205, Table 1).

5—6. Diopside amphibolite: diopside-rich band (5) and hornblende-rich band (6). North of Lake Hautajärvi, Kiuruvesi (Savolahti and Marjonen 1966, p. 210, Table 6).

7. Quartz-bearing amphibolite. Lake Juurikka, Toiviaiskylä, Kiuruvesi (Savolahti 1966, p. 378). The other minerals are apatite, epidote, titanite and potassium feldspar. The pyroxene relicts have been included in the hornblende.

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Fig. 8. Elongated poikiloblastic laths of hornblende-cummingtonite. Photomicrograph, nicols not crossed. Kiuruvesi, north of Majoonjärvi, map sheet 3323 07 7048.92/489.04.

According to the description by Savolahti and Marjonen (1966, pp. 204—206), the diopside amphibolites north of Hautajärvi "are banded, and the bands are foliated and broken up. The thickest bed consists of three different types of rock: 1) greenish gray stretches of rock containing diopside in abundance, 2) blackish gray stretches containing abundant hornblende, and 3) rock of a coarser than normal grain containing garnet, diopside and considerable amounts of plagioclase". The mineral compositions of the diopside amphibolites are given in Table 2.

In thin section the basic tuffaceous schists appear to be very heterogeneous rocks in which the following varieties can be distinguished:

1) hornblende and hornblende-cummingtonite amphibolites
2) pyroxene amphibolites and
3) garnet-bearing amphibolites.

A fourth group consists of quartz veins and dykes composed of silicified amphibolites.

These various types of amphibolites usually occur together, imparting a banded appearance to the rock. The main minerals of all the amphibolites in the area include varying amounts of plagioclase and hornblende.

Plagioclase occurs in the amphibolites as fresh crystals whose An content varies from An_{43} to An_{58}. Rare higher An contents have been noted in discrete crystals. In granitised amphibolites the An content is even lower, for example

$An_{c.27}$ north of Koivujärvi. The composition of plagioclase does not differ in the various bands of hornblende-diopside amphibolites, and is not apparently affected by the amounts of hornblende and cummingtonite.

The hornblende ranges in colour from pale yellow-green or pale yellow to green or blue-green. In the cummingtonite-bearing rocks it is homoaxially intergrown with cummingtonite and forms in laths a green margin to the colourless or very slightly green-hued cummingtonite. The hornblende-cummingtonite is encountered as elongated poikiloblastic laths (Fig. 8), with varying amounts of hornblende and cummingtonite. Polysynthetic twinning is common in the cummingtonite.

The pyroxene in the amphibolites is generally diopside-augite whose $c \wedge z$ ranges from 37° to 45°. It is slightly greenish and the margins of the crystals have often altered into hornblende, especially between the hornblende- and diopside-bearing bands. North of Sulkavanjärvi the amphibolite contains hypersthene that is faintly pleochroic when in association with diopside and hornblende.

The garnets in the amphibolites seldom amount to more than accessories and are inconsistent in occurrence. They are most abundant in the amphibolite inclusions and intercalations in the cordierite-garnet-anthophyllite rocks.

Only minor quartz is present in the amphibolites themselves, but it forms secondary narrow veins, often parallel to the schistosity, and small clusters in the amphibolite. Quartz grains such as these only exhibit faint undulation.

The most common accessory in the amphibolites is titanite, either as wedge-shaped crystals or as leucoxene grains with opaque cores. It is most abundant in skarn-bearing portions, but it is also often encountered in addition to epidote in the cleavages of hornblende. Other accessories are sparse apatite and local carbonate. Zircon is rare, occurring only in inclusions in hornblende. The opaques are represented by sulphide and oxide minerals that are locally present as disseminations of such abundance that the surface of the amphibolite has a rusty appearance, and in thin section reveals a meshlike network of black dots. Biotite is an alteration product of hornblende.

The chemical compositions of amphibolites from three typical sites in the investigation area are given in Table 1, analyses 3—5.

An indication that the Kiuruvesi amphibolites are derived from volcanic tuffs is the layered structure with sedimentary intercalations. Formations such as these are considered to be the result of deposition under the sorting influence of water. These tuffaceous schists are generally heterogeneous and in some localities, for example at Honkaperä and north of Hautajärvi, they also contain agglomeratic variations.

The Kiuruvesi amphibolites in the vicinity of the investigation area may be compared with the basic, partly amphibolite-like tuffites of the supracrustal series in the environment of the Pyhäsalmi ore deposit described by Helovuori (1964).

The Kiuruvesi amphibolites also have affinity with rocks analogous to the amphibolites of the Venetpalo region reported by Hautala (1968). The amphibolites in both regions exhibit similarities in their mineral compositions, although Hautala uses a different classification.

The hornblende-diopside amphibolites at Kiuruvesi resemble the diopside amphibolites of the Haukivesi area on the same Raahe—Ladoga line. According to Gaál and Rauhamäki (1971, p. 276), the common type "is distinctly bedded and schistose, dark green in colour and with light green diopside-skarn intercalates". The main minerals of the layered diopside amphibolites are the same as in the hornblende-diopside-banded amphibolites of Kiuruvesi, that is plagioclase (An_{40-65}), hornblende and diopside. The same accessories, carbonate, titanite, biotite, apatite and sulphide minerals, are also encountered in both areas.

According to Wilkman (1938, p. 165), the plagioclase in the so-called Kuopio amphibolites is of intermediate composition (An_{45-55}) as it is in the amphibolites of the Kiuruvesi area; in the Kuopio amphibolites green hornblende and some biotite and epidote are the only dark minerals, and a little quartz is commonly present.

The hornblende-cummingtonite amphibolites of the Kiuruvesi area display the same features as do the amphibolites of the Aulanko area in south Finland described by Simonen (1948, pp. 38—39) as cummingtonite-amphibolites and cummingtonite-almandine amphibolites, to name but two. At Aulanko, the plagioclase is labradoritic (An_{40-50}), and thus almost analogous in composition to that in the amphibolites at Kiuruvesi. The elongated poikiloblastic laths in the hornblende-cummingtonite of the Kiuruvesi amphibolite may possibly be compared with the cluster-forming cummingtonite needles in the amphibolite of the Aulanko area, which according to Simonen, are probably relicts of earlier uralite phenocrysts. He states (1948, p. 43) that the cummingtonite amphibolites had altered from basic volcanites during magnesia metasomatism, when primary hornblende was altered into cummingtonite; the plagioclase was not attacked.

Some of the Kiuruvesi amphibolites are leptite-banded like the diopside amphibolites described by Eskola (1914, p. 118) from the Orijärvi region, which are distinguished from the corresponding amphibolites at Kiuruvesi by the presence of microcline in addition to plagioclase ($An_{c.60}$). Eskola (1914, p. 119) has written that the diopside-amphibolites of the Orijärvi region "are of a sedimentary origin and that they have originated by the alteration by metamorphism of a series of calcareous shales, probably mingled with volcanic materials". Comparison of the Kiuruvesi amphibolites with the amphibolites of volcanic origin at Orijärvi (Eskola 1914, pp. 97—108) indicates similarity of mineral composition, the Orijärvi amphibolites consisting generally of plagioclase (labradorite-bytownite), hornblende, titanite, faintly undulating quartz and rare apatite. The chemical composition of the Orijärvi amphibolites (Eskola 1914, pp. 100 and 104) is higher in SiO_2 and Al_2O_3 than are the Kiuruvesi amphibolites. The abundances of iron, magnesium and calcium display the same variations in the amphibolites of both areas.

Uralite tuffaceous schists (uralite porphyrites)

Uralite tuffaceous schists are closely associated with amphibolites. Uralite porphyrite is encountered east of Koivujärvi by the side of the road at Koivujoki, Laukkala. The dark hornblende amphibolites are characterised by intermediate and basic layers containing uralite phenocrysts (Fig. 9). The uralite grains are from 2 to 7 mm in size and many of them exhibit a comparatively well-preserved primary crystal form (Fig. 10). The chief constituents of the uralite porphyrite are plagioclase, hornblende and biotite. The accessories are apatite, titanite and opaques. The plagioclase, An_{57-64}, is well-preserved and with conspicuous zonal texture. The hornblende occurs as discrete large grains or clusters of laths in a fine-grained plagioclase-hornblende-biotite groundmass. The shape of the crystals is visible in the large grains, and some of them display twinning according to the augite law. Pleochroism in the hornblende is yellow-green to green and $c \wedge z = 18°$. The biotite occurs as small scales that vary in colour from light brown to red-brown and is partly an alteration product of hornblende. Uralite porphyrite that should probably be included in the same zone as the uralite has been met with in the basic tuffaceous schist (amphibolite) north of Koivujärvi. In this rock the clusters of uralitic hornblende grains have been sheared into broken elongated laths. Chalcopyrite, pyrite, sphalerite and pyrrhotite are present in the narrow joints of the rock and also as a low-grade dissemination throughout the rock.

At Niemiskylä uralite porphyrite occurs in the basic layers of the metamorphosed tuffaceous beds. Acid and basic layers alternate in the rock without clear boundaries. In some parts of the rock the clusters of uralitic hornblende have been stretched out in the direction of lineation.

The chemical composition of the uralite porphyrite at Laukkala is given in Table 1, analysis 7. The essential difference between the chemical compositions of the basic tuffaceous schists (amphibolites) and the uralite porphyrite is the higher contents of K and Al in the latter.

The Kiuruvesi uralite porphyrite displays tuffitic features. Successive eruptive phases are indicated by the phenocrysts of uralite in several thin and indistinctly bounded layers. Phenocrysts of augite have sunk into the ash, which upon consolidation has become conform with the uralite grains that have often preserved the crystal form of augite. The alternation of lava beds also gives

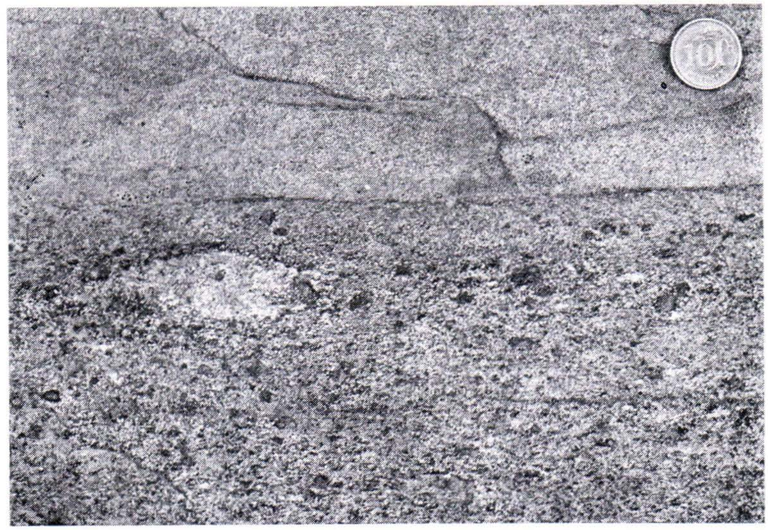

Fig. 9. Uralite phenocrysts in an intermediate tuffaceous layer. Kiuruvesi, Laukkala.

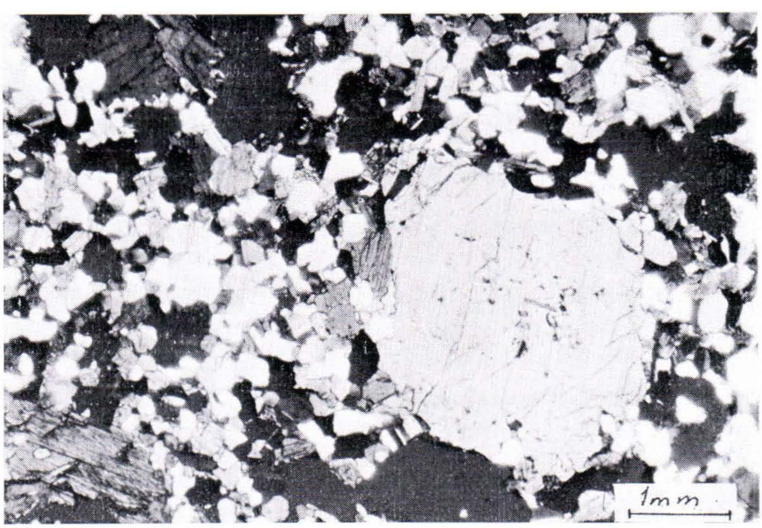

Fig. 10. An uralite phenocryst in uralite tuffaceous schist. Photomicrograph, nicols crossed. Kiuruvesi, Laukkala.

rise to a layered structure, as in the alternation of uralite porphyritic and uralite-plagioclase porphyritic lava beds reported by Neuvonen (1956, p. 9) from the Forssa map-sheet area.

Tuffitic uralite porphyrites have also been encountered elsewhere in Finland. According to Simonen (1948, p. 13), most of the uralite porphyrites in the Aulanko area can be considered "as basaltic lavas, but also some inhomogeneous varieties are met with, indicating a tuffitic mode of origin". Consequently, in the present context the rock selected for comparison is an uralite porphyrite from west of Hämeenlinna; the chemical composition is given in Table 1, analysis 10. Seitsaari (1951, p. 18) has pointed out that also in the Tampere region basic porphyritic tuffites with uralite and plagioclase phenocrysts are widely distributed in connection with basic porphyrites of the same composition.

One explanation for the formation of schist such as this, which is derived from tuff and contains phenocrysts, is that as the crystallising lava erupts with explosive force the crystals are liberated and land as ejecta among the rest of the tephra. According to Ollier (1969, p. 68), "tuffs are distinguished as crystal tuff if well-formed crystals predominate". Augite crystal tuffs are found on Vesuvius, Monte Rossi (a parasitic cone on Etna), and Muhavura in Uganda (Ollier 1969, p. 68).

Plagioclase tuffaceous schist (plagioclase porphyrite)

Plagioclase tuffaceous schist, which occurs as a narrow bed a few metres thick between the basic and acid tuffaceous schists at Vantunmäki, Honkaperä, is distinguished from the darker amphibolite and more light-coloured acid tuffaceous schist by its grey colour. The fine-grained (grain size less than 0.4 mm) tuffaceous matrix is mottled with clusters of plagioclase grains from 1 to 8 mm in size (Fig. 11). On the surface of the rock these clusters appear as individual phenocrysts with rounded edges, but under the microscope they are revealed to be combinations of several plagioclase grains (Fig. 12). The plagioclase in the clusters and in the matrix is andesitic, An_{37-40}, with slight zoning, and contains some sericite as an alteration product. The matrix is composed not only of plagioclase but also of diopside-augite and hornblende, which are unevenly distributed in the rock. The diopside-augite ($c \wedge z$ = c. 47°) is faintly green in pleochroism. In some of the grains hornblende is readily visible as an alteration product; it shows pleochroism in a pale yellowish to blue-green colour and is largely primary. Its laths have well-defined margins and no alteration products. The accessories are appreciable titanite, either as dark brown wedge-like crystals or rounded grain, clusters of epidote in association with the dark minerals, and quartz. The rock displays a granoblastic texture and distinct orientation.

Fig. 11. Plagioclase tuffaceous schist. Kiuruvesi, Honkaperä, Vantunmäki.

Fig. 12. Plagioclase aggregate in plagioclase tuffaceous schist. Photomicrograph, nicols crossed. Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.38/466.32.

The chemical composition of the forementioned plagioclase tuffaceous schist is given in Table 1, analysis 8. It does not differ essentially from the chemical compositions of the basic tuffaceous schists in the same table.

The chemical compositions of the basic and intermediary volcanogeneous rocks of Kiuruvesi are largely similar to those of the lavas and tephra in Iceland (cf. Sigvaldason 1969). Similarity has also been noted with the chemical composition of the tholeitic basalts and andesine basalts from the Erta Ale volcanic range in Ethiopia (Barberi and Varet 1970). The Kiuruvesi amphibolites are characterised by their high iron content, which in analyses 3 and 5 (Table 1) almost reaches that of ferrobasalt. "Intermediate rocks having a strong petrographic affinity with the andesine basalts but characterised by high iron content (total FeO higher than 15 %), have been called 'ferrobasalts' " (Barberi and Varet 1970, p. 12).

Acid tuffaceous and tuffite schists (leptites)

In many places acid schists rich in quartz and feldspar are closely connected with the volcanic complex, and it is often difficult to determine whether they are of volcanic or sedimentary origin. The quartz-feldspar-rich schists of the Kiuruvesi area, however, abound in features suggesting their volcanic origin, probably from acid ash, although it is true that some sedimentary material is also present. In the present study these rocks are entitled leptites.

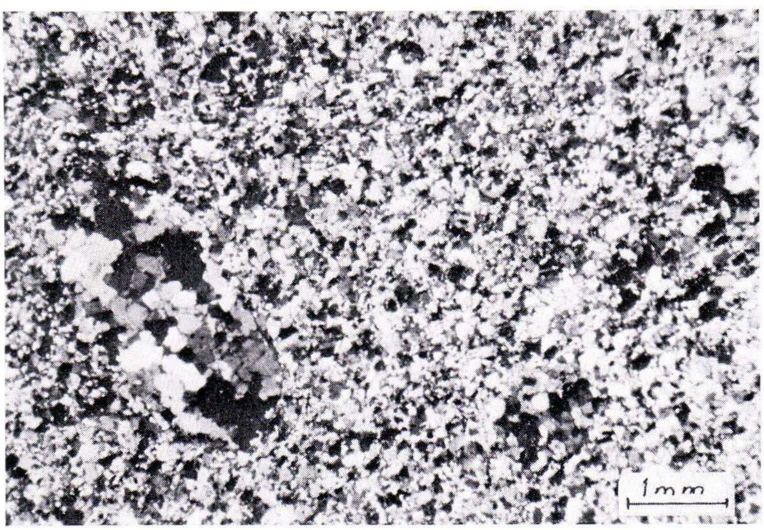

Fig. 13. Acid lapilli tuff schist (leptite). Photomicrograph, nicols crossed. Pyhäjärvi (county of Oulu), Äyhynkorpi, map sheet 3323 03 7069.08/460.90.

Fig. 14. Acid tuffaceous schist (leptite). Kiuruvesi, Honkaperä, Vantunmäki.

The leptites are pale pink or pink-grey in colour, except for the hornfelsic fine-grained and compact varieties, which are either grey or contain light and dark grey bands. Typical of these rocks is the light-coloured weathering surface, 5 to 10 mm thick. In coarse types the grain diameter is less than 0.5 mm, but usually it is less than 0.01 mm. The texture is granoblastic. At Äyhynkorpi small lapilli are visible (Fig. 13), as well as biotite-chlorite-sericite-bearing "flames", from 5 to 20 mm in length, parallel to the schistosity.

The chief constituents of the leptites are quartz and plagioclase. Sparse biotite is also present, as is cummingtonite in the leptite bands associated with the basic tuffaceous schists (amphibolites). Quartz occurs as intensely deformed grains, often with rough margins. The composition of plagioclase varies from oligoclase to andesine (An_{18-45}). At many sites the plagioclase grains are tarnished with sericite and saussurite. There is some myrmekite in the grains in contact with the scarce potassium feldspar, which is flame-perthitic microcline exhibiting hatched texture. The grains are of smaller diameter than are those of plagioclase. If biotite is present, it forms around the quartz and plagioclase grains small scales that are tattered and frequently chloritised. Cummingtonite occurs as small laths with twin lamellae and green-tinged margins. Common accessories are the ore minerals pyrite and pyrrhotite, epidote, titanite (often leucoxene), muscovite-sericite and apatite. Some carbonate is encountered in the leptites associated with the skarns. Noteworthy is the absence of zircon, which "is a common accessory mineral in many sediments, often surviving more than one cycle of weathering and sedimentation" (Deer, Howie and Zussman 1962, p. 65).

Leptites are met with in the nothwestern section of the map area as narrow zones bounding Pyhäjärvi and Kiuruvesi. They are closely associated with volcanic amphibolites and agglomerates. Wilkman (1931, p. 64) postulates that these leptites are of sedimentary origin. At Vantunmäki, Honkaperä, leptite (Fig. 14) occurs between volcanic tuff schists and mica gneiss, and gradually passes into mica gneiss.

In the Koivujärvi area skarn and basic tuffaceous schist occur in association with leptites. Wilkman (1938, pp. 32 and 46) considers these leptites to be quartzites, and Talvitie (1959) has defined them more precisely as arkose quartzites. They are fine-grained and light-coloured rocks with quartz and plagioclase (An_{25-50}) as main constituents. Some biotite and muscotive are also present, and the accessories are apatite, titanite, potassium feldspar and local garnet.

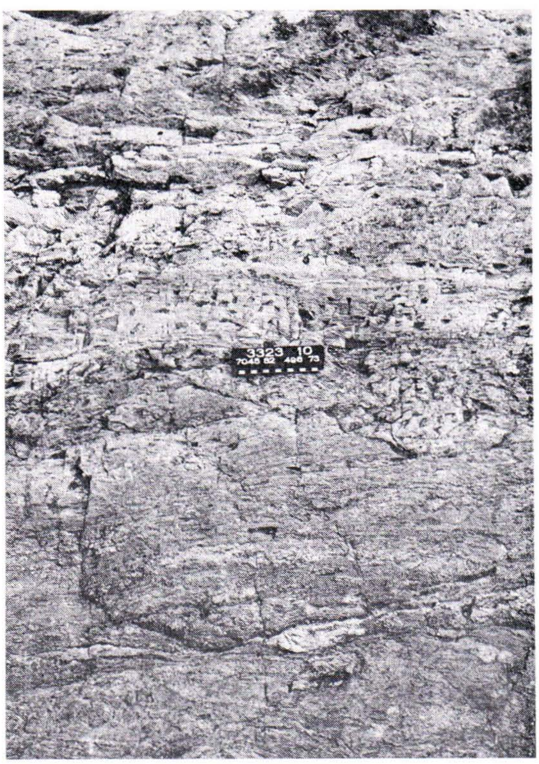

Fig. 15. Leptitic schist with volcanic material as weathering products. Iisalmi, Riitamäki, map sheet 3323 10 7045.82/496.73.

Zircon is rare, and chlorite, epidote and sericite constitute the alteration products. Pyrite and pyrrhotite often form disseminations. Skarn-banded leptite is also encountered north of Lavapuro and west of Niemisjärvi; here too sulphide minerals are present as dissemination, and cordierite-bearing rocks are closely associated with the leptites.

Acid leptitic schists are further encountered east of Riitamäki, in the south-eastern part of the area, as a bed several metres in thickness (Fig. 15), between mica gneiss. They are rocks of heterogeneous grain size, whose layered structure is emphasised by graded bedding, disrupted it is true by intense tectonic movements. They would seem to be of sedimentary origin, despite the intercalations of tuffitic microporphyritic portions. In contrast to the other leptites, these show abundant potassium feldspar.

Savolahti (1966, p. 372) has determined the mineral composition in percentages by volume of one specimen of quartz-feldspar schist from the environment of Juurikkajärvi:

Quartz	46.1	
Hair-perthite	36.7	
Microcline	1.2	
Plagioclase (An_{14})	12.1	
Biotite	3.1	
Other minerals	0.8	(opaques, garnet, zircon and apatite)
	100.0	

This rock differs from those described earlier in that it is associated with cordierite-anthophyllite rocks. Savolahti (1966, p. 383) is of the opinion that the rock is of sedimentary origin as is suggested by the presence of zircon, the abundance of potassium feldspar and the composition of plagioclase. Volcanic leptite is also encountered in the investigation area as felsite-like inclusions in cordierite-bearing rocks and as fragments in dioritic rocks.

The chemical compositions of the acid tuffaceous and tuffite schists (leptites) are given in Table 3. Noteworthy is the high alkali content, which ranges from 6.5 to 4.5 percent. The content of Na_2O is comparatively high, conspicuously exceeding that of K_2O. Studies on the leptites of Finland indicate the possibility that the types rich in sodium are more common than are those rich in potassium. Seitsaari (1951, p. 21) points out, however, that the likelihood of metasomatic changes in the rocks investigated must not be discounted. Potassium has certainly migrated in the acid schists. The total chemical compositions of the acid tuffaceous and tuffite schists in the area approach those of the rhyolitic lavas given by Gorshkov (1970).

Table 3

Chemical compositions of acid tuffaceous and tuffite schists (leptites). Analyses 1—5 are from the Kiuruvesi investigation area.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	77.90	75.69	75.98	74.85	77.73	75.02	71.00
TiO_2	0.09	0.20	0.15	0.36	0.15	0.15	0.61
Al_2O_3	11.42	12.15	11.95	11.28	11.02	12.84	12.45
Fe_2O_3	1.41	0.95	0.17	0.70	1.45	0.45	0.83
FeO	1.10	2.80	2.56	2.80	1.12	1.48	4.10
MnO	0.02	0.06	0.04	0.08	0.03	0.04	0.05
MgO	0.25	0.83	0.51	1.01	0.21	0.42	1.68
CaO	0.90	2.24	1.92	1.41	3.85	1.20	2.28
Na_2O	5.22	4.28	3.88	3.16	4.34	6.00	3.38
K_2O	1.30	1.25	0.70	1.86	0.27	1.20	1.34
P_2O_5	0.05	0.07	0.02	0.08	0.01	0.23	0.43
H_2O+	0.96	0.70	0.70	0.84	0.36	0.73	1.90
H_2O-	0.21	0.15	0.12	0.18	0.09	0.26	0.06
	100.83	101.37	98.70	98.61	100.63	100.02	100.09
Cu ppm	16	33	45	0	9		
Zn ppm	9	95	130	76	13		
Ni ppm	24	31	19	15	15		
Pb ppm	17	20	18	27	6		
S ppm	92	1 290	10 818	171	214		

The samples and their location on the map

1. Acid tuffaceous schist (leptite). Pyhäjärvi (county of Oulu), Äyhynkorpi, map sheet 3323 03 7069.08/460.90.
2. Acid tuffite schist (leptite gneiss). Pyhäjärvi (county of Oulu), Honkaperä, Hanskankangas, map sheet 3323 03 7068.02/464.40.
3. Acid tuffaceous schist (leptite). Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.38/466.35.
4. Acid tuffite schist (veined leptite gneiss). Kiuruvesi, Honkaperä, Vantunmäki, map sheet 3323 03 7065.40/466.36.
5. Acid tuffaceous schist (leptite). Kiuruvesi, Tuomijoki, map sheet 3323 04 7045.68/474.57.
6. Quartz-feldspar schist. Ylöjärvi, southwest of Kiviniemenlahti, anal. H. B. Wiik (Simonen 1952, p. 65, Table V, 4).
7. Leptite. The Aulanko region, 1.5 km west of Ilamo, anal. P. Ojanperä (Simonen 1948, p. 22, Table II, 4).

The quartz-feldspar schists or acid tuffites of the Hämeenlinna area described by Simonen (1948 and 1949, pp. 12—13), as well as the acid tuffite schists described by Seitsaari (1951, pp. 20—21) and Simonen (1952, pp. 12—14) from in and around Tampere bear a great resemblance to the leptites of the Kiuruvesi area. Simonen (1952, p. 14) considers that the quartz-feldspar schist at Kiviniemenlahti, Ylöjärvi, is derived from the sedimentary product of fine volcanic ash. The chemical composition of the rock is given for comparison in Table 3, analysis 6, as is that of the leptite from the Aulanko area (analysis 7), which, according to Simonen (1948, p. 18), probably represents an acid pyroclastic sediment. The analyses of both samples show a high alkali content, and Na_2O clearly in excees of K_2O. The analyses of the acid tuffaceous and tuffite schists (leptites) from Kiuruvesi and the schists taken for comparison reveal that the other elements are the same in both.

The leptites of the Kiuruvesi area also differ from those of southwest Finland, mest of which Simonen (1953) has inferred to be of sedimentary origin. These rocks are characterised by an excess of alumina, and are often clearly layered. In the chemical compositions of the leptites from southwest Finland the K_2O content generally markedly exceeds that of Na_2O (cf. Simonen 1953, pp. 50—51, Table VII). The high abundance of Al_2O_3 is typical of metamorphosed weathering sediments.

Hietanen (1947, pp. 1028—1029) divides the leptites of the Turku district in southwest Finland into volcanic leptites, probably tuffs or weathering products of tuffs and lavas, and sedimentary leptites. Accessory zircon seems to be absent from the mineral description of the volcanic leptites just as it is from that of the leptites derived from tuff in the Kiuruvesi area. The sedimentary leptites contain, in addition to quartz and plagioclase, abundant microcline and biotite, but no hornblende. The accessories are magnetite, titanite, apatite and zircon. Cummingtonite as amphibole occurs in association with the basic volcanites in the volcanic leptites of Kiuruvesi.

According to Salli (1971, pp. 9—13), the volcanic quartz-feldspar schists (leptites) of Pihtipudas are interlayered with volcanic rocks, whereas the sedimentary quartz-feldspar schists (meta-arkose or arkose) are encountered in the same localities as sedimentogeneous rocks. This observation is also true of the leptites in the Kiuruvesi area. The leptitic schist of Riitamäki is encountered in association with sedimentary mica gneiss and it contains volcanic material as weathering products.

The leptites of the Kiuruvesi area differ from those of central Pohjanmaa, which around Ylivieska and Sievi are blastoporphyritic and hälleflinta-like leptites (Wilkman 1931; Saksela 1933, pp. 15—17) probably derived from lavas.

In the immediate vicinity of the investigation area leptites are encountered in association with rocks of the Pyhäsalmi mine (Helovuori 1964) and in the schists mantling the dome of Venetpalo at Kärsämäki (Hautala 1968). At both sites, as at Kiuruvesi the leptites are associated with basic volcanites.

The volcanic rock association from basic lavas to acid tuffites at Vantunmäki, Äyhynkorpi and Lohva (beyond the map area) reveals volcanic activity similar to that reported by Barberi and Varet (1970) from the Erta Ale area in Ethiopia. They describe the evolution as follows (*op. cit.*, p. 66): "The fissure activity has produced only the most basic lavas, i.e. normal basalts . . . The first products of the shield volcanoes are basic lavas. Then, as the volcano develops, the first slightly more advanced members, andesine basalts, begin to appear. The most differentiated lavas of this stage are iron-rich basalts and some dark trachytes . . . The most advanced products of the whole series, i.e. dark trachytes to rhyolites, are found only in the usually more evolved central volcanoes, where a magmatic reservoir does, or did exist". There are indications of subaqueous basaltic flow in the basic lavas of the Kiuruvesi area. The Vantunmäki, Äyhynkorpi and Lohva lavas probably represent fissure eruption, and the source of the volcanic products that cover the lavas may even be shield and central volcanoes. Central Pohjanmaa has obviously been the site of central volcanoes, and it is here that the acid rhyolitic lavas are encountered. At Kiuruvesi only ejecta and pyroclasts are met with. Rhyolitic and basic tuffs mark a period of contemporaneous explosive volcanic activity.

Sedimentogeneous rocks

The gradation from volcanics into sediments

Migmatised mica and hornblende gneisses occur as broad zones between Koivujärvi and Tuomijoki, between Korpijoki and Kiuruvesi, and from there on to the area between Sulkavanjärvi and Kotajärvi. They are also encountered in the Luupuvesi—Haapajärvi area and as narrow patches scattered among other rocks throughout the investigation area.

The volcanogeneous rocks grade into sedimentogeneous rocks. As a rule, there is no clear boundary between the beds of mica gneiss and hornblende gneiss. Hornblende gneiss may be an essential constituent of the areas occupied by mica gneiss, and vice versa. Both display migmatisation and so their readily recognizable primary structures are only distinguished with difficulty. The emplacement into these gneisses of plutonic material as narrow dykes and veins parallel to the schistosity has imparted a veined gneiss structure to the rocks. The veins often form ptygmatic folds. Furthermore, quartz bodies from 1 to 10 cm in diameter and elongated in the direction of schistosity are encountered in many places in the gneisses, as are calc-silicate layers twisted into z-shapes and segregated as boudinages (Fig. 16). Graphite-bearing intercalations have been met with here and there. The gneisses are cut with sharp contacts by aplite and pegmatite veins as well as by diabase dykes, and brecciated by infracrustal granites and diorites that locally exhibit fragments of gneisses as inclusions.

Mica gneisses

The main rocks of the forementioned area are mica gneisses of heterogeneous mineral composition: a) biotite plagioclase gneisses, b) mica gneisses containing aluminium-rich porphyroblasts (almandine and sillimanite), and c) biotite hornblende gneisses with conspicuously less hornblende than biotite.

Fig. 16. Basic twisted and segregated calc-silicate layers as boudinages in migmatitic mica gneiss. Kiuruvesi, east of Sulkavanjärvi, map sheet 3323 07 7040.40/487.60.

Biotite plagioclase gneisses

The majority of the mica gneisses are typical biotite plagioclase gneisses either devoid of or poor in potassium feldspar. The grain size varies, being commonly from 0.5 to 2 mm in diameter. The gneisses display distinct schistosity parallel to which are alternating light-coloured quartz-feldspar-rich bands and narrower dark-coloured biotite-rich bands. In the vicinity of acid tuffaceous and tuffite schists (leptites) the biotite plagioclase gneisses are generally deficient in biotite.

The rock is granoblastic in texture. The main minerals are quartz, plagioclase, biotite and local potassium feldspar, the latter, however, in smaller amounts than plagioclase. The quartz is intensely undulating and its margins often exhibit a mortar-like deformation. The plagioclase is generally fresh despite the local occurrence of minor sericitisation and saussuritisation. It varies in composition from An_{25} to An_{40}, the average being $An_{c.30}$. In the deformed grains biotite has grown like a weed into the fracture joints. Myrmekite and antiperthite are encountered in the plagioclase in the vicinity of potassium feldspar grains. The biotite is strongly pleochroic from light brown and yellow-brown to dark brown. Tattered scales with very small inclusions of dark-rimmed zircon are often present. Small grains of titanite are locally visible in the cleavage of the scales. Potassium feldspar, when present, is microcline with cross-twinning. Orthoclase has been encountered in one sample only from Sulkavanjärvi. There is appreciably less potassium felspar than plagioclase, and thus the term biotite plagioclase gneiss is used to emphasize the plagioclase content in the mica gneiss. Accessories are apatite, zircon, titanite, epidote and muscovite, with graphite, oxide and sulphide minerals as opaques.

Porphyroblastic mica gneisses

Almandine and sillimanite occur in the mica gneisses as aluminium-rich porphyroblasts. Almandine, which has a strong affinity with the mica gneisses in the vicinity of the cordierite-bearing rocks, occurs as fractures and poikiloblastic crystals, from 2 to 15 mm in diameter, and containing inclusions of quartz, biotite and opaques. In the mica gneisses at Pieni Sulkavanjärvi and Ruotaanmäki (Fig. 17) the sillimanite appears porphyroblastic even to the unaided eye, whereas north of Taipaleenlahti and in the Perhonsiipi area it is encountered as microscopically small porphyroblasts. The occurrence of almandine regularly follows that of sillimanite.

Fig. 17. Garnet and sillimanite porphyroblasts in mica gneiss. Iisalmi, Ruotaanmäki, map sheet 3323 10.

Biotite horblende gneisses

Although a minor hornblende content is quite common in the mica gneisses of the investigation area, it is subordinate to biotite. Hornblende is most abundant in the mica gneisses in the vicinity of amphibolites and hornblende gneisses. These mica gneisses are granoblastic in texture. The hornblende laths are generally tattered, and pleochroic from yellow green to blue green. The plagioclase is usually somewhat more An-rich than it is in the biotite plagioclase gneisses. Epidote is a fairly common accessory; in other respects this rock corresponds to the biotite plagioclase gneisses.

Hornblende gneisses

Hornblende gneisses are encountered as narrow zones and lenses in association with basic tuff schists (amphibolites) and mica gneisses. The boundary between the hornblende gneisses and mica gneisses is far from distinct, and that between the hornblende gneisses and the tuff schists (amphibolites) is often gradual. Stringers of amphibolite are encountered as relicts in the hornblende gneisses. Often, however, these structures are lacking because of recrystallisation in the course of migmatisation.

The hornblende gneisses are dark grey, green-hued and distinctly schistose rocks that often display banding due to the alternation of hornblende- and biotite-bearing layers. The grain size of the rock varies, the average diameter being from 0.2 to 2 mm. Plagioclase is sometimes present as discrete grains of larger than average diameter. Discrete potassium feldspar grains are common in the hornblende gneisses in association with porphyry and pyroxene granites even though potassium feldspar is not one of the main rock-forming minerals. Myrmekite is encountered in the plagioclases in the vicinity of the potassium feldspar grains.

The hornblende gneisses are granoblastic in texture, with plagioclase, hornblende and quartz as chief components. Biotite and cummingtonite are sometimes present in addition to hornblende. The plagioclase is andesine An_{30-40}. The grains are generally fresh, and display conspicuous polysynthetic twinning according to the albite law and to a lesser degree according to the pericline law. The hornblende is pleochroic from pale yellow or yellow-green to blue-green or dirty green. In many places the laths have altered marginally into biotite. Homoaxial cummingtonite is often present in the hornblende laths in the vicinity of volcanic rocks. Quartz grains occur as flattened augen between the other grains; undulating extinction is marked and the margins are commonly fractures. Quartz is also present as secondary veins and lenses. Accessory minerals are epidote, titanite and opaques as well as garnet and small crystals of euhedral apatite in many places. The epidote is commonly encountered as fine-grained clusters in association with hornblende and biotite. Zircon seems to be rare in hornblende gneisses.

The biotite-plagioclase gneisses were originally mainly greywacke-like rocks, but they include more finely assorted sediments mixed with pyroclastic material. The mica gneisses with Al-rich blastoporphyritic textures, however, are suggestive of purer pelitic sediments commonly with a large excess of Al_2O_3. The position of the hornblende gneisses as intercalations in mica gneisses and rocks of volcanic origin together with their mineralogical composition indicates that they were originally intermediary tuffs or sediments derived from the simultaneous deposition of volcanic ash and weathering material. The absence of marls from the bedrock of the investigation area supports the view that the hornblende gneisses are not derived from marly clay.

According to Mäkinen (1916, p. 27), it is possible that the plagioclase gneisses in central Pohjanmaa derive from volcanic ash or mechanically weathered volcanic rocks deposited in water. In the opinion of Wilkman (1931, p. 38), the close relationship of the Kiuruvesi biotite plagioclase gneisses, veined gneisses and hornblende gneisses to effusive rocks and volcanic tuffs confirms the hypothesis that the plagioclase gneisses found here are most likely derived from sedimentary volcanic gyttja or ash.

Black schists and graphite gneisses

Black schists or graphite-bearing schists are scarce in the area. Many of them have been disclosed by electric anomalies. Rocks with a distinct graphite content are encountered in association with the gneiss granite at the western margin of the area northwest of Hirvimäki, between the gabbro and mica gneiss south of Patamäki and in several places in the hornblende-bearing mica gneisses east of Sulkavanjärvi. As Savolahti (1966, pp. 203—204) has pointed out, a graphite content is revealed in the garnet mica gneisses and diopside amphibolites that extend in a zone from northeast of Majoonjärvi to Hautajärvi and from there to Niemiskylä. Random minor graphite contents have also been noted elsewhere among the mica gneisses and amphibolites.

Black schist forms intercalations in biotite plagioclase gneisses and amphibolites. The main minerals are quartz, plagioclase, graphite, biotite and potassium feldspar as well as pyrrhotite and pyrite. Accessory minerals are apatite, titanite (often leucoxene), zircon and muscovite-sericite.

According to Väyrynen (1954, pp. 157—158), graphite-bearing schists are more abundant in the Savo schist area than in Pohjanmaa. In the middle of the province of Savo the graphite schists occur together with biotite plagioclase gneisses, but farther south they favour the gneisses containing Al-rich minerals. Väyrynen (1954, p. 159) has not noted graphite to any degree worth mentioning either in the Al_2O_3-rich schists from the Pyhäntä—Kiuruvesi—Pielavesi zone in the northwestern sector of the Savo schist area or in those in southern Savo.

Rocks of the Vieremä—Haajainen area

Both the geologic map of Central Pohjanmaa at a scale of 1:800 000 published by Mäkinen in 1916, and that of Kajaani at a scale of 1:400 000 produced by Wilkman in 1929 reveal a triangular area of conglomerate-schist at Vieremä. Its southerly tip extends as far as the village of Haajainen in the northeastern corner of the investigation area. This Vieremä—Haajainen conglomerate-schist has also been designated the Salahmi schist area (Väyrynen 1954, p. 153). Other descriptions besides those by Mäkinen (1916, 1917) and Wilkman (1931), include those by Väyrynen (1954) and Savolahti (1965).

The Vieremä—Haajainen conglomerate-schist zone constitutes a depositional series with the following beds from top to bottom:

a) mica schist
b) greywacke schist
c) augen gneiss or augen schist
d) conglomerate

The conglomerate is polymictic, being composed of pebbles of various rock species, and quartz and feldspar grains with a clayey matrix (Fig. 18). The pebbles range in size from one to several cm, and farther north beyond the investigation area they may be as large as 20 cm in diameter. Petrographically these pebbles represent the rock species encountered in the adjacent bedrock, namely aplite granite and gneiss analogous to those in the basement in the east, acid volcanic tuffaceous and tuffite schists (leptites), mica gneisses and mica schists. The fragments in conglomerate are highly schistose and rolled as elongated rods parallel to the lineation. The schist fragments are distinctly chloritised, and some of them may be derived from tuffaceous schists (amphibolites). The acid volcanic schist fragments are fine-grained and compact, pale and dark grey or pink in colour. The larger fragments display faint banding. The quartz and feldspar grains (both plagioclase and potassium feldspar) vary in size, the largest being from 5 to 10 mm. Coarse-grained quartz and feldspar grains are generally mixed in among the other fragments, although they also form interbeds in conglomerate together with psammitic material. The grains are locally deformed into eye-shaped

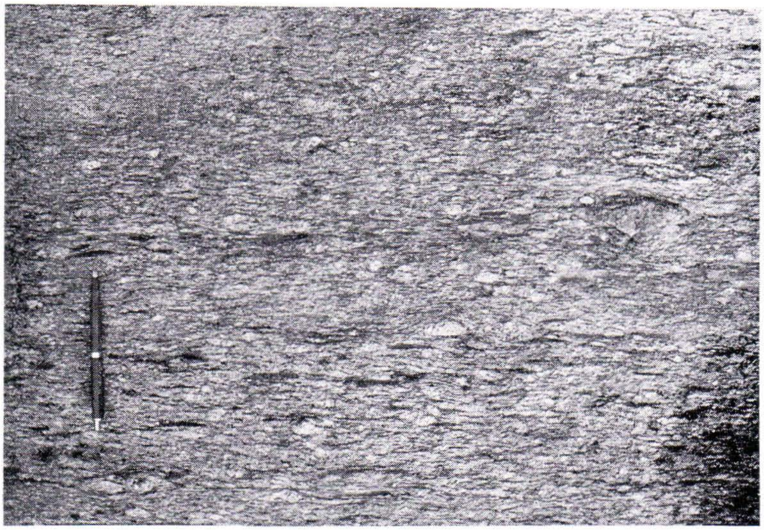

Fig. 18. Polymictic conglomerate. Vieremä, Haajainen, map sheet 3323 11 7059.40/499.80.

lenses, and in the west the conglomerate does in fact grade into intensely deformed augen gneiss or augen schist with conspicuous cataclastic texture. The rock is then also suggestive of mylonite.

Greywacke schist, west of the augen gneiss, is composed of angular quartz and feldspar grains, small random rock fragments, fine-grained clastic quartz and feldspar grains, and clay material. The finest sedimentary material overlying the depositional series constitutes a distinctly schistose mica schist in which psammitic bands from 1 to 2 cm in thickness alternate with pelitic bands from 3 to 4 cm in thickness, as is clearly demonstrated on the way to Vieremä in roadcuts at Petäjäselkä. Locally the mica schist at Petäjäselkä also contains garnet-bearing layers in which the dimensions of the garnets range from 3 to 6 mm. Farther north beyond the investigation area the mica schist exhibits staurolite-bearing layers (Savolahti 1965) from which the large floats containing staurolite at Petäjäselkä may derive. It is not improbable that the source of the floats is the bedrock locally covered by overburden. Staurolite crystals about 1 cm in length occur in the floats in layers from 5 to 10 cm thick. Graded bedding is also visible, the top of the bed being oriented to the west. A strong lineation distinguishes the conglomerate, augen gneiss and basal granite especially along the eastern margin.

According to Mäkinen (1916, p. 105), Wilkman (1931, p. 161), Väyrynen (1954, p. 154) and Savolahti (1965, p. 79), abundant basement formations, conglomerates and augen gneisses occur along the eastern boundary of the Vieremä—Haajainen depositional zone. Previous studies reveal that the rock species encountered along the southern boundary are migmatitic granite-gneiss and migmatite granite (Wilkman 1931, pp. 161—162); eastwards they are migmatite granite and westwards migmatite granodiorite and quartz diorite (Mäkinen 1916, map and 1917, p. 8). All the forementioned researchers are of the opinion that these migmatitic rocks constitute the depositional basement. The conglomerate-schist zone is younger than the surrounding rocks and represents the lowest part of the intensely compressed syncline that was preserved from erosion (Mäkinen 1916, p. 105). According to Väyrynen (1954, p. 154), the schist formation is para-autochthonous and was deposited on gneiss granite. The breccias, mylonites and augen gneisses at Haajainen are the result of shearing against the gneiss granite (Väyrynen 1954, p. 154).

At the southern tip of the Vieremä—Haajainen schist zone, however, the conglomerate has apparently been deposited on the migmatitic mica gneiss, in many places hornblende-bearing, that outcrops in the west. The conglomerate is separated from the aplitic granite and gneiss granite in the east by a tectonic fault that causes a discordance between the conglomerate and granite, and thus the conglomerate does not directly overlie the granite basement. Associated with this fault zone are basic gabbro and peridotic bodies. The Vieremä—Haajainen schist zone appears to be located in a trough (Fig. 32) whose eastern margin can be traced in a line trending N 10° W from the Kiuruvesi—Iisalmi road at Haajainen to Petäjäselkä and from there to Savimäki. Observations indicate that the conglomerate-augen schist bed is about 1 km in thickness. The width of the schist zone in the investigation area is about 3 km.

Carbonate and skarn rocks

No carbonate deposits of economic significance have been found in the area. The carbonate and skarn rocks are in mutual association and form smallish bands and lenses in the leptites and associated migmatitic mica gneisses. Furthermore, narrow bands of skarn some centimetres in width occur in the amphibolites of volcanic origin. In many places these skarn intercalations display boudinated structures.

Wilkman (1931, p. 49) has described an old disused limestone quarry on the southern slope of Kippolanmäki, a hill in Niemiskylä. The quarry is in a SW—NE trending skarn lens about 30×10 m in size that occurs in a migmatitic mica gneiss containing amphibolite schlieren and leptites. Hypersthene-bearing pyroxene quartz diorite and hypersthene-bearing diorite bodies are encountered in the immediate vicinity. The quarry itself is in a wollastonite-bearing metamorphosed limestone that is separated from the migmatite gneiss by a banded skarn formation.

Wilkman (1938, p. 46) and Talvitie (1959) have both described limestone and skarn deposits on an island in Lake Koivujärvi. Carbonate rock occurs as a bed some 2 m in thickness on the island Huutsaari and the skerry to the north of it. Investigations have shown this carbonate to be calcite (Talvitie 1959). The skarns, which form intercalations and lenses in the limestone and leptites, may be several metres in thickness and with a grain size that ranges from coarse to fine.

Skarns are also encountered north of Koivujärvi, where the exposed deposits are from 2 to 3 m in width and are associated with leptites. The surface of the outcrops is rough, and rusty owing to sulphides.

Other sites where skarn bands associated with leptites are met with include the western shore of Niemisjärvi, an area north of Lavapuro and the southern shore of Lake Jynkkä where the skarn bands occur in both leptites and amphibolites.

Minerals typical of the skarn rocks are diopside, tremolite-actinolite, plagioclase and scapolite. Accessories are titanite, epidote, garnet, hornblende, chlorite and opaques that are commonly sulphides.

The diopside ($c \wedge z = 38—41°$) is usually a fine-grained variety but in the coarse-grained skarn of Huutsaari it occurs as crystals up to 4 cm in length. It is often altered marginally into tremolite, which on Kippolanmäki occurs as long black laths (5 to 10 cm) suggestive of anthophyllite. The composition of plagioclase varies from place to place and even locally, ranging from An_{30} to An_{75}. In many of the skarns it has partially altered into scapolite.

The diopside skarn in the southeastern part of Rytkynjärvi displays a curious mode of occurrence. This skarn, of heterogeneous mineral composition, is located between pyroxene granite and pyroxene quartz diorite. Its minerals nestle together as small groups and as discrete crystals in rock whose dominant component is plagioclase. The diopside is fresh and slightly yellowish-green. The plagioclase ($An_{33—38}$) is somewhat scapolitised in the interior of the grains, and together with potassium feldspar and quartz forms veins in the skarn. Locally titanite occurs as abundant crystals from 2 to 15 mm in diameter. Biotite and tremolite-actinolite are accessories interspersed among the diopside grains. Other accessories are carbonate, epidote and sparse opaque minerals and apatite.

At Siikalahti in the southwestern part of Haapajärvi there is a skarn associated with hornblende gneiss and amphibolite that is 50 cm in width and exhibits sharp contacts with the hosts. In mineral composition it is analogous to the Tommonmäki skarn, containing diopside, tremolite-actinolite, plagioclase, titanite crystals and carbonate.

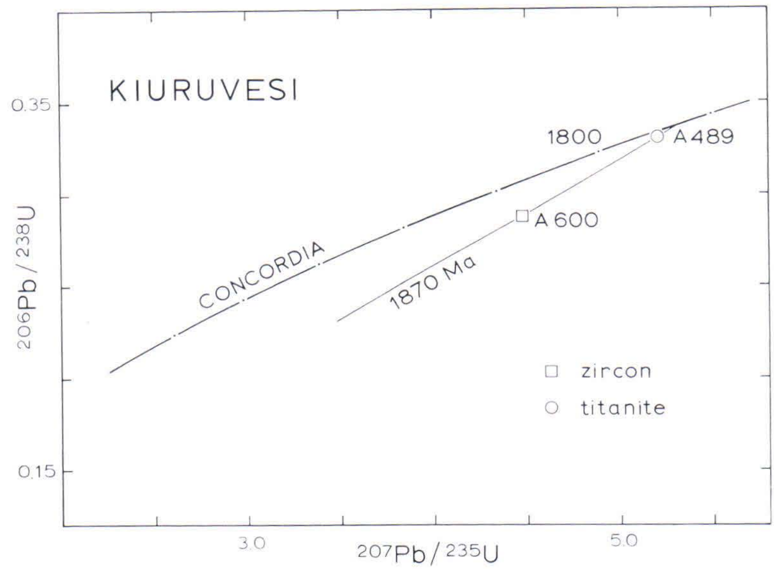

Fig. 19. U-Pb concordia diagram showing the data points of titanite from Rytky (A489) and zircon from Lammasaho granodiorite (A600), Kiuruvesi. The continuous trajectory through data-points is calculated for 1870 Ma.

Table 4

Apparent ages for titanite from Rytky and zircon from Lammasaho, Kiuruvesi.

Sample No.	Location and rock	Mineral	Age (million years) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A489	skarn rock, Rytky, Kiuruvesi	titanite	1 840±16	1 853±9	1 868±6
A600	granodiorite, Lammasaho, Kiuruvesi	zircon	1 630±41	1 726±27	1 843±25

Constants used
238U = 0.155125×10^{-9} a^{-1}
235U = 0.984850×10^{-9} a^{-1}

Table 5

Analytical data (zircon and titanite).

Sample No.	U, p.p.m.	Radiogenic ^{206}Pb, p.p.m.	Isotopic abundance relative to ^{206}Pb: 204	206	207	208
A489	75.6	21.49	0.0650	100	12.38	65.68
A600	1 403	347.0	0.0386	100	11.86	10.10

The prevailing skarn in the area seems to be the diopside-scapolite-titanite variety, which in many places passes directly or by transitions into hypersthene-bearing rocks as do the scapolite skarns described by Holland (1900, p. 127) from the charnockites in India.

Age determinations, made by O. Kouvo at the Geological Survey, for the skarn at Tommonmäki, Rytky, indicate a concordant age pattern for the titanite. The age data of the titanite in skarn are given in Tables 4 and 5 and in Fig. 19.

Cordierite and hypersthene rocks

Cordierite rocks

Cordierite rocks are encountered mainly in a ring that can be drawn through western Sulkavanjärvi — Majoonjärvi — Hautajärvi — Niemisjärvi and its surroundings — northwestern Kalliojärvi and Tuomijoki. Some outcrops have been noted inside the ring, for example in the environment of Juurikkajärvi, and also a few outside it, for example near Lavapuro and at Hallaperä. The cordierite-bearing rocks seem to favour the marginal zones of pyroxene granite massifs and shear zones, where they are allied with pyroxene quartz diorites and diorites. They are also encountered in fractures outside the ring.

Cordierite occurs in mineral assemblages that commonly form narrow bands alternating with other rock types, as a rule amphibolite or mica gneiss and their remetamorphosed products, and thus, the surface of an outcrop shows bands of different rock types of irregular width and sequence (Figs. 20, 21 and 22). The rock as a whole exhibits distinct orientation despite the possible lack of orientation in the minerals of the cordierite-bearing bands. Cordierite has not been encountered as porphyroblasts in the mica gneisses of the investigation area. On the basis of their mineral assemblage the cordierite-bearing rocks in the area may be classified into three groups:

1) cordierite-garnet-biotite rocks
2) cordierite-garnet-anthophyllite rocks
3) cordierite-garnet-hypersthene rocks.

Cordierite-garnet-biotite rocks

In the investigation area the three rock types listed above are generally so closely associated with one another that in banded rocks the composition may vary from one rock type to another. Occurrences of typical cordierite-garnet-biotite rocks include those in the northern part of Körtinvuori, along the northern margin of the granite dome at Rapakkojoki and in a line extending from Hirvijärvi to south of Osmanginjärvi, where they merge with a fracture zone in mica gneiss.

The cordierite-garnet-biotite rocks are strongly metamorphosed and coarse-grained, with marked variation of grain size. They display migmatisation due to aplitic and granitic dykes and veins. The dark cordierite-garnet-biotite-bearing streaks form sinuous ribbons together with other streaks granitic to quartz dioritic in composition. Garnets, either discrete or in clusters, are common in the granitic material, the abundance of which is an essential feature of the rock as a whole. Other features that complete the image of the rock are the fine-grained mica gneiss bands, which are also indicative of the origin of the rock. These mica gneiss bands are frequently broken, forming boudinages of elongated rods that are further twisted into z-shaped fragments.

Various mineral assemblages are represented in the cordierite-garnet-biotite rock, the most common being:

a) Pl + Qu + Bi + Cor + Gar + Mi + Sil ± Spi ± Ru + Zir + Op
b) Pl + Qu + Bi + Cor + Gar + Sil ± Spi ± Ru + Zir + Op
c) Pl + Qu + Bi + Cor ± Sil ± Ru ± Mu + Zir + Op

(Symbols: Pl = plagioclase, Qu = quartz, Bi = biotite, Cor = cordierite, Gar = garnet, Mi = microcline, Sil = sillimanite, Spi = spinel, Ru = rutile, Zir = zircon, Op = opaques and Mu = muscovite).

The plagioclase grains are well-preserved and without zonality. In composition the plagioclase varies from An_{25} to An_{40}, generally being $An_{c.33}$. When in contact with potassium feldspar its grains are myrmekitic in texture; antiperthite is also in evidence in the plagioclase in potassium feldspar-bearing rocks. Twinning according to the albite law is common as is that according to the pericline law in some grains.

Quartz is unevenly distributed as small nests and veins throughout the rock. It either displays faint undulatory extinction or its grains are distinctly granulated.

Biotite occurs as scales that are intensely pleochroic from pale yellow-brown to red-brown, frequently with small inclusions of zircon. In the fissures and along the margins of the scales cloudiness due to the presence of opaques is visible. The margins of the scales may also exhibit small clusters of sillimanite needles and worm-like quartz skeletons.

The cordierite is generally fresh, minor pinitisation being visible in the cleavages of a few grains only. As inclusions there are small zircons with a yellow halo and fan-shaped radiating needles of sillimanite (Fig. 24), which are also visible between the grains and along their margins, as well as opaque grains of oxide and sulphide minerals in many places. Some lamellar twinning is exhibited in the cordierite.

Garnet is present as large broken poikiloblastic crystals with inclusions of biotite, sillimanite, quartz, feldspar and opaques. Occasionally there is a kelyphitic seam of chlorite in the garnets in contact with potassium feldspar.

Potassium feldspar, when present, is hair-perthitic and cross-twinned microcline. It varies in amount from being an accessory mineral to rare phenocrysts.

Sillimanite may be one of the main constituents of the rock, and as such it is present as laths and clusters of small needles. It is closely allied with cordierite, biotite and garnet. Zircon and opaques (oxide and sulphide minerals) are common accessories; more rare are rutile and green hercynite. Sparse apatite is also in evidence.

The chemical composition of the cordierite-garnet-biotite rocks is revealed by two type analyses, presented in Table 6, analyses 1 and 2. The triangular diagram in Fig. 31 (p. 96) indicates that in total composition the cordierite-garnet-biotite rocks can be distinguished from the cordierite-garnet-anthophyllite (and -hypersthene) rocks by the lower content of Fe and Mg and higher content of Al, Na and K in the former.

In mineral composition and structure the cordierite-garnet-biotite rocks of the Kiuruvesi area may be compared with the coarse-grained cordierite-garnet-biotite gneisses (kinzigites) of south and southwest Finland described by many workers, including Wegman and Kranck (1931), Pehrman (1931, 1936), Parras (1941, 1946), Hietanen (1943, 1947), Hausen (1944) and Härme (1954, 1960). They are also analogous to the so-called cordierite-granulites of Lapland, whose mineralogy and habit have been portrayed by Eskola (1952, 1961, 1963), Scheumann *et al.* (1961), and others.

Parras (1946 p. 3) proposed that the name "lutogenite" be applied to coarse-grained garnet-cordierite gneisses instead of "kinzigite". Although the descripition of lutogenites (Parras, 1946 p. 3) does in fact fit the cordierite-garnet-biotite rock of the Kiuruvesi area, it is a term with genetic implications and is not correct here.

Härme (1974 p. 9) compares the kinzigites of south Finland with the cordierite-granulites of Lapland; the resemblance between them is so striking that he suggests that both be known by the name garnet-cordierite gneiss. Since plagioclase and quartz are invariably present in the cordierite-garnet-biotite-bearing rocks of the Kiuruvesi area their mineral composition is that of gneiss. Cordierite, however, does not occur here as porphyroblasts as it may do in rocks with the same mineral composition elsewhere, for example in the Haukivesi area (Gaál and Rauhamäki 1971, p. 275), and thus the term cordierite-garnet-biotite rocks is used in the present discussion.

Table 6

Chemical compositions of cordierite-bearing rocks.
Analyses 1—8 are from the Kiuruvesi investigation area.

	1.	2.	3.	4.	5.	6.	7.		8.	9.
SiO_2	62.10	62.91	55.08	43.61	62.29	60.00	55.39		72.50	59.71
TiO_2	0.69	0.59	1.42	0.95	0.62	0.72	1.05		0.62	1.50
Al_2O_3 ...	17.02	15.80	16.20	17.92	13.44	15.83	11.68		13.50	14.28
Fe_2O_3 ...	0.91	0.73	1.10	2.54	0.80	1.41	4.56		1.07	1.08
FeO	6.68	7.54	15.28	23.04	10.49	14.03	14.62		4.06	12.14
MnO	0.09	0.11	0.15	0.45	0.37	0.50	0.37		0.10	0.20
MgO	4.03	3.64	7.48	7.71	6.45	5.29	5.19		4.41	5.79
CaO	2.44	0.96	0.83	0.26	0.51	0.64	3.08		0.97	1.34
Na_2O ...	3.58	1.99	1.40	0.49	0.47	1.35	2.83		0.84	0.97
K_2O	1.66	2.13	0.14	1.19	0.36	0.46	0.13		0.97	0.19
P_2O_5	0.07	0.10	0.17	0.15	0.00	0.05	0.06		0.04	0.64
H_2O+ ..	1.64	1.62	1.78	2.30	0.74	0.62	0.60		0.66	2.03
H_2O- ..	0.27	0.29	0.11	0.14	0.25	0.17	0.19		0.02	0.05
	101.18	98.41	101.14	100.75	96.79	101.07	99.75			99.92
Cu ppm	29	10	0	31	8	14	9	CO_2	0.05	
Zn ppm	118	87	44	188	267	160	362	F	0.05	
Ni ppm	79	124	24	38	17	26	24	Cl	0.01	
Pb ppm	45	34	27	44	20	38	32		99.87	
S ppm	1 138	175	295	2 121	842	437	328	—O	0.02	
									99.85	

The samples and their location on the map

1. Cordierite-garnet-biotite rock. Kiuruvesi, Rapakkojoki, map sheet 3323 08 7052.60/482.22.
2. Cordierite-garnet-biotite-sillimanite rock. Kiuruvesi, southeast of Iso Hanhilampi, map sheet 3323 07 7042.64/489.66.
3. Cordierite-garnet-anthophyllite rock. Kiuruvesi, Aittojärvi, railway cutting, map sheet 3323 06 7062.60/471.05.
4. Cordierite-garnet-anthophyllite rock. Kiuruvesi, north of Majoonjärvi, map sheet 3323 07 7048.66/488.77.
5. Cordierite-garnet-hypersthene rock. Kiuruvesi, Salmenkylä, Sahinperä, map sheet 3323 07 7043.02/481.44.
6. Cordierite-garnet-hypersthene rock. Kiuruvesi, Salmenkylä, Sahinperä, map sheet 3323 07 7043.06/482.18.
7. Cordierite-garnet-hypersthene rock. Kiuruvesi, Tuomijoki, map sheet 3323 04 7045.70/474.50.
8. Heterogeneous cordierite gneiss. Kiuruvesi, Toiviaiskylä, Lake Juurikka, point 1, anal. A. Heikkinen (Savolahti 1966, p. 369, Table 9).
9. Anthophyllite-cordierite rock. Hämeenlinna, east of Lake Katumajärvi, anal. P. Ojanperä (Simonen 1948, p. 24, Table II, 15).

Cordierite-garnet-anthophyllite rocks

Typical cordierite-garnet-anthophyllite rocks occur about 1.5 km northwest of Kalliojärvi at Kalliokylä, in the environment of Niemisjärvi, north of Majoonjärvi, west and northwest of Sulkavanjärvi, and northeast and east of Juurikkajärvi (cf. Savolahti 1966). There are also some smaller occurrences north of the Lavapuro rail halt and around Koivujärvi.

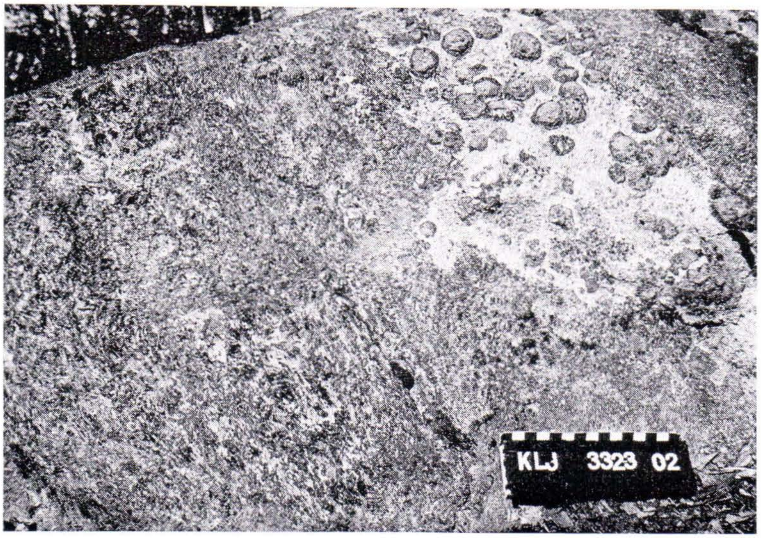

Fig. 20. Coarse-grained cordierite-garnet-anthophyllite rock. Kiuruvesi, northwest of Kalliojärvi, Ruosteenmäki, map sheet 3323 02.

Fig. 21. Kink band structure in cordierite-garnet-anthophyllite rock. Kiuruvesi, northwest of Kalliojärvi, Ruosteenmäki, map sheet 3323 02.

The cordierite-garnet-anthophyllite rocks are essential constituents of the rock association that includes amphibolites, leptites and hornblende gneisses of volcanic origin. They occur as bands of diverse width that form lenses within layers. Locally the rock types appear to merge with one another without clear boundaries. The cordierite-garnet-anthophyllite rock exhibits pronounced banding (Figs. 20, 21) due to the concentration of different minerals either singly or in pairs. In some places the rock exhibits a very coarse-grained and "plutonic" habit. Coarse-grained minerals are particularly conspicuous in the outcrop at Ruosteenmäki, Kalliojärvi, where they tend to form pegmatitic clusters (Fig. 20). Dark red garnet crystals, from 3 to 5 cm in diameter, may occur in clusters. Anthophyllite may be present as black laths, over 5 cm in length, exhibiting fan-like structures. Cordierite is in evidence between both of the forementioned minerals as smaller grains or larger nest-like portions with a distinctive light to dark blue colour; it may even occur as euhedral grains, indicating the possibility that the cordierite crystallised directly from volcanic melt or that it was a product of interaction between granitic magma and molten country rock. Other minerals besides cordierite, garnet and anthophyllite, are plagioclase, quartz and biotite. The accessories include magnetite and sulphide minerals, which may be present as disseminations and clusters.

The cordierite-garnet-anthophyllite occurrences generally exhibit great local variation in their mutual mineral composition, habit and structure. On the basis of their mineral composition these rocks may be classified as follows:

a) Cor + Gar + Anth + Qu + Bi + Pl ± Sil ± Ap ± Zir + Op
b) Cor + Gar + Anth + Qu + Bi ± Sil ± Ru ± Spi ± Zir ± Ap + Op
c) Cor + Gar + Anth + Qu ± Sil ± Ru + Op

(Symbols: the same as on p. 42 with the addition of Anth = anthophyllite, Ap = apatite).

Cordierite is present as grains of irregular shape although euhedral crystals are also encountered occasionally. The mineral contains inclusions of opaques, zircon and biotite. Small sillimanite needles are fairly common in the fractures and at the margins of the grains, whereas alteration products have only been noted at the margins of a few grains. Lamellar twinning is common. The optical character of cordierite varies, being biaxial (—) or (+).

Garnet occurs as large poikiloblasts with inclusions of quartz, biotite, plagioclase, cordierite, hercynite, sillimanite and opaques. Biotite is commonly present at the margins of the grains.

Anthophyllite forms laths and radiating bundles of laths, which seem to have grown through the other minerals. In thin section it is almost colourless or distinctly pleochroic x = red-brown, z = grey-green. It shows ordinary optical orientation with a = x, b = y, c = z, (+) or (—). The more rare colourless variety is generally (—), and thus it is probably Mg-anthophyllite (Heinrich 1965, pp. 246—247). In thin section the anthophyllite bundles may exhibit colourless (possibly gedrite) or conspicuously pleochroic laths. Locally the anthophyllite has altered into biotite; it contains inclusions of quartz, an essential mineral in these rocks, as grains of varying size and with undulatory extinction.

Minor biotite is present as small scales. It is pleochroic from yellow-brown or almost colourless to dark brown or brown. Zircon is sparse and occurs as small inclusions surrounded by dark halos.

Plagioclase, one of the minerals from mineral assemblage a), occurs locally and is between oligoclase and andesine (An_{27-35}) in composition. Simonen (1948, p. 40) employs the term anthophyllite-cordierite amphibolite for the rock that contains plagioclase and grades into anthophyllite-cordierite rock with the disappearance of plagioclase. Both rocks contain garnet. In the Kiuruvesi area the rocks are designated cordierite-garnet-anthophyllite rocks, irrespective of whether they contain plagioclase or not, since the plagioclase may occur either in the rock itself or as plagioclase-bearing veins.

The most common accessories are sillimanite, local rutile and hercynite-spinel; apatite and zircon are also in evidence but in smaller amounts than in the cordietite-garnet-biotite rock. Iron oxide and sulphide ore minerals constitute the opaques.

The chemical compositions of the cordierite-garnet-anthophyllite rocks in the area are given in Table 6, analyses 3 and 4. Analysis 3 is of the rock containing minor plagioclase, and analysis 4 of the coarse-grained plagioclase-free variety. The abundance of ferrous iron in these rocks is conspicuously high. Similarly, the Mg content is higher than that in the cordierite-garnet-biotite rock. Analysis 9, taken for comparison from the vicinity of Hämeenlinna, is probably a sample of typical cordierite-anthophyllite rock from an environment similar to that of the cordierite-garnet-anthophyllite rocks from the Kiuruvesi area. The composition of the Hämeenlinna rock, however, is nearer that of cordierite-garnet-hypersthene rock than that of cordierite-garnet-anthophyllite rock.

Cordierite-garnet-hypersthene rock

Cordierite-garnet-hypersthene is encountered west of Sulkavanjärvi at Sahinperä, Salmenkylä, at Tuomijoki, east of Juurikkajärvi (cf. Savolahti 1966), northwest of Kalliojärvi and south of Hautajärvi. In habit these rocks refer to the cordierite-garnet-biotite and -anthophyllite rocks, with which they are also intimately associated. The best examples of hypersthene-bearing rocks are at Salmenkylä (Fig. 22), where they occur together with pyroxene diorites and pyroxene quartz diorites. The cordierite-garnet-hypersthene rocks are very heterogeneous, banded

Fig. 22. Banded cordierite-garnet-hypersthene rock. Kiuruvesi, Salmenkylä, Sahinperä.

Fig. 23. Fragments of amphibolite in cordierite-garnet-hypersthene rock. Kiuruvesi, Salmenkylä, Sahinperä.

rocks with a maximum grain size of 1.5 to 2.5 cm, the coarse-grained bands being apparently plutonic. In composition the fine-grained and massive bands are pyroxene dioritic and pyroxene quartz dioritic gneisses. These bands are often broken, and form boudinages and rods as do the mica gneiss bands in the cordierite-garnet-biotite rock, and the amphibolitic and hornblende gneiss bands in the anthophyllite rock. They, like amphibolite, may also occur as breccia fragments (Fig. 23). The brecciated material appears to be anatectic and is probably of the same genesis as are the boudinages and fragments.

Microscope study reveals the presence of various mineral assemblages in the hypersthene-bearing cordierite rock, for example:

a) Cor + Gar + Hy + Pl + Qu ± Bi ± Anth ± Sil ± Spi ± Ru ± Ap + Op
b) Cor + Gar + Hy + Pl + Qu + Kfs ± Bi ± Sil ± Zir ± Ap + Op
c) Sapphirine-bearing assemblages

(Symbols: the same as before with the addition of Hy = hypersthene and Kfs = potassium feldspar).

Hypersthene is present as brown-black grais, up to 2.5 cm in diameter, displaying a dull lustre and a cleavage face. It is strongly pleochroic from red brown to grey green or blue green. Its optic character is negative with a = x, b = y, c = z. The hypersthene in the cordierite-garnet-hypersthene rocks of the pyroxene diorite area exhibits sparse biotite as an alteration product, whereas elsewhere, for example east of Juurikkajärvi, "wherever gedrite (anthophyllite) occurs in abundance, the edges and fissures of the hypersthene grains situated in it as inclusions are covered by a fine-grained, yellow stuff" (Savolahti 1966, p. 361).

Garnet is brown-red with cataclastic crystals of varying size. The large poikiloblastic crystals contain inclusions of quartz, opaques, biotite, cordierite, hypersthene, hercynite-spinel and rutile needles. Sillimanite needles are often visible in the boundary between garnet and cordierite.

Cordierite occurs as dark blue grains among the other minerals. It is optically (+) or (—). Although lamellar twinning is not common, it does occur locally as pronounced cross-hatching. In rocks containing potassium feldspar the cordierite exhibits small crystals of zircon surrounded by a yellow pleochroic halo. Some of the grains also contain inclusions of rutile. Alteration products are very sparse in the cordierite of these rocks, but sillimanite needles are often in evidence between the grains.

Plagioclase occurs in variable amounts and with a composition from An_{30} to An_{48}, the average being An_{33}. Twinning appears to be exclusively according to the albite law. The plagioclase grains are generally fresh, but when in contact with potassium feldspar and biotite they contain myrmekite and often also antiperthite.

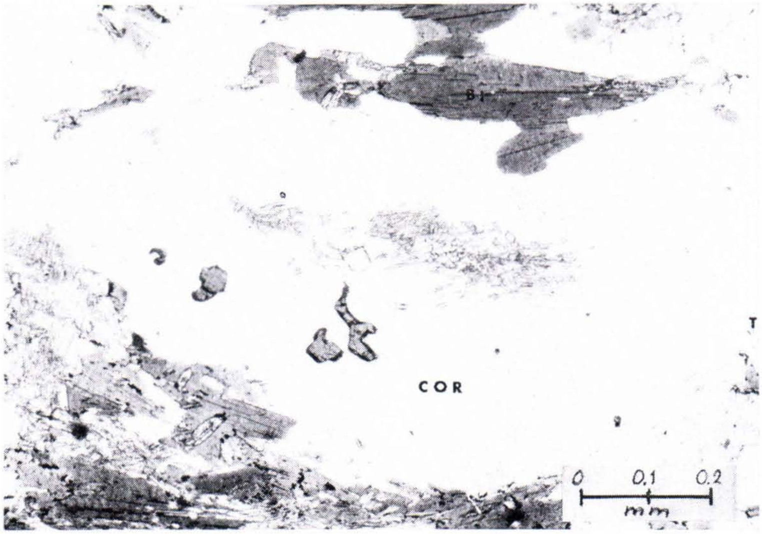

Fig. 24. Small clusters of sillimanite needles in cordierite-garnet-biotite rock. Photomicrograph nicols crossed. Kiuruvesi, Niemisjärvi, railway cutting, map sheet 3323 06.

Quartz occurs among the other minerals as grey-coloured grains exhibiting undulatory extinction.

Biotite varies in abundance from a major component to a minor accessory. It is pleochroic from pale yellow or pale brown to dark brown or brown. The margins of many of the scales reveal poikilitic texture together with quartz and inclusions of small zircon crystals.

Potassium feldspar, when present, is hair-perthitic orthoclase or microcline.

The accessories are sillimanite, apatite, hercynite-spinel, rutile, zircon and opaques (oxide and sulphide minerals and graphite).

Samples taken by diamond core drilling from the orebody northwest of Kalliojärvi reveal sapphirine in cordierite rocks in the following mineral assemblages:

a) Specimen, Klj-82, depth 55.33 m: anthophyllite-cordierite-sapphirine-hypersthene-phlogopite-hercynite-rutile-zircon-opaque (Fig. 25).

b) Specimen, Klj-1, depth 121.36 m: anthophyllite-cordierite-sapphirine-rutile-hercynite-corundum(?)-apatite-zircon-opaque-chlorite-talc-serpentine-epidote-titanite (Fig. 26).

The sapphirine occurs as grains from 2 to 6 mm in diameter, some of which display crystal faces. In thin section it is pleochroic, blue-grey or almost colourless. Optically it is bi-axial (—). Some alternation products are present to a certain extent in the fissures of the grains. Green hercynite-spinel is found in association with sapphirine.

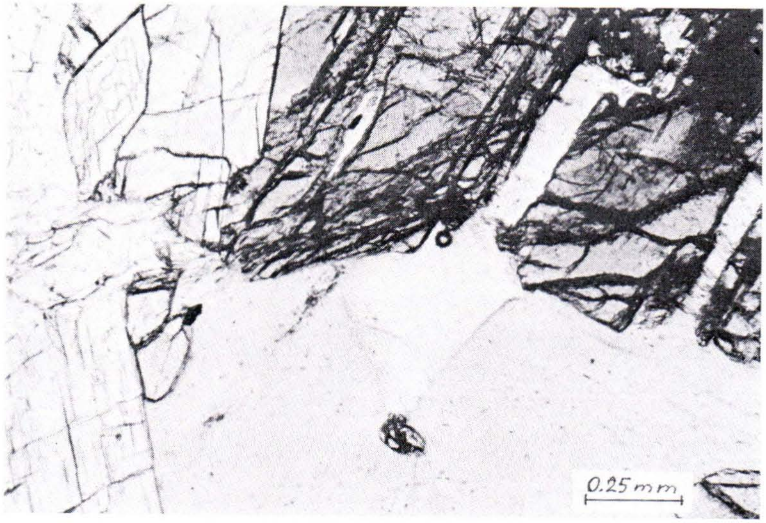

Fig. 25. Sapphirine-anthophyllite-cordierite-phlogopite paragenesis. Photomicrograph, nicols not crossed. Kiuruvesi, northwest of Kalliojärvi, Ruosteenmäki, drill hole Klj-82, map sheet 3323 02.

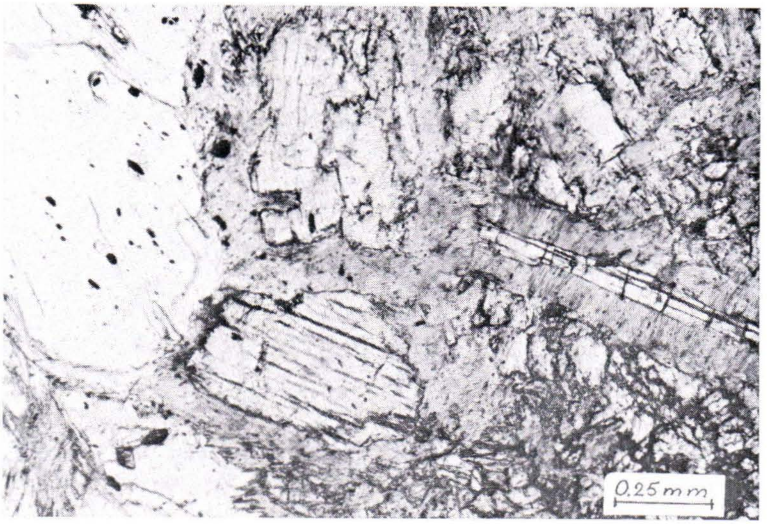

Fig. 26. Cordierite-anthophyllite-sapphirine-talc-rutile paragenesis. Photomicrograph, nicols not crossed. Kiuruvesi, northwest of Kalliojärvi, Ruosteenmäki, drill hole Klj-1, map sheet 3323 02.

Cordierite is optically negative in assemblage a) and positive in assemblage b). In the latter it is also intensely altered and contains inclusions of rutile. Anthophyllite is almost colourless. Hypersthene is light brown and very faintly pleochroic.

Phlogopite is slightly brownish and its scales are bent. Optically it is negative. Talc, chlorite (probably margarite) and serpentine (chrysotile) constitute an altered matrix in the shear seams. The occurrence of corundum is still open to conjecture.

The chemical compositions of three cordierite-garnet-hypersthene rocks from the Kiuruvesi area are given on p. 44, in Table 6, analyses 5, 6 and 7. Analysis 8 is the chemical composition of the hypersthene-bearing heterogeneous cordierite gneiss of Juurikkajärvi. The minerals in the sample are quartz, cordierite, biotite, plagioclase and sillimanite, opaques, hypersthene, apatite and zircon (Savolahti 1966, p. 369). Although "the vein portions were totally removed from the analyzed specimen before the rock was pulverized" (Savolahti 1966, p. 369), it still exhibits an appreciably high content of SiO_2. Likewise, although there is markedly less iron than in the other cordierite-hypersthene rocks in the area, the iron content is well comparable with that of the cordierite-biotite rocks.

Hypersthene-bearing dioritic and granitic rocks

In the present study hypersthene-bearing rocks are understood as rocks that consist of plutonic intrusive and gneissic pyroxene diorites, -quartz diorites, -granodiorites and -granites. Hypersthene-bearing gneisses, the so-called charnockites, are not readily distinguished as a separate rock species and so they are discussed in conjunction with the hypersthene-bearing pyroxene diorites and pyroxene quartz diorites. Gaál and Rauhamäki (1971, p. 294) consider the charnockites as a particular rock species, although they pointed out the strong resemblance between them and the gneissic pyroxene quartz diorites.

Pyroxenes, either hypersthene alone or with diopside-augite, are included in the constituents of these hypersthene-bearing rocks. Irrespective of whether the rock contains one or two pyroxenes, the rocks are here designated as pyroxene diorite, pyroxene quartz diorite, pyroxene granodiorite or pyroxene granite.

Pyroxene quartz diorite and pyroxene diorite

In the investigation area the pyroxene-bearing diorites and quartz diorites are located in the inner part of the ring that goes through Sulkavanjärvi—Hautajärvi —Niemisjärvi—Kalliojärvi—Sulkavanjärvi. The pyroxene diorites and pyroxene

Fig. 27. Fine-grained and banded pyroxene diorite. Kiuruvesi, Salmenkylä, map sheet 3323 70 7040.23/482.76.

Fig. 28. Breccia. Kiuruvesi, Salmenkylä.

quartz diorites are greenish grey or greenish brown, the weathering surface being lighter in colour than the fresh fracture surface. They are often mottled owing to slight variations in mineral composition, and banded possibly as a result of rolling and compression. Rocks of this type are fine-grained and massive (Fig. 27). As a rule the rocks are medium-grained and equigranular, apparently of plutonic origin. In the vicinity of porphyry and pyroxene granite and pyroxene granodiorite the diorites exhibit fairly large phenocrysts of potassium feldspar.

The pyroxene diorites and pyroxene quartz diorites contain abundant inclusions of older rocks, e.g. gneiss granite, veined gneiss, mica and hornblende gneiss, and amphibolite. These breccia fragments are especially abundant in the fracture zones and at the margins of the intrusives. The margins of the fragments often display a narrow more light-coloured contact seam. The brecciating more light-coloured rocks exhibit flow structure, the lightest ones containing garnets as random clusters. In the fracture zones in the vicinity of the cordierite-bearing rocks, the fragments are fine-grained, massive and striped pyroxene diorite (Fig. 28). The breccia material is pyroxene quartz diorite, marked by the presence of blue quartz. The fragments often contain pyrite and pyrrhotite as disseminations. Diabase dykes cut with sharp contacts both the pyroxene diorites and the pyroxene quartz diorites, and these are cut in turn by pyroxene granite and porphyry granite as well as by dykes of aplite and pegmatite.

The pyroxene diorites and pyroxene quartz diorites contain the following assemblages, in which hypersthene occurs either alone or with diopside-augite:

The dioritic type:

a) Plagioclase + Hypersthene ± Biotite ± Garnet
b) Plagioclase + Hypersthene + Diopside-Augite ± Biotite

The quartz dioritic type:

a) Plagioclase + Hypersthene + Quartz ± Biotite ± Garnet
b) Plagioclase + Hypersthene + Diopside-Augite + Quartz ± Hornblende ± Biotite.

The pyroxene diorites tend to be darker in colour and of finer grain size than their quartz-bearing counterparts. The composition of plagioclase in the pyroxene diorites rarely exceeds An_{38-50}, and in the pyroxene quartz diorites it is commonly An_{30-40}, exceptionally being either higher or lower. Plagioclase generally occurs as fresh grains exhibiting twinning according to the albite and pericline laws; in the vicinity of granites, however, minor myrmekite and antiperthite are revealed. Locally, there are inclusions of pale amphibole needles and apatite.

Hypersthene is distinctly pleochroic and in the rocks deficient in diopside-augite it generally ranges from an intense reddish-brown to greenish colour.

Minor alteration into hornblende and biotite is also often in evidence in the grains, which are then commonly tattered at the margins and reveal opaques along the cleavages.

Diopside-augite often occurs as fairly large poikilitic and greenish grains with hornblende and biotite as alteration products at the margins. Its $c \wedge z$ varies from 37° to 45°.

Quartz is faintly undulatory and ranges from being an accessory to veins and larger bodies.

Biotite may be present in such abundance as to be counted as a main component. It also occurs in minor amounts in association with and as an alteration product of hypersthene and hornblende. It is pleochroic light yellow-brown to intense dark brown. Inclusions of apatite and zircon are in evidence.

The hornblende in the pyroxene quartz diorites may surpass its status as an accessory, but usually it is only an alteration product at the margins of the pyroxene grains.

Garnets, the majority of which occur as nests in the light-coloured portions of the pyroxene diorites and pyroxene quartz diorites, are commonly tattered and sieve-like with biotite, quartz and plagioclase as inclusions.

The accessories proper in these rocks are apatite and opaques (ore minerals and graphite).

In thin section the pyroxene diorites and pyroxene quartz diorites exhibit hypidiomorphic texture.

Pyroxene granite and pyroxene granodiorite

Pyroxene granite and -granodiorite are encountered in the immediate vicinity of and outside the pyroxene diorites and pyroxene quartz diorites. Most of the pyroxene granites occur in the rocky area that extends from northern Sulkavanjärvi to Hautajärvi. A second occurrence of pyroxene granites is the roundish area in northeastern Sulkavanjärvi, where they are encountered together with ophitic gabbros. Yet a third occurrence is the ridge, 1.5 to 2 km wide, of pyroxene granites that can be traced from west of Sulkavanjärvi northwestwards to Tuomijoki and from there to Kangaslampi as a steadily narrowing porphyry granite with only local pyroxene.

The pyroxene-bearing granites are readily recognized by their colour and intense surface weathering, which in places may form a layer from 40 to 80 cm thick. Fresh pyroxene granite is a dirty grey-brown colour, sometimes with a greenish tinge. It tends to be much darker than the common porphyric or equigranular granites. In grain size and mineral composition the pyroxene granites are heterogeneous (Fig. 29), and some microporphyric variations are in evidence

Fig. 29. Pyroxene granite. Kiuruvesi, Tuomijoki, map sheet 3323 04.

in the marginal zones of the coarse-grained porphyric pyroxene granite massifs. The older rock types of the area, basement gneiss, amphibolite, mica and hornblende gneiss as well as pyroxene diorites and pyroxene quartz diorites, are encountered as angular and elongated twisted fragments in the pyroxene granite and pyroxene granodiorite along the margins of the massifs and in tectonic fracture zones.

Wilkman (1931, pp. 140—142 and 1938, pp. 93—96) has described in considerable detail equigranular and porphyric pyroxene granite and pyroxene granodiorite from the Kiuruvesi area. The chief components of pyroxene granite are potassium feldspar, quartz, plagioclase, varying amounts of hypersthene and diopside-augite as well as biotite and hornblende.

Potassium feldspar, microcline, occurs as yellowish brown-grey, ellipsoidal or rectangular Karlsbad twins that vary in size from 1.5 to as much as 6 cm. Microscopically the mineral is fine-perthitic with cross-hatched texture. Orthoclase allied with microcline has been met with at Salmenkylä and other sites.

Quartz is grey in colour and is present as bundles of grains or discrete grains about 5 mm in diameter. It is somewhat deformed, as is revealed by the undulatory extinction.

Plagioclase is grey in colour and occurs as rare large grains. Microscope study revealed that its composition varies from An_{24} to An_{48}, most commonly being $An_{28—34}$. It is generally fresh, but when in contact with potassium feldspar abundant myrmekite is present. Small exsolution bodies of antiperthite are common. The grains often exhibit twinning according to the pericline law in addition to the albite law, some of the large grains showing Karlsbad twinning as well.

The dark minerals include pyroxene that is either wholly hypersthene or a combination of hypersthene and diopside-augite. The hypersthene commonly occurs as small grains with well-defined margins; there are, however, some tattered grains whose margins exhibit hornblende as an alteration product and also occasional yellow-brown serpentine. Pleochroism varies in intensity, being generally distinct: x = reddish, z = greenish. Twinning with very closely spaced lamellae is visible locally in the hypersthene of the pyroxene granite, but it is still not as common as in the hypersthene of the charnockites in the area. Parras (1958) has described similar lamellar twinning from western Uusimaa. In thin section, diopside-augite appears as colourless or faintly green-coloured grains whose $c \wedge z$ ranges from 38° to c. 45°. Some alteration into hornblende is revealed in the tattered grains.

A common dark mineral in the pyroxene granites is almost ubiquitous biotite. It is generally intensely pleochroic from pale yellow-brown to dark brown. Minor alteration into chlorite is visible, and crystals of zircon and apatite with dark halos occur as inclusions.

Hornblende occurs predominantly as an alteration product, but it is possibly of primary origin in the pyroxene granites and pyroxene granodiorites adjacent to amphibolites. The hornblende exhibits pleochroism from a distinct pale yellow-green to dark green. Minor biotite is an alteration product of hornblende.

Worm-shaped forms of quartz, which structurally refer to the myrmekite in plagioclase, may be present as inclusions in the margins of the hypersthene and biotite grains. The opaques, hematite and ilmenite or magnetite, tend to occur in small amounts in association with the dark minerals, and are together with apatite and zircon the most common accessories in these rocks.

The chemical compositions of the pyroxene granites, pyroxene granodiorites and pyroxene quartz diorites of the Kiuruvesi area as well as those taken for comparison from elsewhere in the Raahe — Ladoga zone are given in Table 7. A comparison of the analyses reveals that the abundances of certain elements differ in the granitic and dioritic rock types, the tenors of Fe_2O_3, MnO, MgO and CaO being highest in the quartz diorites.

In Finland, hypersthene-bearing granitic and dioritic rocks have been encountered in a zone extending from Ladoga to Raahe (Wahl 1963), and in the southern part of the country, where Parras (1941 and 1958) has described them from western Uusimaa.

The zone mentioned by Wahl (1963), which includes hypersthene granites and dioritic rocks of the same group, crosses Finland as a SE—NW trending belt, 100 km wide and c. 450 km long; its southwestern edge can be traced from

Table 7

Chemical compositions of hypersthene-bearing granites, granodiorites and quartz diorites. Analyses 1—3 are from the Kiuruvesi investigation area.

	1.	2.	3.	4.	5.	6.
SiO_2	59.38	67.35	59.69	67.07	61.85	60.58
TiO_2	0.95	0.47	0.60	1.03	1.88	1.35
Al_2O_3	16.59	16.72	14.50	14.59	15.80	15.43
Fe_2O_3	0.45	0.45	1.09	0.56	0.32	2.04
FeO	7.48	2.35	5.81	5.18	8.35	5.18
MnO	0.09	0.04	0.13	0.06	0.01	0.14
MgO	1.34	1.11	2.18	1.02	1.02	3.36
CaO	3.59	3.08	5.38	3.99	3.82	5.95
Na_2O	3.76	5.10	3.98	2.90	3.78	2.63
K_2O	3.18	1.95	1.43	2.41	2.80	2.23
P_2O_5	0.26	0.13	0.20	0.21	0.48	0.23
H_2O+	0.66	0.68	0.72	0.76	0.44	0.62
H_2O-	0.17	0.22	0.21	0.05		0.09
	97.90	99.65	95.92	99.83	99.85	99.83
Cu ppm	38	10	0			
Zn ppm	156	65	105			
Ni ppm	35	26	29			
Pb ppm	41	23	23			
S ppm	1 068	94	389			

The samples and their location on the map

1. Porphyritic pyroxene granite. Kiuruvesi, Jynkänmäki, map sheet 3323 07 7046.50/485.20.
2. Pyroxene granodiorite. Kiuruvesi, north of Paljakkavuori, map sheet 3323 08 7051.66/484.60.
3. Pyroxene quartz diorite. Kiuruvesi, Toiviaiskylä, map sheet 3323 05 7051.60/477.45.
4. Porphyritic hypersthene granite. Viitasaari, Kymönkoski, anal. L. Lokka (Wilkman 1938, p. 100).
5. Equigranular hypersthene granodiorite. Kiuruvesi, Näläntöjärvi, anal. L. Lokka (Wilkman 1931, pp. 141—142).
6. Pyroxene quartz diorite. Rautalampi, Kilpimäki, anal. L. Lokka (Wilkman 1938, p. 85).

Table 8

Age determinations made by O. Kouvo for pyroxene granites and pyroxene quartz diorites in Finland.

Mineral	Rock type	Locality	Pb^{207}/Pb^{206}	Pb^{207}/U^{235}	Pb^{206}/U^{238}	Pb^{208}/Th^{232}
Zircon [1])	Pyroxene granite	Vaaraslahti, Pielavesi	1 910	1 810	1 725	1 725
Zircon [2])	Hypersthene granite	Voinsalmi, Rantasalmi	1 910	1 865	1 830	—
Zircon [2])	Hypersthene quartz diorite	Voinsalmi, Rantasalmi	1 905	1 830	1 771	—

[1]) Geological Survey of Finland. Annual Report on the Activites for the Year 1970, and [2]) for the Year 1971.

Wiborg (USSR) to Kalajoki on the Gulf of Bothnia, and its northeastern edge from Sortavala (USSR), north of Ladoga, to Oulu on the northeastern shore of the Gulf.

The hypersthene-bearing dioritic and granitic rocks of the Kiuruvesi area and its immediate vicinity, described previously by Wilkman (1931, 1938) and Savolahti (1966), are composed of analogous rock types, and thus they are similar to one another. In mineral composition and owing to the presence of plutonic structures they also refer to the hypersthene-bearing rocks described by Gaál and Rauhamäki (1971) from Haukivesi, another area in the zone of Wahl.

The ages determined by O. Kouvo for the hypersthene granites and hypersthene quartz diorites of Voinsalmi in the Haukivesi area and for the pyroxene granites of Vaaraslahti, Pielavesi, south of the investigation area, are given in Table 8. The zircons in the Voinsalmi pyroxene rocks "give the absolute age of about 1925 Ma." (Gaál and Rauhamäki 1971, p. 335). The same age is obtained for the zircon from the pyroxene granite of Vaaraslahti.

It is clear that the pyroxene granites and pyroxene diorites are intrusions of the Svecokarelian orogeny, and that they were formed during the same phase despite the slight differences in their mutual age relationships, e.g. at Kiuruvesi, where the coarse-grained and porphyric pyroxene granite has been shown to intrude the pyroxene quartz diorite and pyroxene diorite.

INFRACRUSTAL ROCKS

Serpentinite

Serpentinite has been encountered at Saarisperä, west of Sulkavanjärvi, in three outcrops each of which covers a few square metres. It is a dark-coloured rock with a rough weathering surface. Orientation is generally lacking, but some fractures bearing N 10° E are visible in the northern part of the outcrops, and N 10° W, 55° E in the southern part.

The minerals include olivine, which is serpentinised and spreads out in a net-like structure from the fracture joints. It is optically (—) $2V_X$ = c. 85°, which suggests a composition of c. 75 mol. % Fo (Deer *et al.,* 1962). There is also colourless or almost colourless cummingtonite, with $c \wedge z = 14°$. Accessories are pentlandite-bearing pyrrhotite and random chalcopyrite. The sulphides seem to favour the fractures, in which they may occur as zones 10 cm in width (northern part), or the joints, in which they constitute a filling from 6 to 7 cm in width (southern part). Minor sulphide dissemination and brecciated quartz-feldspar veins are also visible in the rock. There is an occurrence of chloritised peridotite at the centre of the outcropping area.

The serpentinite occurs as a basic intrusion in the NNW-trending fracture zone. It is bounded in the east by migmatic garnet-bearing mica gneiss and in the north by a gabbro brecciated by veins of granite.

Gabbros and peridotites

Basic plutonic rocks are met with in various parts of the investigation area as lumpy and vein-like occursences in association with other rock types. Petrographically they are gabbros and peridotites.

Between Sulkava and Niemisjärvi there are several rather small occurrences, from a few square metres to several tens of square metres in extent, whose composition is peridotitic. The peridotite as a whole is very heterogeneous, although over a small area it appears to be homogeneous. Savolahti (1966, pp. 373—374) has described peridotites from between Juurikkajärvi and Rytkynjärvi, from the same area, that occur as lenses in hypersthene-bearing quartz diorites and in association with amphibolites and mica gneisses. The surface of these peridotites is greenish grey and rough when weathered, but greenish grey-black when fresh. They are medium-grained rocks, grain size 1 to 4 mm, but in places coarse-grained varieties are in evidence. According to Savolahti (1966), the minerals are olivine (75 mol. % Fo) that has partly altered into chlorite and serpentine, hypersthene with some cummingtonite as an alteration product, diopside-augite partly altered into amphibole, hornblende and some fairly large random grains of plagioclase (An_{30-80}). Accessories are apatite, carbonate, epidote and opaques. Quartz occurs as narrow joint veins. A small coarse-grained hornblendite body has been encountered between the mica gneiss, pyroxene granodiorite and pyroxene quartz diorite in the northern part of Sulkavanjärvi. A similar small body of coarse-grained unoriented hornblende peridotite penetrated by coarse-grained pegmatites has been met with in the northern part of Niemisjärvi.

Lenses and bodies of peridotite and gabbros, covering several tens of square metres, are met with between the conglomerate and basement gneiss of Vieremä—Haajainen. Although the rocks in the outcrops seem to be homogeneous, their mineral compositions vary from hornblenditic to hornblende gabbroic. They are generally coarse-grained with faint or no orientation. The accessories in the peridotites are local scant carbonate and weak sulphide dissemination (pyrrhotite, pyrite and chalcopyrite). In the western part of the area between Niinimäki and Kalliojärvi there is an occurrence of hornblendite about 200 m in width and about 2 km in length in a SSW—NNE direction and whose northern end turns to the east for about 0.5 km. This hornblendite is an unoriented, greenish black rock, whose grain size varies from 5 to 7 mm. Macroscopically hornblende is practically the sole component of the rock, although here and there sparse plagioclase is also present. The peridotite is cut by narrow sinuous aplitic dykes and veins.

The gabbros and peridotites are hypidiomorphic in texture. Unlike the diabases and ophitic gabbro-diabases, the gabbroic rocks are not ophitic. It is apparent that the gabbros and peridotites in the area were formed at greater depth during an anorogenic phase and that they crystallised under peaceful conditions from slowly cooling magma.

Granites

Porphyry granite is encountered in addition to pyroxene granite in the environment of Sulkavanjärvi, in a WNW-trending granite zone that extends from west of Sulkavanjärvi to Kangaslampi, at Rapakkojoki and in a ridge trending northwestwards from Hautajärvi. Pink porphyry granite with markedly schistose margins covers a large area west of Koivujärvi.

The porphyry granite contains inclusions of the older rocks of the area, for example mica and hornblende gneisses, amphibolites, pyroxene diorites and pyroxene quartz diorites. In the protruding veins garnets are visible in the vicinity of garnetiferous mica gneisses. Conspicuous features of the porphyry granites and the coarse-grained pyroxene granites are the horizontal or slightly curved cleavage joints parallel to the surface of the ground, perpendicular to which are vertical or subvertical cross and longitudinal joints. The porphyry granite is either unoriented or it displays a distinct direction of compression due to the parallel arrangement of the feldspar augen. Orientation is particularly marked at the margins of the massif.

The tabular grains of potassium feldspar in the porphyry granite are 1.5 to 2 × 2.5 cm in size, and light grey, yellowish grey or pink-grey in colour. The potassium feldspar is microcline with cross-hatched texture in which Karlsbad twins are rather common. The dark biotite-rich matrix contains smaller grains of potassium feldspar and plagioclase as well as grey-coloured quartz and rare hornblende. The plagioclase is oligoclase ($An_{c.28}$) in composition, and its margins exhibit abundant myrmekite. Biotite is pleochroic from cloudy grey-brown to yellowish, and it has partially altered into chlorite. Fine-grained quartz is interspersed among the grains of microcline and oligoclase. Hornblende, when present, is yellow-green to blue-green. Common accessory minerals are apatite and zircon, which occur as euhedral crystals.

There is a slight age difference between the porphyry and pyroxene granites, the former apparently intruding the latter, not with sharp but with gradual contacts.

Analogous porphyry granites are encountered at some sites outside the investigation area (Wilkman 1931 and 1938).

Biotite granite occurs between the lakes Valkeisjärvi and Haapajärvi in the central granite massifs of the domes that form part of the basement gneiss complex. The northern massif consists of medium-grained, homogeneous and unoriented biotite granite that is light grey in colour and whose minerals in order of abundance are quartz, microcline, plagioclase (oligoclase), biotite and the accessories epidote, apatite and opaques. In the northern part of the massif slightly pinkish, medium-grained and unoriented granite is visible. In the northern part of the southern massif, east of Lake Kiuruvesi, grey or pinkish, medium- to coarse-grained biotite granite has been met with in which orientation is lacking or weakly developed. Towards the centre of the massif the granite is slightly porphyric, although the microcline phenocrysts are less than 1 cm in diameter. Mica gneiss, hornblende gneiss and amphibolite occur as inclusions in the biotite granite, which cuts with sharp contacts the granodiorites and quartz diorites of the basement gneiss complex as well as the granite veins intruding them. The biotite granite in its turn is cut with sharp contacts by veins of coarse-grained pegmatite.

The biotite granites of this area have been described by Wilkman (1931, p. 144), who associated them with the "granular" granite-aplites discussed in the present paper later.

Epidote-rich granite is met with east of Saarisjärvi (in the northeastern section of the map). It owes its red-green colour to the reddish plagioclase grains interspersed with yellow-green epidote and chlorite. The granite is a homogeneous, fine- to medium-grained rock with pronounced orientation that has developed into shearing in some places. The chief constituents include plagioclase, hornblende, green chlorite and epidote. The accessories are leucoxene-titanite, apatite and magnetite. The plagioclase is intensely altered albite filled with epidote, chlorite and sericite. Locally, microcline and chloritised biotite are also visible. The epidote forms clusters of crystals between the albite grains.

Here and there in this granite there are inclusions of mica gneiss and the granite is cut obliquely by a metadiabase dyke, some 15 cm wide, which is broken as a consequence of faulting. The granite and the diabase dyke are both cut by a narrow aplite vein.

The epidote-rich granite of Saarisjärvi should probably be included in the rather widespread unakites of central Finland described by several authors, e.g. Mäkinen (1916), Wilkman (1928, p. 14, 1931 p. 35, and 1938) and Wahl (1963). The Saarisjärvi unakite is mentioned by Wilkman on the pages given above. These unakites are conceivably of the same age as the pyroxene granites.

Granite-aplite occurs south of Liittovuori right in the northwestern corner of the map, at Honkaperä, north of Koivujärvi and on Vuohensaari an island in Koivujärvi. At these sites the rock is hypabyssal; it cuts the acid and basic volcanites with discordant contacts, and is itself intruded by coarse-grained granite pegmatites. The granite aplite is a pale grey, medium-grained rock in which only vestiges of flow structure are visible. The weathering surface is "granular" and rough. Microscope study reveals that the rock contains the following minerals in order of abundance: potassium feldspar, quartz, plagioclase and biotite, with chlorite, muscovite-sericite, epidote and apatite as accessories. The potassium feldspar is microcline with pronounced cross-twinning and "flame" perthite. The grains are fresh and embedded in the matrix of intensely deformed and fine-grained quartz. The plagioclase is oligoclase (An_{15-16}) with a somewhat deformed and zonal texture, the core being cloudy owing to sericite and saussurite. The biotite scales are dark brown, the margins being darker than the core. Some scales have undergone marked chloritisation, and bend around the margins of the feldspar grains.

North of Vaaksjärvi, a similar pale grey, medium-grained granite brecciates mica gneiss and amphibolite, and is cut by coarse-grained granite pegmatite veins.

The granite-aplite seems to have been emplaced during a late orogenic phase. Its relationship with other granites, e.g. pyroxene granite, cannot be established owing to the lack of contact exposures between them. The granite-aplite can be distinguished by its colour and "granular" habit from the common aplite in the area.

DYKE ROCKS

Ophitic gabbros and diabase dykes

The ophitic gabbros and diabases of the Kiuruvesi area can be distinguished from one another by their mode of formation. The ophitic gabbros occur in extensive formations in association with pyroxene granite around Sulkava and Körttilampi, where they overlie the pyroxene granite in sills displaying sharp contacts between the rocks. Other sites where ophitic gabbros are encountered are northwest of Kalliojärvi at Patamäki and farther off in the Sikokangas area, at Niemiskylä and south of Osmanginjärvi. The diabase dykes proper occur between Sulkava and Niemisjärvi, where they intrude basal gneisses, pyroxene-bearing granodiorites, quartz diorites and diorites. In places they also intrude intensely migmatised mica gneisses and hornblende gneisses as well as cordierite-bearing rocks.

The diabase dykes trend in three main directions, N—S, NW—SE and NE—SW; there are also some minor dykes trending W—E. These directions are consistent with the observations made by Wilkman (1925, 1931 and 1938), who noted that the diabase dykes in the communes of Varpaisjärvi and Sonkajärvi, east of the Kiuruvesi area, were primarily oriented in NW—SE and WNW—ESE directions, less commonly in NNW—SSE and W—E directions (Wilkman 1925, p. 29); further, he has described diabase dykes from west of Pyhäjärvi that trend N 75°W and W—E as well as N 60°E (Wilkman 1931, p. 150). Some diabase dykes observed in road cuts at Hallaperä and south of Kilpijärvi dip 60—70°E.

The diabase dykes vary in width from less than a metre to 200 to 300 metres, and they often extend into laccoliths 3 to 4 km long. The narrow dykes are generally fine-grained and often massive, as are those at Hallaperä, Niemiskylä, south of Kilpisjärvi and in the environment of Sulkavanjärvi. In the wider dykes and laccoliths the rocks are fine-grained and compact near the contact, but farther away they gradually become more coarse. The texture is distinctly ophitic, plagioclase occurring as lath-shaped tabular crystals. Very coarse-grained pegmatitic gabbro-diabase occurs north of Tuli—Toiviainen west of Rytkynjärvi, where plagioclase laths and intergrowths of hornblende-cummingtonite exhibit grains from 5 to 10 cm in diameter. The rock also contains abundant magnetite as large grains from 2 to 3 cm in diameter. The plagioclase is andesine ($An_{c.40}$),

The mineral parageneses of the ophitic gabbros and diabases in the area reveal certain differences on the basis of which the rocks may be classified into three groups:

1. Plagioclase + Hypersthene ± Diopside-Augite ± Hornblende ± Biotite and accessories Opaques and Apatite
2. Plagioclase + Diopside-Augite + Hornblende-Cummingtonite + Biotite and accessories Opaques + Apatite
3. Plagioclase + Hornblende or Hornblende-Cummingtonite ± Biotite and accessories Opaques + Apatite ± Titanite.

The composition of plagioclase varies appreciably, generally being labradorite (An_{62-71}), now and then even bytownite (An_{82}). An-contents lower than average (An_{40-47}, even An_{34}) are possibly the result of the intrusion of diabases by pegmatites and granites.

Orthopyroxene occurs in the first group alone or with clinopyroxene. It is generally hypersthene, although enstatite has been encountered in one dyke. The hypersthene is faintly, yet distinctly, pleochroic x = brown-reddish, z = greenish. The margins of the grains display some alteration into diopside-augite and further into hornblende or hornblende-cummingtonite.

Diopside-augite occurs in the second group without hypersthene. It is very pale green, optically positive, and with $c \wedge z$ that ranges from 40° to 48°. Lamellar twinning is visible in some of the grains. The margins and cleavages of several of the diopside-augite grains have altered into hornblende or hornblende-cummingtonite.

The pleochroism of hornblende in the intergrowths of hornblende and cummingtonite is pale yellow-green to blue-green or green, and in the homoaxial cummingtonite almost or wholly colourless. Lamellar twinning is also present in the cummingtonite. The core of the amphibole grains in the coarse-grained gabbro diabase at Tuli—Toiviainen is cummingtonite, whereas the margins in contact with plagioclase are hornblende.

Biotite may by present in the mineral assemblages of all the groups. It is evidently a secondary alteration product of pyroxenes or amphiboles. Its pleochroism is light brown to dark brown.

The accessories are generally apatite and the opaques magnetite, ilmenite and sulphide minerals. A more rare accessory is titanite, which occurs as leucoxene with a core of ilmenite. The most common sulphide mineral is pyrrhotite with a scant Ni tenor in some places, e.g. at Niemiskylä and south of Osmanginjärvi. Other sulphides are sparse chalcopyrite and pyrite.

In the pyroxene granite area, porphyry granite and coarse-grained pyroxene granite intrude the diabases and ophitic gabbros with sharp contacts and often contain angular or rounded fragments of diabases. The diabase dykes are further cut by veins of aplitic and pegmatitic granite.

The radiometric ages of the ophitic gabbros and diabases in the Kiuruvesi area have not yet been determined. Wilkman (1925, pp. 30—31) estimated that the diabases of Sonkajärvi and Varpaisjärvi are at least Postjatulian, if not Postjotnian in age; radiometric determinations are also lacking for the diabases in those areas. The mineral assemblage of the gabbros and diabases of central Pohjanmaa (cf. Mäkinen 1916, pp. 65—70) is similar in some respects to that of the ophitic gabbro diabases of the Kiuruvesi area except that to olivine has been noted in the Kiuruvesi rocks. In the 1971 Annual Report of the Geological Survey (1972, p. 16) the zircon from gabbro of Someronperä, Ylivieska, was dated by Kouvo at Pb^{207}/Pb^{206} 1920, Pb^{207}/U^{235} 1895 and Pb^{206}/U^{238} 1875 Ma. "It is quite probable that the rest of the gabbros in the Pohjanmaa region are of similar age" (Pesonen and Stigzelius 1972, p. 9). The diabases of the Kiuruvesi area are between the hypersthene-bearing dioritic rocks and pyroxne granites in age, since it has been observed that whereas the diabases cut the hypersthene-bearing granodiorites, quartz diorites and diorites, the diabases themselves are crosscut by pyroxene granites and porphyry granites. The age differences between all these rocks are small, as shown by the ages of the pyroxene granites, the hypersthene-bearing granodiorites and the quartz diorites of the Raahe—Lake Ladoga zone compared with those of the Ylivieska gabbro. The gabbro diabases, at least the ophitic varieties, are probably contemporaneous with the Ylivieska gabbro.

According to Neuvonen (oral communication 1974), the remanent magnetisation of all the diabase rocks in the area reveals the same orientation, consistent with the direction observed in the synorogenic Svecokarelian intrusive rocks in Finland, e.g. the Ylivieska gabbro.

Pegmatite and aplite dykes

The pegmatites in the area are members of the granite pegmatite group and are simple pegmatites. They are encountered throughout the area, either as irregularly oriented dykes, 10 m in width at the most, or as smallish bodies from 5 to 50 m^2 in extent. The pegmatites cut all the other rock types and constitute two distinct series, different in age and formed during different orogenic phases, which cut each other and display sharp contacts with their country rocks.

The main constituents of the pegmatites are quartz, generally pale or watery grey, sometimes smokey grey in colour, poikilitic microcline, commonly pink in colour, and frequently also biotite or muscovite. Readily recognizable plagioclase is more sparse. At Salmenkylä a plagioclase-bearing pegmatite dyke cuts pyroxene quartz diorite. Northwest of Kalliojärvi, oligoclase-microcline pegmatite occurs as dykes and bodies cutting their host rock. In addition to quartz, potassium feldspar and micas, local occurrences of tourmaline and garnet as well as clusters of fine-grained apatite are met with. Tourmaline-bearing pegmatite has been encountered at some sites, e.g. in the dyke intruding the hornblende gneiss and porphyry granite east of Kangaslampi, in the garnetiferous dyke that crosscuts the veined gneiss west of Vaaksjärvi, in outcrops at Huttumäki and in dykes penetrating the garnetiferous mica gneiss in the environment of Iso Hanhilampi northeast of Sulkavanjärvi. At the last-mentioned site the crystals of tourmaline and garnet are in the core of a pegmatite dyke, 0.5 to 1 m in width, whose margins are composed of a mixture of finer-grained quartz and potassium feldspar.

TECTONICS

Great tectonics: The Raahe—Ladoga zone

The bedrock in Finland is cut by a major fracture zone over 100 km in width that crosses the country from Ladoga in the USSR to Raahe on the Gulf of Bothnia. The presence of this zone is corroborated in a variety of ways including:

1. Aerial photography and topography, which show the zone to be composed of wery pronounced fault lines trending northwest to southeast. The waterways, valleys and eskers (Hyyppä 1954) tend to trend northwest to southeast conformably with the tectonic fault lines (Härme 1961, 1963 and 1966). The fracture maps compiled by Härme (1961, p. 440) and Mikkola and Niini (1968, p. 26) show the Raahe—Ladoga zone to be one of the most marked fault lines in Finland. The main fracture trends of the zone have been depicted by Salli (1970 p. 4) for central Pohjanmaa and by Talvitie (1971) for the Kuopio area. Less conspicuous fractures run sub-perpendicularly or diagonally to the NW—SE fault lines. Tuominen *et al.* (1973, Plate 2) have discerned the Raahe—Ladoga zone in ERTS pictures of the central Baltic Shield, in which it is crosscut by shear zones of other trends.

2. Penttilä (1963, pp. 26 and 28) has noted a third group of epicentres in eastern and central Finland running from Ladoga to Raahe—Oulu. According to Beloussov (1969 p. 541), "at the present time, all rifts appear to be zones of very high seismic activity, which indicates that the displacements along faults are still occurring".

3. The aeromagnetic map published by the Geological Survey of Finland in 1973 indicates strong magnetic anomalies in the direction Raahe—Ladoga. This observation had been made earlier by Paarma (1963, p. 34).

4. The Bouguer gravity anomaly map by Honkasalo (1962) shows a trend of 325° right through central Finland (Talvitie 1971, p. 28).

5. The trends of the diabase dykes at many localities in this zone coincide with those of the joints (Wilkman 1925, 1931 and 1938), indicating that jointing developed deep in the crust contemporaneously with the formation of the diabase dykes (Laitakari 1969). Peive (1960) proposed that the movements in the crust took place not only vertically but also horizontally, even along the Mohorovičić discontinuity.

6. Wahl (1963) pointed out the occurrence of abundant hypersthene granites in this zone.

7. The abundance of ore deposits is striking in this zone, and as Peive (1960) pointed out, mineralisations favour major fracture zones. According to Paarma and Marmo (1961), Mikkola and Niini (1968), Mikkola (1971), Gaál (1972) and Kahma (1973), the movements associated with the fault zone running northwestwards from Lake Ladoga controlled the genesis of the sulphide ore melts in the vicinity of this zone.

Tectonics of the Kiuruvesi area

The Kiuruvesi area is a part of the Raahe-Ladoga zone (p. 7, Fig. 1). Its tectonic structure is marked by diversity, but by gathering the abundance of details into one coherent image, we may do much to solve the geologic evolution of the area.

Planar structures

Bedding

The only rock with moderately well-preserved bedding is the mica schist-conglomerate at Vieremä—Haajainen. Elsewhere the bedding is manifested as the alternation of acid and basic volcanites in particular. Migmatisation and granitisation have destroyed bedding structures in the mica gneisses and hornblende gneisses, and thus the bedding is not readily determined.

In many places the conglomerate-mica schist of Vieremä—Haajainen trends conformably with the bedding; shearing along the basal formation, however, has given rise to intense fracture cleavage with a dip steeper than that of the bedding. In the southern part of the area the bedding strikes N 5—10°W, but in the northern part in the mica schist it may strike N 45—50°W. The dip is 30—40°W. The top of the bedding, where definable, faces to the west.

Schistosity

The schistosity is variable, the prevailing strike being NW—SE (see Appendix 2). Between the lakes Kiuruvesi and Hautajärvi the schistosity curves conformably around the margin of the pyroxene granite massif. Its dip becomes steeper from southwest of Kiuruvesi towards Hautajärvi. In the area between Koivujärvi and Tuomijoki the schistosity strikes mainly from northwest to southeast; its dip is c. 40° NE and steepens towards Tuomijoki.

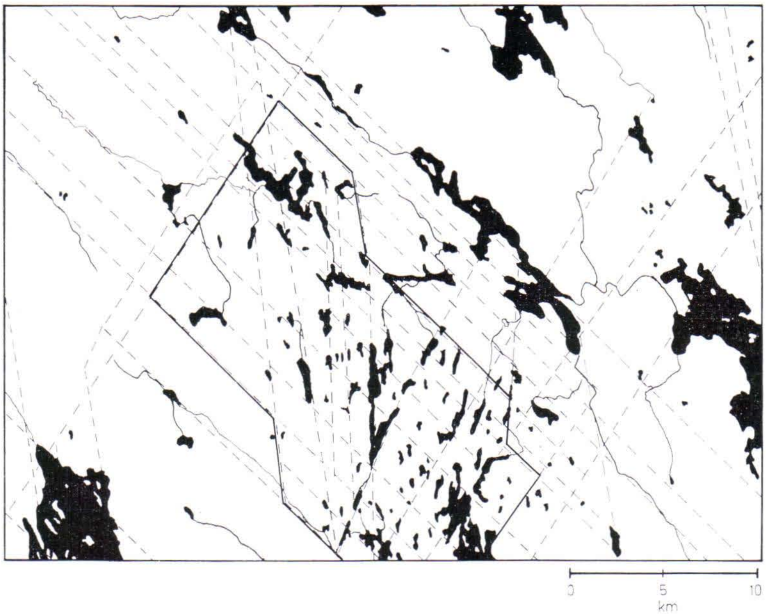

Fig. 30. Main fracture directions in the Kiuruvesi investigation area. The heavy line outlines the Sulkavanjärvi—Niemisjärvi block.

Another prevailing strike of schistosity is N 10—20° W, well marked in many places in the eastern part of the area and at Koivujärvi. In the central and western parts of the area the schistosity strikes almost N—S and the dip tends to be steep. There are also some zones in which the schistosity is N 45° E and N 30° E.

In the environment of Niinimäki, in the western part of the area, the schistosity seems to emphasize the dome-like structure of the basement gneiss complex. To the north the schistosity dips 70—85° N and to the south 70—85° S. At Sulkavanjärvi the schistosity curves around the edges of the granite massifs as at Hautajärvi.

Jointing, faults and shear fractures

The crust in the area has obviously been broken on many occasions. The joints that originated at various depths during the Precambrian have filled with basic and acid melts. The direction of these opened joints can be determined from the trends of the dykes of diabase (cf. p. 65), peridotite (cf. p. 61), pegmatite and aplite.

The joints tend to conform to the faults and fractures. The exposures in the valleys and on their slopes display parallel jointing and minor faults due to movements in the main fracture zone. Poorly developed jointing perpendicular or sub-perpendicular to the schistosity is visible in the schists and gneisses. Typical of the granite massifs are two vertical joints that intersect each other perpendicularly and sub-horizontal jointing perpendicular to them. At Salmenkylä, this horizontal jointing forms dome-like shapes in pyroxene granite. The fractures in the area constitute narrow parallel zones with the following trends: 1. dominant c. N 45° W; 2. ubiquitous but only locally distinct c. N 10° E; 3. from Koivujärvi to Hallaperä c. N 35° E, the parallel set from Salmenkylä to Petäjäselkä and that trending c. N 25° E from Rytky to Ryönänjoki; 4. almost N—S, most clearly visible from Rytky to Hautakylä (Fig. 30).

The faults and fractures are "en échelon", and the age relations of the fractures are discernible in several places. The older fractures occur as breccias, banded structures and mylonites. The oldest indications, which derive from orogenic movements and include the breccias along the boundary of the communes of Kiuruvesi and Pielavesi on both sides of Sulkavanjärvi, are located at the intersection of fracture lines. Augen schist and mylonite occur in fracture direction N 5—10° W, 65—75° W at the eastern margin of the Vieremä—Haajainen sequence. In the younger fractures the rocks are broken, as in the railway cut at Aittojärvi where they trend N 45° W and N 30° E. Other examples of young faults are the slickensides in the pegmatite dyke west of Jysynmäki, near the Koivujärvi road.

The sequence of the fracturing is manifest in the fracture directions, the fractures trending NW—SE and N 25—35° E being older than those trending N 10°W and N—S, since the latter cut the former.

Steep faults trending in different directions seem to break up the bedrock of the area into blocks.

Linear structures

Folding and fracturing have produced lineations that are revealed as the stretching of individual minerals, fragments and conglomerate pebbles in the direction of movement. The slickensides of the various rock types exhibit, conform with the main fractures, lineations that are no doubt related to faults generated by fragmentation of the bedrock.

In the southwestern and western parts of the area the lineations trend between SE and E, the plunge being rather moderate, from 15° to 40°. In the northeastern quarter of the area, however, the predominant strike is SW, the plunge fluctuating between 45° and 80°. This trend is pronounced between Hautajärvi and Kiuruvesi. The lineations measured from the stretched pebbles of conglomerate at Vieremä—Haajainen are S 40—55° W, 60—75°.

Folding

The rocks in the area exhibit minor folds whose axes are often parallel to the lineation, and whose axial plane represents the local plane of foliation. Such folds resemble the plastic deformation created by faulting, and are suggestive of the drag folds of major folds.

The kink band structure in some rocks, for example in the cordierite-garnet-anthophyllite rock north of Ruosteenmäki, some 2 km northwest of Kalliojärvi (Fig. 21), is the result of compression in a W—E direction that folded the earlier schistosity and banding through the agency of faults trending NE—SW. Compression in this direction produced drag folds with an axial trend of N 10° E, 5° N in the Vieremä—Haajainen mica schist. Simultaneously, the pelitic intercalations in psammitic beds were foliated as at Petäjäselkä.

Geosynclines

According to Väyrynen (1954, p. 172), the area west of Kuopio constituted an extensive marine geosyncline and was the site of deposition of the Savokarelian sediments.

Stille (1941), Kay (1951) and Badgley (1965) classify geosynclines as eugeosynclines and miogeosynclines. According to Stille (1941, p. 15), abundant volcanic eruptions are associated with eugeosynclines ("truly or wholly geosynclines"), especially during their late stage, but are totally lacking from a miogeosyncline ("lesser geosyncline"). A eugeosyncline is defined by Kay (1951, pp. 4 and 107) as a surface that has subsided deeply and relatively rapidly in a belt having active volcanism. A miogeosyncline is also a surface of deep subsidence, but in a belt lacking active volcanism. The subsidence is not so rapid as in the eugeosyncline (Badgley 1965, p. 475).

In the present investigation area there are sedimentary sequences whose genesis is consistent with the forementioned geosynclinal stages. Kiuruvesi is the site of a typical eugeosyncline sedimentary series associated with volcanites and sediments; Vieremä is representative of a miogeosyncline series, and is marked by the occurrence of Vieremä—Haajainen sediments.

Gaál and Rauhamäki (1971) have described eu- and miogeosyncline stages from the Haukivesi area, likewise in the Raahe—Ladoga zone.

Block tectonics

According to Jenks (1971, p. 1218), "the eugeosynclines are principal zones of relative vertical movements. During an active tectonic stage there will be blocks rising and relatively hot adjacent to blocks sinking and relatively cool. In geologically old terranes, the roots of the former may now be exposed as domal or diapiric gneiss and segments of other high-grade metamorphic rocks. These once deep rocks may now be close to blocks which sank syntectonically in compensation". He also maintains that the marginal belts, tilted and faulted between rising and sinking blocks, are zones of instability.

The following block model may be constructed in the Kiuruvesi area on the basis of tectonic elements and the petrology of the rocks. The area between Sulkavanjärvi and Niemisjärvi, outlined in Fig. 30 by heavy lines, constitutes a tectonic block distinct from the rest of the environment. Inside this so-called Sulkavanjärvi—Niemisjärvi block the majority of the rocks were crystallised at high temperature and high pressure under conditions of the pyroxene gabbro-granulite facies (p. 101), whereas outside it, conditions were akin to those of the amphibolite facies. The narrow transitional zone from the amphibolite facies to the pyroxene gabbro-granulite facies is composed of rock types whose formation requires high temperature but not high pressure. It may be inferred from the breccias and banded structures that movements played a key role in this contact zone. Northeast of the Sulkavanjärvi—Niemisjärvi block, the dips and lineations of schistosity grow steadily steeper in a southwestern direction, that is, towards the block; similarly, southwest of the block the dips of schistosity steepen in a northeastern direction, likewise towards the block (cf. Appendix 2). The NE—SW direction at the northwestern edge of the block is not so well defined, but at the southeastern edge the transition between rock types and facies clearly distinguishes the block from its environment.

The block was probably formed during an early stage of orogenic movements. The forces trending NNE—SSW caused a part of the geosyncline basin to subside (Fig. 32 II). The rocks in this block were deformed under the new conditions as a result of partial or total melting and recrystallisation. At a later stage of orogeny the block was uplifted once more at the same time as or immediately before the subsidence of the Vieremä—Haajainen area (Fig. 32 III).

Kauppinen (1973) has described faults from the nearby Iisalmi area that trend in various directions and are the result of horizontal movements along a subvertical plane (wrench faults). Furthermore, the blocks bounded by the faults have been squeezed upwards. According to Kauppinen (1973), evidence of block movements is provided by the gneisses in the elevated blocks; these gneisses underwent a higher degree of metamorphism and are more intensely magnetised than are the gneisses in the environment. Typical of the marginal zones of these blocks are the secondary schistosity and the aplitic potassium feldspar-rich rocks.

Some features in the Kiuruvesi block are analogous to those in the Jotunheimen block in the Norwegian Caledonides described by Battey and McRitchie (1973). Here the core of the central massif comprises ultramafic rocks and pyroxene-gneisses of pyroxene-granulite metamorphism, peripheral gabbros, and granitic rocks of amphibolite facies metamorphism. Sparagmites are encountered outside the central massif. According to Battey and McRitchie (1973), the core rocks were metamorphosed at pressure > 4 kb and tectonically elevated from a root in the Faltungsgrabe during the Caledonian orogeny. It is the opinion of these two authors (*op.cit.,* p. 240) that the fault lines trending in various directions and bounding the central massif dip towards the core, and also that feldspathic crush-rock and retrograded pyroxene gneisses occur in the fault lines.

STRATIGRAPHY

Regional stratigraphy

The general geologic features of the Kiuruvesi area show it to be part of a large fracture zone affected by vertical block movements as well as the ensuing partial melting (p. 85) and recrystallisation of the rocks. The stratigraphy of the rocks is not readily established owing to the almost total lack of primary structural features.

The basement gneiss complex constitutes a depositional basement for the volcanic rock sequence in the area. The sequence commonly progresses from basic to acid volcanites by way of alteration varieties whose existence refers to numerous stages of volcanic activity.

On the eastern flank of Liittovuori the acid tuffitic leptites occur in the lower part of the volcanic sequence. They are overlain by banded diopside amphibolites containing leptite beds as narrow ribbons. At Honkaperä the volcanic sequence starts with a bed of fragmentary lava underlain by intesely migmatised basement gneiss. The sequence overlying the fragmentary lava from bottom to top is agglomerate, basic and intermediary tuffaceous schist (amphibolite and plagioclase tuffaceous schist), and banded leptite derived from tuff that grades upwards into acid leptite.

Bands of skarn are encountered in these acid schists at several localites, including Koivujärvi, north of Lavapuro and the western shore of Niemisjärvi. Stratigraphically, the carbonate-skarn rocks are located in the lower part of the volcanic rock sequence and are thus often associated with the leptites. The occurrence of skarn-carbonates on Huutsaari is apparently overlain by the leptite referred to as quartzite by Wilkman (1938, p. 46).

The Tommonmäki and Siikalahti skarns were presumably formed in the interval between the formation of pyroxene quartz diorites and pyroxene granites during the orogenic phase.

The rocks of the volcanic sequence pass gradually into sediments. At Honkaperä the acid leptites with increasing biotite content grade into mica gneiss. East of Riitamäki, in the southeastern part of the investigation area, acid leptitic schists are encountered in a bed several metres thick in mica gneiss (Fig. 15). In many places there are also intercalations of amphibolite in the mica gneiss.

Black schists and graphite-bearing gneisses are located in the boundary between the volcanic and sedimentary schists that initiate the sedimentary phase. According to Pettijohn (1957), black shales are typical of euxinic sedimentation, often at an initial geosynclinal stage.

Table 9
Stratigraphy of the Kiuruvesi area.

Phase	Event		Rock types	Age	
Erosive phase	Weathering and erosion		Discordance		
Orogeny II	Vertical tectonic movements Jointing	 Dykes	Broken quartz dykes in mica schist (Petäjäselkä) and faults in pegmatite dyke (northern part of Koivujärvi road) Pegmatite and quartz dykes		
	Folding	Regional metamorphism	Mica schists (Vieremä—Haajainen) Greywacke schists Conglomerate schist		
	Jointing and faults	Dykes and intrusions	Pegmatite and aplite dykes Gabbro and peridotite bodies		
Miogeosyncline phase	Sedimentation		Pelites and psammites (Vieremä—Haajainen) Greywackes Conglomerates		Svecokarelian
Erosive phase	Erosion Weathering		Faint discordance		
Orogeny I: Late orogenic phase	Jointing, faults and block movements: uprising block. Folding reduced	Dykes and intrusions Granite intrusions	Pegmatite, granite and aplite dykes intruding one another and the older rock types Basic intrusions Tectonic breccias Porphyry granites intruding pyroxene granites Pyroxene granites intruding ophitic gabbros and diabases	1870—1900 Ma	
Orogeny I: Intraorogenic phase	Jointing and faults	Dyke intrusions	Skarn-like dykes (Tommonmäki) Ophitic gabbros and diabases	about 1900 Ma	
Orogeny I: Synorogenic phase	Block movements: sinking block	Partial anatexis	Partially melted and recrystallised pyroxene-bearing granodiorites, quartz diorites, diorites and cordierite-bearing rocks of the basement, volcanic and sedimentary layers. Breccia and migmatisation	1910—1930 Ma	
	Folding starts	Metamorphism	Gneissation of pelitic and psammitic sediments Metamorphism of volcanites: amphibolites and leptites Gneissation continues in basement complex		
Eugeosyncline phase	Sedimentation Volcanism		Pelitic and psammitic sediments Acid, intermediate and basic volcanites: tuffs, tuffites, agglomerates and lavas		
Erosive phase	Erosion Weathering		Discordance		
			Basement: ortho and paragneisses containing ghostlike inclusions	Presvecokarelian ~ 2500 Ma	

Table

A comparison of the strati-

The Haukivesi area Gaál and Rauhamäki (1971)	Central Pohjanmaa Saksela (1932, 1933)	Central Pohjanmaa Salli (1956, 1964)
Granite veins		
Basic dykes		
Coarse-porphyrite granite to quartz diorites	Microcline aplite (late orogenic)	Microcline granite (late orogenic)
Intermediate to ultrabasic mangeritic intrusion (1925 Ma) and schollen-migmatites	Microcline quartz diorite and diorites Gabbros (late orogenic)	Granodiorites (synorogenic)
Trondhjemite and migmatisation	Granodioritic orthogneiss (synorogenic)	Ophitic gabbro-diorites (synorogenic)
Miogeosynclinal stage: Savonlinna: Cordierite-gneiss | Rantasalmi: Meta-turbidites	Migmatised biotite-plagioclase gneisses	Volcanogeneous schists
Miogeosynclinal stage: Conglomerates	Black schists, intercalations of greenstones	Eugeosyncline deposition: Porphyroblastic mica gneisses
Eugeosynclinal stage: Volcanic amphibolites Basic pillow lavas Leptite Metapelites (Veined gneiss complex)	Leptite formation (volcanic leptites and biotite-plagioclase gneiss)	Eugeosyncline deposition: Greywacke-conglomerate schist Arkose-like leptite
Old basement probably existent	Basement unknown	Basement unknown

Owing to tectonic block movements during the initial orogenic phase, the basement gneiss and the overlying volcanic and sedimentary rocks were reworked as a metamorphosed gneiss complex. The orogeny was marked by the emplacement of anatectic intrusions (synorogenic hypersthene-bearing dioritic rocks) and purely intrusive rocks (late orogenic granites).

In the Vieremä-Haajainen area a new sedimentary sequence overlying migmatised mica gneiss was deposited in the newly developed depression, the miogeosyncline, that was the outcome of tectonic movements. This sedimentary sequence, which is composed of the erosion products of earlier rocks, begins with conglomerates that grade upwards into greywacke and pelitic sediments. During the second orogenic phase they were metamorphosed into the schists that are now visible in the Vieremä—Haajainen area.

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graphy of different regions.

	The Skellefte district in Sweden Kautsky (1957, 1959)		The Kiuruvesi area
	Revsund granite and pegmatites		Pegmatite and aplite dykes
Elvaberg series Marine facies	Fine-grained slates, lime-cemented weathering breccias Mensträsk-conglomerate **Fluvial facies (Vargfors series):** Dömanberg-conglomerate Greywackes, arkoses and sandstones Abborrtjärn-conglomerate	Miogeosyncline deposition (Vieremä—Haajainen)	Metamorphosed pelite, greywacke and conglomerate
			Porphyry granite Pyroxene granite Ophitic gabbros and diabases Breccia
			Pyroxene granodiorite
	Jörn granite (primorogenic, Geijer 1963)		Pyroxene quartz diorite and diorite (synorogenic)
Maurliden series	Graphitic slates and phyllites The Maurliden volcanites in the Skellefte volcanites Metamorphosed conglomerates, greywackes and pelites (The Maurliden slates)	Eugeosyncline deposition	Migmatitic mica gneisses, local graphite content Metamorphosed volcanites: leptites, amphibolites, agglomerates and lavas
	Basement unknown		Basement: ortho- and paragneisses

The stratigraphy and geologic evolution of the area are illustrated schematically in Table 9.

A comparison of stratigraphy

Other regions suitable for stratigraphic comparison with Kiuruvesi are Haukivesi in Savo and Ylivieska in central Pohjanmaa, both of which are in the Raahe—Ladoga zone. Another region of interest for its rock types and their stratigraphy, despite its distance from the Kiuruvesi area, is the Skellefte district in Sweden. Similarities abound in the stratigraphic sequences and their crosscutting intrusive rocks in all these regions (Table 10).

The same two phases (eu- and miogeosyncline) noted in the Haukivesi area by Gaál and Rauhamäki (1971) are also present in the Kiuruvesi area. At Haukivesi the eugeosyncline phase starts with the deposition of pelitic and psammitic sediments, now metamorphosed into veined gneisses. A deposit of volcanic rocks is stratigraphically on top of these veined gneisses (Gaál and Rauhamäki 1971). This position is the reverse of that in the Kiuruvesi area, where the volcanites start the sequence. According to Saksela (1932, 1933), the lowest unit is a leptite formation consisting mainly of volcanic leptites and biotite-plagioclase gneisses as well as arkose-like leptites. The biotite-plagioclase gneisses proper overlie the leptites with black schists intervening. According to Salli (1964, p. 45), the Ylivieska—Himanka formation is part of a eugeosyncline with arkose-like leptites on the bottom and volcanites at the top. In the Kiuruvesi area the stratigraphy of the volcanic rocks and the migmatitic mica gneisses overlying them seems to be analogous to that described by Saksela (1932, 1933) from central Pohjanmaa.

In the Skellefte district, Kautsky (1957) has divided the supracrustal rocks into two sedimentary cycles of different ages, the older being the Maurliden series and the younger the Elvaberg series. In the Kiuruvesi area the equivalent of the Maurliden series seems to be the volcanic series of the eugeosyncline.

Saksela (1932, p. 32) and Salli (1964) both maintain that the basement of the deposits is not known. Neuvonen (1971, p. 22), on the other hand, has proposed that the Kannus granodiorite, an apparently recrystallised orthogneiss, represents the basement upon which the biotite-plagioclase gneiss was deposited. In the Haukivesi area, Gaál and Rauhamäki (1971, p. 270) consider that the basement will be found, but in the Skellefte district at any rate, the basement has still not been established (Kautsky 1957). In the Kiuruvesi area the basement probably consists of ortho- and paragneisses.

The miogeosyncline sediments of the Haukivesi and Kiuruvesi areas, as well as the Vargfors fluvial sediments of the Elvaberg series (Kautsky 1957; Geijer 1963, p. 114) are all alike in stratigraphic position. The conglomerate of Vieremä—Haajainen contains pebbles of volcanic and sedimentary schists just as does the Savonlinna conglomerate in the Haukivesi area (Gaál and Rauhamäki 1971) and the Abborrtjärn conglomerate in the Vargfors series of the Skellefte district (Kautsky 1957, 1959).

In the Ylivieska—Himanka area in central Pohjanmaa the pebbles in the conglomerate are mainly quartz, volcanogeneous rocks and quartz-feldspar schist (Salli 1964). Plutonic pebbles proper seem to be lacking, but the stratigraphically similar Haapajärvi conglomerate near Lake Settijärvi contains quartz dioritic as well as volcanite and leptite pebbles (Mäkinen 1916, p. 24; Wilkman 1930, p. 45; 1931, p. 82). In the stratigraphic column of the Ylivieska—Himanka area given by Salli (1964) conglomerate underlies basic volcanites. The conglomerate pebbles described by the same author (1964, p. 36) include abundant volcanic rock types (plagioclase porphyrite, uralite porphyrite and amphibolite), but in his stratigraphic column he places these above the conglomerate. It is simpler to assume that the sequence of beds is the reverse, in other words, the same as in the Vieremä area.

The deposits overlying the eugeosyncline sediments in the Kiuruvesi area and the sediments of the Maurliden series in the Skellefte district are absent from the Ylivieska—Himanka area (Salli 1964, p. 45) even though the conglomerates seem to occupy an analogous position.

The intrusives in these areas consist of syn- and late orogenic rocks intruding older schists. The granitic and dioritic intrusions and gabbros were emplaced during the synorogenic phase, and the coarse-grained and porphyric microcline granites during the late orogenic phase. In the Haukivesi area there are mangeritic intrusions (Gaál and Rauhamäki 1971) that correspond to the hypersthene-bearing pyroxene quartz diorites and pyroxene diorites of the Kiuruvesi area. In both areas the rocks have been dated to c. 1925 Ma. The rocks of the Haukivesi and Kiuruvesi areas have their counterparts, but stratigraphically the most marked difference is in the location of the intrusive rocks. The difference in age is not great, since the miogeosyncline in the Kiuruvesi area was formed immediately after or because of the elevation of the central block at Sulkavanjärvi—Niemisjärvi. Young intrusions include the Revsund granite in the Skellefte district, which intrudes the Maurliden and Elvaberg series (Kautsky 1957, 1959). By applying other methods, Welin (1970, p. 441) has estimated its age as 1 785±40 Ma. In the same stratigraphic position as the Revsund granite are the pegmatite and aplite dykes of the Kiuruvesi area, which crosscut the Vieremä—Haajainen series as well as the older schists and intrusive rocks. The age of these pegmatite dykes has not been determined.

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ORE MINERALISATION

Ore showings are encountered at several sites in the investigation area. Uneconomic sulphide occurrences are located 1 to 1.5 km northwest of Kalliojärvi (the Kalliojärvi ore deposit) and at Hallaperä on both sides of the Pyhäsalmi—Kiuruvesi road (the Hallaperä ore deposit). Ore mineralisation also occurs in the Koivujärvi area, in the volcanic zone extending from Lavapuro through Niemisjärvi to south of Hautajärvi, at Sahinperä west of Sulkavanjärvi and at Tuomijoki. In all these occurrences the ore deposits consist of Fe-, Cu- and Zn-sulphides. Nickel abundances worth mentioning have been met with in a serpentinite body on the northern bank of the pool Saarinen northwest of Sulkavanjärvi and in a gabbro at Niemiskylä south of Suolampi.

The Kalliojärvi ore deposit, which consists of five discrete ore bodies, is located in the contact zone of a cordierite-garnet-anthophyllite formation with migmatitic gneiss granites and mica gneisses intensely intruded by granitic material (Helovuori 1962). As a rule the Kalliokylä ore bodies exhibit breccia structure. The sulphidic matrix contains abundant fragments of country rock that are practically free from sulphides. The ore minerals, pyrite, pyrrhotite, chalcopyrite and sphalerite, are distributed heterogeneously between and within the ore bodies (Helovuori 1962).

The Hallaperä ore deposit is a narrow occurrence over one kilometre in length in a NW—SE trending fracture. The ore exhibits sharp contacts with the country rocks, which are composed of cordierite-garnet-sillimanite-biotite rocks and garnetiferous mica gneisses. The country rocks contain amphibolite inclusions parallel to the schistosity. Diamond core drilling has shown that the ore body is cut by faults trending northeast to southwest. The sulphides, pyrite, pyrrhotite, chalcopyrite and sphalerite, may have migrated to the fracture zone from a considerable distance.

The ore showing at Koivujärvi seems to be associated with acid volcanites in which sulphides may occur as veins of massive ore, about 2 m thick, composed almost solely of pyrrhotite. Outside the veins the sulphides are met with as bands and dissemination (Wilkman 1938, p. 46; Talvitie 1959). In the skarns and other adjacent rocks the sulphides occur only as dissemination or minor veins composed without exception of pyrite or pyrrhotite (Talvitie 1959).

Intensely folded pyrrhotite-rich hornblende schist is encountered on an island southwest of Huutsaari (Wilkman 1938, p. 32). The mineralisation seems to follow tectonic fracture zones. The sulphides of Fe, Cu and Zn are in association with acid and basic schists of volcanic origin as well as with cordierite-bearing rocks. At Koivujärvi, the country rocks include skarn-bearing limestone although here too cordierite-garnet-anthophyllite rocks are encountered in the vicinity.

The ore deposits in the Kiuruvesi area are located in the main sulphide ore belt of Finland (Kahma 1973). Nearby deposits are the Pyhäsalmi mine to the west and the Säviä ore deposit at Pielavesi to the south.

According to Helovuori (1964), the Pyhäsalmi ore deposit is located in a tectonic bend with volcanic leptites and amphibolites, cordierite and cordierite-anthophyllite rocks, mica gneisses and mica schists as country rocks. Carbonate rocks occur as inclusions in the ore. The ore, which consists of pyrite, chalcopyrite, sphalerite and pyrrhotite, exhibits breccia structures and contains locally abundant angular or subangular fragments of country rock.

The Säviä mineralisation, which contains pyrite, chalcopyrite and sphalerite, is located in a fracture system crosscutting the schistosity at a low angle (Laitakari 1968). The country rocks are cordierite-garnet-anthophyllite-sillimanite rocks and amphibolite (Kahma 1973, p. 12), and the mineralisation is largely of the breccia type.

The average date for Karelian lead is 2120 Ma (O. Kouvo in Rouhunkoski 1968, p. 84). Included in this age group are the Pyhäsalmi deposit, the Vihanti deposit about 100 km to the northwest and the Säviä mineralisation. The lead model age for the ore of the Pyhäsalmi mine is 2055 Ma (Kouvo and Kulp 1961), for the galenas of the Vihanti mine from 2025 to 2100 Ma and for the Säviä ore deposit 2080 Ma (O. Kouvo in the Geological Suvery of Finland, Annual Report on the Activities for the Year 1965, p. 15 and 1966, p. 15). Rouhunkoski (1968, p. 85) is of the opinion that the ore deposits of Karelian age are situated in a zone near the old basement.

The Skellefte district in Sweden is in the extension of the Lake Ladoga-Raahe belt. According to Vessby (1968, p. 293), "the sulphide ores (iron, zinc and copper sulphides) of Skellefte District formed in the upper parts of the Acid Volcanics or at the lower border of the Phyllite Formation". He further maintains that there are also cordierite-bearing rocks in connection with the ore deposits and that the large and important ores are strictly confined to zones of shearing. Welin (1971, p. 265) has dated the Skellefte district to about 2000 Ma.

Many typical massive Fe-Cu-Zn sulphide deposits seem to be associated with syngenetic eugeosynclinal sediments exhibiting submarine volcanism (Anderson 1969; Jenks 1971; Hutchinson 1973). The volcanites range in composition from basalts to rhyolites (Hutchinson 1973) and have been deformed as a consequence of intense movements including block movements and advanced metamorphism (Jenks 1971). Mobilisation and remobilisation of the ore material was marked during the later geologic processes that mobilised dispersed ore minerals into a concentration, or remobilised an existing concentration into a new locale (Jenks 1971). Hence, the ores may have been redeposited at sites up to several kilometers from the source (Jenks 1971). The mineralisation is probably confined to narrow zones of shear and fracture.

The frequent coexistence of cordierite-garnet-anthophyllite (or hypersthene) rocks and pyrite-chalcopyrite-sphalerite mineralisations may be attributed to the genetic implications of these rocks for volcanism and shear and fracture zones. The cordierite-bearing rocks indicate zones favourable for the formation of the Fe-Cu-Zn sulphides and so they may have an indicative value in exploration for sulphide ores of the forementioned type.

ANATEXIS AND PARTIAL MELTING OF THE ROCKS

Various anatectic phenomena are apparent in the rocks at Kiuruvesi and particularly in the Sulkavanjärvi—Niemisjärvi area. To clarify the circumstances in which these events took place, the author has collected from the literature accounts of laboratory experiments conducted on the melting and crystallisation conditions of the different rock types. The findings were applied to the conditions in Nature.

The numerical value of the geothermal gradient varies somewhat, the current average being about 30°C/km. It is assumed that the thermal gradient was appreciably higher during the Precambrian owing to the higher rate of heat generation caused by radioactive elements in the crust of the Earth (Brown and Fyfe 1972, p. 34; Heier 1973, p. 431). In the early history of the Earth the crust was thinner (Heier 1973, p. 431) and slushy crust may have been common at quite shallow depths (Brown and Fyte 1972, p. 34). The geothermal gradient may also vary locally. According to Barth (1962, pp. 303—304), the two main reasons for temperature increase are: 1. heat flow from the interior of the Earth, and 2. radioactive heat generated in the sediments themselves. Since there is more radioactivity in the geosynclinal sediments than in the average rock of the crust, the geosynclinal regions must be hotter than the enveloping crustal rocks. According to Wyllie and Tuttle (1960, p. 227), a value of 30°C/km is reasonable for the geothermal gradient in geosynclines, and if this remains constant with increasing depth, a temperature of 620°C is attained at 20 km (at about 5000 bars pressure). Fyfe (1973, p. 459) postulates that if Archean gradients approached 100°C/km, granulites could form at the base of a crust 8 to 9 km thick.

In the opinion of Wyllie and Tuttle (1960, p. 227), anatexis and partial melting play a key role in the metamorphism and deformation of rocks in orogenic zones. Winkler (1967, p. 195) maintains that the temperature required for anatexis is surprisingly low; at P_{H_2O} = 2000 bars, the temperature is about 700°C, and at P_{H_2O} = 4000 bars, it is about 680°C. These conditions are the same as those of the high-temperature part of the amphibolite facies. The maximum temperature attained by anatectic melts is probably about 800°C (Winkler 1967, p. 208).

Rocks with different compositions start to melt at different temperatures. According to Wyllie and Tuttle (1960, p. 234), "using a conservative estimate of 30°C/km (linear) for the geothermal gradient, the experimental data show that granitic rocks, arkosic sediments, and shales will begin to melt in the depth range from 20 to 25 km. The amount of liquid developed will depend upon the availability of water and other volatile substances. The liquid is granitic or granodioritic in composition". In most natural rocks where the biotite-hornblende content greatly exceeds the muscovite content, maximum melt production can be between about 750° and 950°C. Over this range, liquids are granodioritic in composition and tend to dioritic compositions at the higher temperatures; they also become correspondingly drier (Brown and Fyfe 1972, p. 30). "Amphibolite will melt first at temperatures of 1000°C or less and the product will be partially wet basaltic andesite. The residue will be peridotite or basic eclogite which, being anhydrous, will not melt until much greater depths are attained" (Brown and Fyfe 1972, p. 33).

In the light of the findings of Wyllie and Tuttle (1961) and Yoder and Tilley (1962), Miyashiro (1973, p. 22 Fig. 1—1) has compiled the variation in the melting temperature of the rocks as a function of temperature in the presence of aqueous solutions. Referring to these data, Miyashiro (1973, p. 21) states that the high-temperature limit of metamorphism may be estimated at about 700° to 900°C for most rock compositions in the presence of an aqueous fluid. The high-temperature limit of metamorphism should be considerably raised under dry conditions.

The origin and genesis of the hypersthene-bearing rocks

Holland (1900) proposed the term charnockite, which he defined as a hypersthene granite composed of quartz, microcline, hypersthene and accessory iron ores. He considers that the charnockite series is of magmatic origin and the various members, which vary from ultrabasic to acidic composition, are formed by magmatic differentiation.

According to Goldschmidt (1922), diorites and eventually granites are formed from basic magmas in the presence of water, as a consequence of fractional crystallisation. If the magma is exceptionally low in water, noritic magma develops into mangeritic magma, which further develops into hypersthene-granitic magma.

Dunn (1942, p. 23) considers that the evidence provided by rocks in India does not oppose the view that the hypersthene gneisses (charnockites) are products of the partial or complete palingenesis of very deep-seated rocks that had lost their water content.

Väyrynen (1954, pp. 112—113) emphazises that "pyroxene granites and granodiorites are distinctly sodium-predominant rocks of which some are located on the line describing the path of the crystallization of a dry feldspar mixture". According to him, "the coexistence of hypersthene with the both feldspars is possible only when there is a shortage of water, otherwise biotite would form. These rocks were completely solidified at high temperatures".

Parras (1958, p. 53) maintains that all the charnockites in western Uusimaa are of anatectic origin. The hypidiomorphic pyroxene granites were also recrystallised through the action of mobilisation.

According to Wahl (1963), the hypersthene-bearing rocks crystallised at high temperature from a magma depleted in water and volatile substances under high pressure. He suggests that the primary biotite granite magma was split or segregated into three magmas, one of which produced hypersthene granite. The crystallisation differentiation took place at great depth and the magmas were emplaced along the fractures in the crust.

Subramaniam (1967, p. 491) proposes that a granitic magma generated at lower crustal levels would, at depth, assimilate the granulites constituting the present basement, and differentiation would give rise to the charnockite suite of rocks. Thus he considers that charnockites are variants found in regions of granulite facies which have undergone magmatic crystallisation under high pressure environments. The high pressures and temperatures involved in granulite facies metamorphism may often induce mobilisation or melting, with consequent convergence of metamorphism and magmatism. To quote Subramaniam (*op.cit.* p. 491), " it seems therefore possible that rocks of the charnockite suite may have been emplaced, as any other granites during different orogenic epochs but under very dry conditions and high rock pressures".

According to Ramaswamy and Murty (1973, p. 171), "the charnockite series consisting of pyroxene granulites and charnockites are not formed by magmatic differentiation, although both units had their antecedents in igneous material . . . . The pyroxene granulites with the associated paragneisses are formed from the original sedimentary-volcanic sequence under granulite facies of metamorphism. The magmatic charnockites emplaced into these rocks resulting in the development of intermediate varieties by the partial assimilation and incorporation of the pyroxene granulites".

Deer *et al.* (1965, p. 151) propose the following reaction to describe the change in the rocks from the conditions of amphibolite facies to those of granulite facies:

$$\underset{\text{amphibole}}{Ca_2Mg_3Al_4Si_6O_{22}(OH)_2} + SiO_2 \longrightarrow 2\ \underset{\text{anorthite}}{CaAl_2Si_2O_8} + \underset{\text{orthopyroxene}}{MgSiO_3} + H_2O$$

The plagioclase feldspars of the intermediate and acid rocks of the granulite facies commonly have compositions in the sodic andesine range. Hornblende is unstable in the pyroxene-hornfels facies and plagioclase is one of the breakdown products. In Deer *et al.* (1965, p. 151) these reactions are expressed by the equation:

$$NaCa_2Mg_3Fe^{2+}Al_3Si_6O_{22}(OH)_2 + 4\ SiO_2 \longrightarrow NaAlSi_3O_8 + CaAl_2Si_2O_8$$

amphibole plagioclase

$$+ CaMgSi_2O_6 + Mg_2FeSi_3O_9 + H_2O$$

diopside orthopyroxene

The origin and genesis of the hypersthene-bearing granitic and dioritic rocks in the Kiuruvesi area

Holland (1900) proposed that the terms "charnockite series" and "charnockite" should not be used outside India, and so I have not applied these terms to the hypersthene-bearing granites and diorites of the Kiuruvesi area. All the hypersthene-bearing rocks in this area seem to be genetically related to each other.

Block movement took place in the Kiuruvesi area during the first orogenic stage (cf. p. 74). The basal formation and the overlying volcanic and sedimentary deposits were deformed during the sinking of the geosynclinal furrow and recrystallised under the conditions of amphibolite facies. The water-bearing minerals (biotite, hornblende, etc.) lowered the melting point of the rocks. Anatexis and partial melting took place in the lowermost part of the column (Fig. 32 II).

The anatectic "magma", dilated at high temperature, lifted the overlying crust and gave rise to fracturing. The volatiles and water escaped from the "magma", which then became dry. As a result of the decrease in pressure and temperature, the upper part of the "magma" recrystallised, and hypersthene-bearing quartz-diorites and diorites were procuced. Less space was required and fractures appeared in the crystallised crust. The fractures were filled with diabase dykes and laccolithic ophitic gabbros.

As the block continued to rise, granitic "magmas" later penetrated its margins (Fig. 32 III). They also crosscut the dioritic rocks crystallised earlier (pyroxene quartz diorites and pyroxene diorites) as well as the diabase dykes and ophitic gabbros. Porphyric granites were emplaced at the same time as and after the pyroxene granites. The latter derived from "magma" drier than that producing the porphyry granites, which is why the pyroxene granites contain hypersthene and diopside.

As Cann (1970, p. 339) has suggested, "granite formed by partial melting of wet sediments cannot rise far from the place where it is formed, and the high-level batholiths of orogenic belts must originate in a deep and drier environment, most probably from the cratonic crust forming the floor of the original geosyncline". Other wet magmas would not, he continues, be expected to be erupted as liquids.

Brown and Fyfe (1972, p. 33) hold that if a crustal block sinks fast, the sinking material remains relatively cold and thus the melt contains fragments. This is obviously what happened when the sedimentation furrow of the Sulkavanjärvi—Niemisjärvi block sank, as is suggested by the abundance of extensive bodies of mica gneiss and hornblende gneiss as well as of boudinage-like formations and distinct eruptive breccia structures within and along the margin of this block. Simultaneous vertical and horizontal movements also produced brecciation. The boudinages and fragments often exhibit zonal structures, from which it may be inferred that the cores of the bodies were once cold.

On the origin and genesis of the cordierite-bearing rocks

Several Finnish investigators share the opinion that the cordierite-garnet-biotite gneisses (the so-called kinzigites) are of sedimentary origin, to be more precise, of pelitic or greywacke-like origin (Eskola 1941, p. 459 and 1963, p. 201; Parras 1941, 1946; Hietanen 1943, p. 97 and 1947, p. 1023; Metzger 1945, p. 34; Simonen 1949, p. 18; Härme 1954, p. 36; Väyrynen 1954, p. 41). The cordierite-garnet-biotite gneisses in Lapland (cordierite granulites) are also sedimentary in origin, that is, argillaceous sediments or Al-rich claystones (Eskola 1952, p. 157 and 1963, p. 163; Scheumann *et al.* 1961, p. 334).

In the literature dealing with the origin of the cordierite-garnet-biotite gneisses it is widely accepted that they are derived from pelites (Turner and Verhoogen 1960; Turner 1968; Winkler 1967; Miyashiro 1973), although a volcanogeneous origin has also been suggested for these rocks (Kano 1961, pp. 3 and 5). According to Hietanen (1947), in the Turku region kinzigite layers are often intercalated with volcanics, especially in the border zones of the formations.

The cordierite-garnet-anthophyllite rocks, on the other hand, are regarded to be of both sedimentary and volcanic origin. It has been proposed that they are derived from volcanic-sedimentary leptites (Eskola 1914, p. 262 and 1950, pp. 93—95) and volcanic leptites (Geijer 1917), argillites (Tuominen and Mikkola 1950; Tuominen 1957, p. 19) or argillaceous rocks (Lal and Moorhouse

1969, p. 164), calcareous sediments (Reynolds 1947), hornblende- and quartz-hornblende schists (Tilley 1937) or schists very rich in hornblende (Vokes 1957), amphibolites, melanocrate to leucocrate plagioclase gneisses, quartzites and sillimanite gneisses (Bugge 1943). It has also been suggested that cordierite-garnet-anthophyllite rocks are alteration products of basic rocks such as amphibolites (Brøgger 1934), greenstones (Tilley 1935), basic volcanites (Simonen 1948, 1949, p. 40; Kano 1961) and mafic lavas (Vallance 1967).

According to Eskola (1914), metasomatic replacement caused the alteration of the leptites around the Orijärvi granite massif or other siliceous rocks into cordierite-anthophyllite rocks. Magnesium, iron and silicon migrated from the granite into the enveloping leptites, which were simultaneously depleted in lime, soda and potash. Geijer (1917) agrees with Eskola in his discussion of the genesis of the cordierite-anthophyllite rocks in the Falun region, Sweden. This model of metasomatic genesis, according to which the elements migrate in and out of a rock, has also been applied to the cordierite-garnet-biotite gneisses (kinzigites) of south and southwest Finland (Pehrman 1931, pp. 31—32 Wegman and Kranck 1931, p. 84). Tilley (1935, 1937) maintains that metasomatism, in which chiefly lime is removed and silica introduced, leads to the formation of cordierite-anthophyllite rocks.

Brøgger (1934) states that the formation of cordierite-anthophyllite rocks is an internal event and has no need of substances from an external source. Rather, elements are depleted from the rock, and thus its composition is altered. The metamorphic removal of calcium and alkalies from amphibolites makes the rock richer in Mg, Fe and Al. Gavelin (1939) likewise attributes the formation of cordierite-anthophyllite rocks to internal migration and metamorphic differentiation. In his opinion, the rock does not receive magnesium from outside.

Other supporters of internal migration are Pehrman (1936), Parras (1941, 1946), Hietanen (1943, 1947) and Metzger (1945, p. 333) in discussions on the genesis of the kinzigites in southwest Finland.

Reynolds (1947) introduced a new approach when he suggested that the Fe-Mg-rich hornfelses were produced Fe-Mg metasomatically by "an advancing basic front" during contact metamorphism. Simonen (1948, 1949, p. 40) maintains that the alteration into cordierite-anthophyllite rocks is a gradual process. The basic volcanites alter in connection with magnesia metasomatism into cummingtonite amphibolites and anthophyllite-cordierite rocks. Similarly, Vokes (1957) states that in the cordierite-anthophyllite rocks hornblende is first altered into cummingtonite and later into anthophyllite. According to Tuominen and Mikkola (1950, p. 90), cordierite-anthophyllite rocks are products of metamorphic differentiation. The process took place during strong penetrative movements and under hydrothermal conditions as a consequence of progressive regional (dynamothermal) metamorphism. Vokes (1957) further adds intense penetrative movement to the factors contributing to the formation of cordierite-anthophyllite rocks.

Kano (1961, 1963) is of the opinion that the cordierite-anthophyllite rocks are produced during metasomatic metamorphism through enrichment in Fe and Mg. This leads to an increase in volume in the cordierite-bearing rocks, and some features, such as schistosity, shear and fracture, may be due to the increase in volume through the one-way introduction of Fe and Mg (Kano 1961).

According to Sørbye (1964, p. 336), in the Haugesund peninsular, western Norway, "the metamorphism took place first during high temperature and moderate pressure when cordierite was formed at the expense of plagioclase and biotite. During slightly higher pressure anthophyllite was formed, possibly partly also at the expense of biotite. The peak of metamorphism is characterized by initial anatexis combined with partial metamorphic and tectonic differentiation". Vallance (1967) suggests that some altered mafic lavas have been converted locally to cordierite-anthophyllite hornfels by essentially isochemical metamorphism. According to Grant (1968, pp. 927—928), the assemblage plagioclase-biotite-cordierite-garnet-anthophyllite-quartz may be formed from metamorphosed sediments in the greywacke compositional range and to a lesser extent from some pyroclastic and igneous rocks of granodioritic to quartz dioritic compositions by the process of partial melting, filter pressing and recrystallisation.

Lal and Moorhouse (1969, p. 164) suggested a similar mode of formation for the cordierite-gedrite rocks. The removal of the granitic melt forming in the anatexis of rocks results in the relative enrichment of MgO and FeO. Cordierite and gedrite form at this stage. The chemical composition of the rocks is characterised by higher MgO and FeO and lower lime and alkalies than in the argillaceous and metamorphic rocks derived from them.

Robinson and Jaffe (1969, pp. 391 and 394) suggest three possible origins for the anthophyllite-cordierite-gneiss: 1) high temperature contact metamorphism and partial melting of previously existing rocks, 2) local low temperature hydrothermal alteration of volcanics to produce chlorite rocks, 3) volcanic-derived sediments of peculiar composition from weathered or hydrothermally altered terrains, perhaps by partial reaction with sea water.

Researchers have proposed the following modes of formation for cordierite-bearing rocks: a) the migration of metasomatic substances into and out of the original rock, b) the direct alteration of the original rock into cordierite rock, without metasomatism, and c) the current notion, that it was the partial melting of the rocks, together with anatexis accompanied by contemporaneous movements that gave rise to the metamorphic process due to which substances, often granitic and granodioritic fluid, migrated out of the primary rock. The melt left behind was enriched in iron and magnesium and crystallised under appropriate conditions as cordierite-garnet-biotite rocks.

On the conditions pertinent to the formation of cordierite-bearing rocks

In laboratory experiments 5 kb at 700°C is adopted as the limit of cordierite stability. Mg-cordierite is table at pressures of about 5 kb in K-bearing rocks, Fe-cordierites at 3.5 kb at c. 700°C (Schreyer and Seifert 1969; Seifert 1970). Cordierite-garnet assemblages may occur in the upper part of the cordierite stability field, garnet becoming unstable at a minimum pressure of 3.5 kb; below this only cordierite is stable (Seifert 1970). Most cordierite assemblages contain garnet, the cordierite tending to replace the garnet. The coexistence of cordierite and garnet has been used as a thermometer to evaluate the temperature of formation of the cordierite-bearing rocks. Gable and Sims (1969) have inferred that the cordierite assemblages and associated rocks in the central part of the Front Range, Colorado, were formed at a load pressure of 3 to 5 kbars and at a temperature of somewhat more than 620°C. Cordierite occurs there in three principal rock types: 1. potassium feldspar-bearing cordierite-garnet-sillimanite-biotite gneiss, 2. cordierite-biotite gneiss, and 3. cordierite-gedrite-biotite gneiss, each type containing several characteristic mineral assemblages. The composition and properties of the the minerals vary somewhat from one rock type to another.

Currie (1971) applies the rection

3 cordierite = 2 garnet + 4 sillimanite + 5 quartz

as a geological thermometer in the Opinicon Lake region, Ontario. According to him, the thermometer indicates temperatures of 600°C to 750°C and pressures of 5.7 to 6.7 kbars when it is applied to rocks showing petrographic evidence of equilibrium and chemical evidence of reaction between garnet and cordierite. These conditions for cordierite-garnet gneisses are believed to represent the hornblende granulite grade of metamorphism (Currie 1971).

Hensen (1972) has studied experimentally the $Mg/Mg+Fe^{2+}$ ratio of coexisting garnet and cordierite as a function of pressure and temperature for the rections

cordierite = garnet + sillimanite + quartz, and
cordierite + hypersthene = garnet + quartz.

The experimentally derived P-T grid has been tentatively used to determine the conditions of formation of natural cordierite and garnet-bearing rocks. The results indicate that most rocks of this type formed at temperatures between 700° and 850°C and pressures between 5 and 9 kb. Rarely temperatures as high as 950°C appear to have been reached during high-grade metamorphism (Hensen 1972).

Cordierite is characteristic of rocks rich in aluminium in the high temperature facies at low and medium pressures. It has a relatively low density, and is most typical in the metapelites of the high- and partly medium-temperature stages of contact and regional metamorphism. According to Dallmeyer (1972, p. 52), assemblages including cordierite, garnet, biotite and sillimanite are observed in high-grade, regionally metamorphosed areas the world over. They occur in pelitic gneisses, which are usually closely associated with charnockites and other granulitic rocks and are generally thought to reflect metamorphic conditions intermediate between the granulite and upper-amphibolite facies.

According to Miyashiro (1973, p. 212), the composition field of the rocks that form cordierite narrows with increasing pressure. Scheumann *et al.* (1961, p. 332) are of the opinion that cordierite may not extend to the granulitic deformation stage. They maintain *(op.cit.* pp. 334—335) that in the granulite area of Lapland for example, great parts of the rock association are formed by sedimentogeneous migmatic garnet gneisses with various amounts of cordierite. These rocks contain minerals or mineral combinations that usually occur either in the amphibolite facies or in the granulite facies. The amphibolite facies is indicated by green amphibole, cordierite and biotite, and the granulite facies by pyrope-rich pyralspite, hypersthene and hercynite. Shear or flow deformation is important in the development of the facies. In certain spheres of granulitic depth, these rocks intermediate between the amphibolitic and granulitic facies have been strained by shear movements (Scheumann *et al.* 1961, p. 335).

Eskola (1952, p. 164; 1963, p. 162) and Hietanen (1967) class the cordierite-garnet-biotite gneisses of Lapland (cordierite granulites) in a cordierite granulite subfacies of the granulite facies proper. Referring to Scheumann's studies of granulites, Eskola (1963, p. 162) admits that cordierite is an essential constituent of shear zones, and thus he changed the opinion he held previously as to the characteristics of cordierite rocks (Eskola 1952, p. 164). Also de Waard (1966) considers the biotite-cordierite-almandine assemblage to be a discrete subfacies. He states *(op.cit.* p. 481): ". . . the biotite-cordierite-almandine subfacies forms the lower P_{load} (or higher T) portion of the hornblende-granulite facies, bordering on the pyroxene-hornfels facies, and occupying that part of P_{load}-T conditions in which cordierite and almandine are stable in common pelitic rocks . . . The biotite-cordierite-almandine subfacies occurs predominantly in a regional-metamorphic setting, but it is also represented in some contact-metamorphic aureoles, and in intermediate cases it is found on a limited scale in and around plutonic domes" (de Waard 1966, p. 490). An example of the presence of the biotite-cordierite-almandine subfacies in contact-metamorphic aureoles is the occurrence of biotite-cordierite-almandine-orthoclase hornfelses, described by Chinner (1962), that developed from medium-grade regional-metamorphic schists adjacent to the Lochnager granodioritic intrusions in Scotland.

According to Winkler (1967, p. 72), as temperature increases, the hornblende-hornfels facies is succeeded by the K-feldspar-cordierite-hornfels facies, and it becomes possible for K-feldspar (commonly orthoclase) to coexist with cordierite.

Turner (1968, p. 308) maintains that the amphibolite facies does not include pelitic assemblages in which micas are associated with almandine, sillimanite and cordierite. These belong to the hornblende-hornfels facies. Turner *(op.cit.,* p. 255) holds that the association of sillimanite and cordierite with K-feldspar in pelitic rocks is a mineralogical characteristic of the pyroxene-hornfelds facies.

Katz (1972) classifies the high-grade regional metamorphic cordierite-bearing rocks of the Abukuma type from Ceylon into several groups. The pelitic groups comprises the following mineral assemblages: quartz-microcline-cordierite-biotite-(andalusite-muscovite-sillimanite), quartz-antiperthite-cordierite-garnet-biotite-(sillimanite-spinel), quartz-microperthite-sillimanite-garnet-biotite. Sapphirine is often present as a minor mineral and corundum has been found in some silica-deficient members. The basic group comprises the assemblages of plagioclase-hypersthene-diopside-hornblende-(biotite-garnet) and cordierite-hypersthene-biotite.

The critical conditions that determine the presence or absence of anthophyllite are still unknown (Turner 1968, p. 225). Eskola (1915) considered that the rock assemblages in the Orijärvi district belong to the amphibolite facies. More recently, Turner (1968, p. 195) has included such assemblages in the hornblende-hornfels facies. Turner *(op.cit.,* p. 195) places the assemblages cordierite-anthophyllite (-biotite) and cordierite-anthophyllite-almandine (-biotite) in the magnesium-rich paragenesis of this facies.

In the mineralogy of the various facies according to Mason (1966, pp. 268—269), the paragenesis anthophyllite-cordierite-almandine-biotite belongs to the amphibolite facies. Anthophyllite is completely lacking from the pyroxene-hornfels facies (Turner 1968, p. 225).

The occurrence of sapphirine the cordierite-anthophyllite(hypersthene)-bearing assemblages permits us to evaluate the conditions under which these rocks were formed. Schreyer and Yoder (1959, p. 102) report that the disintegration of cordierite may lead to the formation of sapphirine. Under water pressure the melting of cordierite is incongruent. At 5 kbars and 1090°C cordierite melts into spinel-sapphirine liquid, and at 10 kbars and 960°C to sapphirine liquid. According to Hensen and Green (1971), in the system MgO-FeO-Al_2O_3-CaO-K_2O-SiO_2 above 1000°C the breakdown of cordierite involves the phases sapphirine and hercynite-rich spinel in Mg-rich and Fe-rich compositions.

Nixon *et al.* (1973) give the mineral composition of the sapphirine granulite in Labwor, northern Uganda, as sapphirine, ilmenite, magnetite, hercynite-spinel, garnet, sillimanite, cordierite, hypersthene, corundum, biotite, feldspar and quartz.

They maintain *(op.cit.,* p. 427) that the depositions of ferruginous shales with siliceous bands was followed by burial and regional metamorphism under high-temperature and high-pressure (granulite) conditions, during which water and alkalies were removed as anatectic granitic liquid, pegmatites, etc. Sillimanite, garnet, ore/spinel, hypersthene and corundum were crystallised during this stage. Finally, cordierite, sapphirine and second generation sillimanite were unloaded and crystallised at high temperature. Experimental data indicate that the pressure must have fallen below 3 kb but that temperatures above 1050°C were maintained (Nixon *et al.* 1973, p. 427). The same authors further envisage this latter state as having taken place during refoliation in the roots of large shear zones several miles in dimension, which are represented at higher levels by belts of mylonites and shear gneisses.

According to Turner and Verhoogen (1960 p. 556), petrographic records are inadequate to show whether cordierite and sapphirine occur in the hornblende-granulite facies alone, or in both the pyroxene and the hornblende-granulite subfacies. They even suggest the possibility of defining a third subfacies. Nixon *et al.* (1973, p. 427) hold that the sapphirine granulites may be regarded as transitional to pyroxene hornfels facies.

The origin and genesis of the cordierite-bearing rocks in the Kiuruvesi area

According to Savolahti (1966, p. 383), at Juurikkajärvi in the Kiurvesi area the rocks containing garnet, hypersthene, cordierite and/or gedrite evolved from very different sedimentogeneous rocks such as amphibolites, mica gneisses and quartz-feldspar schists. Anatexis may have played a prominent part in their formation, and thus tectonic movements would have significance also as a factor producing the facies (Savolahti *op.cit.,* p. 384).

Earlier in the present paper (p. 41) the author described how the cordierite rocks occur in narrow zones alongside pyroxene granites and granodiorites, and in fracture lines inside and outside the Sulkavanjärvi—Niemisjärvi block. They are associated with rock assemblages characterised by the presence of volcanic amphibolites and leptites as well as sedimentary mica gneisses. It is often maintained that cordierite-anthophyllite rocks are derived from volcanites. Consequently, in the triangular diagram in Fig. 31 the points for the oxide contents of the elements in the basic and acid volcanites and cordierite rocks of the zone in question as well as of the rocks selected for comparison are taken from Tables 1, 3 and 6. The Fe_2O_3 of the analyses has been calculated to FeO. The diagram indicates that the formation of the cordierite rocks was accompanied by a change in total chemical composition. In the basic volcanites the Al_2O_2 content is much the same, whereas the $CaO+Na_2O+K_2O$

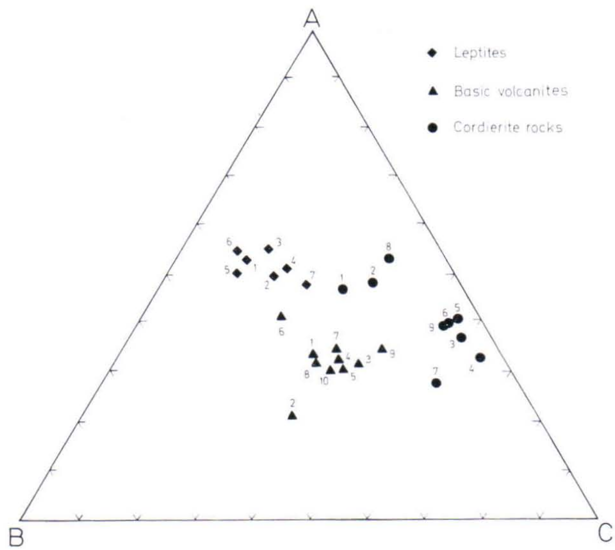

Fig. 31. The Al_2O_3 (A)-, $CaO + Na_2O + K_2O$ (B)- and $FeO + MnO + MgO$ (C) contents of leptites (Analyses 1—7 in Table 3, p. 29), basic volcanites (Analyses 1—10 in Table 1, p. 15) and cordierite rocks (Analyses 1—9 in Table 6, p. 44).

content is appreciably higher than in the cordierite-garnet-anthophyllite(hypersthene) rock. In fact, only the $CaO+Na_2O$ tenor is higher, there being so little K_2O in the two rock types. $FeO+MgO$ is considerably more abundant in the cordierite-garnet-anthophyllite(hypersthene) rocks than it is in the basic volcanites. In the cordierite rocks variation is observed not only in the amounts of oxides as shown in the triangular diagram but also in the abundance of SiO_2, the average of which is somewhat above that in the basic volcanites.

The total chemical compositions reveal that the alteration of basic volcanite into cordierite-garnet-anthophyllite(hypersthene) rock requires a marked decrease in $CaO+Na_2O$ and a corresponding increase in $FeO+MgO$. Only minor changes occur in Al_2O_3 and SiO_2.

On the basis of the mineral descriptions on pp. 10—25, the average mineral composition of the basic volcanites is as follows: hornblende + plagioclase, $An_{c.50}$, (An_{37-60}), + diopside-augite + accessory quartz + titanite. The relative abundances of the minerals vary from one rock to another, but in the amphibolites, the prevailing rock type, the order of abundances is as given above.

The cordierite-garnet-anthophyllite(hypersthene) rocks contain not only the minerals after which the rocks were named but also plagioclase ($An_{c.35}$), quartz and biotite (commonly as an alteration product); the more important accessories are sillimanite and rutile. The relative abundances of the minerals vary.

For the basic volcanite the author has based the left hand side of reaction (1) on the average mineralogical composition of the amphibolites. Similarly, the right hand side of the reaction is based on the average composition of the cordierite-garnet-anthophyllite rocks. In reaction (1) the name of the mineral is preceded by its weight percentage in the reaction. The formulae for the minerals in the reactions are according to those by Winchell and Winchell (1959). The composition of hornblende is that of hastingsite-ferrohastingsite and that of garnet is almandine-pyrope. Diopside-augite and anthophyllite-gedrite would require minor Al in their formulae.

1) 4 $NaCa_2(Mg,Fe)_4Al(OH)_2Si_6Al_2O_{22}$ + 4 $CaAl_2Si_2O_8$ + 4 $NaAlSi_3O_8$ +
45.9 % hornblende 27.6 % plagioclase (An_{51-52})

5 $Ca(Mg,Fe)Si_2O_6$ + 12 SiO_2 + $CaTiOSiO_4$ $\longrightarrow$ 2 $(Mg,Fe)_2Al_3Si_5AlO_{18}$ +
14.8 % diopside 9.2 % quartz 2.5 % titanite 24.4 % cordierite

$(Fe,Mg)_3Al_2Si_3O_{12}$ + 2 $(Mg,Fe)_7(OH)_2Si_8O_{22}$ + $CaAl_2Si_2O_8$ + 2 $NaAlSi_3O_8$ +
8.9 % garnet 35.2 % anthophyllite 15.9 % plagioclase (An_{34-35})

10 ½ SiO_2 + ½ Al_2OSiO_4 + TiO_2 + [15 CaO + ½ Na_2O + 2 H_2O +
12.5 % quartz 1.6 % sillimanite 1.6 % rutile

5 $NaAlSi_3O_8$ + 2 $CaAl_2Si_2O_8$]
plagioclase An_{30}

The expelled material in square brackets amounts to 35.4 percent of the amphibolite, and thus 64.6 percent of the amphibolite is converted into cordierite-garnet-anthophyllite rock, whose relative mineral abundances are given by the reaction.

The above reaction (1) takes places under conditions of the hornblende-hornfels facies. At a higher temperature, under conditions of the pyroxene-hornfels facies, anthophyllite loses its water and alters into hypersthene. The following change then arises in reaction (1):

2) $(Mg,Fe)_7(OH)_2Si_8O_{22}$ $\longrightarrow$ 7 $(Mg,Fe)SiO_3$ + SiO_2 + H_2O
anthophyllite hypersthene quartz

By calculating the percentages of oxides by weight for the elements of the basic volcanite (A_2) and the cordierite-garnet-anthophyllite rock (B_2) in reaction (1), we obtain the results given in Table 11. The average composition of the basic volcanites in the area was calculated from analyses 1—8 in Table 1 (p. 15); likewise, the average composition (B_1) of the cordierite-garnet-anthophyllite(hypersthene) rocks was calculated from analyses 3—7 in Table 6.

Table 11

The average chemical composition of basic volcanites (A_1) and cordierite-garnet-anthophyllite (hypersthene) rocks (B_1), as well as the weight percentages (A_2 and B_2) for the above rocks calculated on the basis of reaction (1).

	A_1		A_2	B_1		B_2
SiO_2	50.9		51.4	55.3		57.0
TiO_2	0.7		1.0	1.0		1.6
Al_2O_3	15.0		15.6	15.0		15.1
(Mg, Fe)O	17.2		15.0	23.1		23.3
CaO	11.0		12.9	1.1		1.1
Na_2O	3.2		3.2	1.3		1.2
K_2O	0.4			0.5		
P_2O_5	0.1			0.1		
H_2O+	1.3			1.2		
		H_2O	0.9		H_2O	0.7
H_2O-	0.1			0.2		
	99.9		100.0	98.8		100.0

In Table 11 the results are given together with the oxide contents (A_2 and B_2) calculated from the reaction. The oxide contents obtained for the same rocks from the reaction and from the analyses are in good agreement with each other.

From this it is inferred that in the Kiuruvesi area the cordierite-garnet-anthophyllite(hypersthene) rocks are derived from basic volcanites. The volcanites have released about 35 percent of their substances as a fluid, that is the bulk of the calcium, sodium and water as well as plagioclase. These components may be expelled from anatectic melt as a result of filter-pressing activity in shear movements. The expulsion is followed by the concentration of the residual anatectic melt (c. 65 %) in iron-magnesium and SiO_2, which then crystallises as either cordierite-garnet-anthophyllite or cordierite-garnet-hypersthene rock, depending on the conditions. The expelled fluid may form veins in the cordierite rocks themselves and migmatise the volcanites and gneisses associated with them.

On the other hand, the cordierite-garnet-biotite rocks in the area, may be considered to derive from pelites containing some volcanic material. This is indicated by the higher Al_2O_3 and lower FeO+MgO content in the cordierite-garnet-biotite rocks than in the cordierite-garnet-anthophyllite rocks (Fig. 31). The oxide points for the cordierite-garnet-biotite rocks are fairly close to the oxide points for the leptites (Fig. 31), and thus the cordierite-garnet-biotite rocks may also derive from leptites. Anatexis, filter pressing and shear movements all had important parts to play in the formation of the cordierite-garnet-biotite rocks.

THE GEOLOGIC EVOLUTION OF THE KIURUVESI AREA

General evolution

A scheme can be drawn up for the geologic evolution of the Kiuruvesi area on the basis of the mode of occurrence of the rocks, the tectonic structures and the stratigraphy in the area. The geosyncline zone that was formed during the Early Precambrian developed into a eugeosynclinal region in which sedimentation was accompanied by submarine volcanic activity. Basic to acid volcanism was accompanied by the deposition of intercalations of pelites and psammites that, as the volcanic activity slackened, formed thick beds containing only minor amounts of volcanic material (Fig. 32 I). The limestone content in the beds is very low, which confirms the opinion expressed by Väyrynen (1954, p. 172) that a marine area extended westwards from the Kuopio district and that the geosyncline sediments proper are biotite-plagioclase gneisses. Väyrynen also points out that quartzites, limestones and graphite schists fade out west of Kuopio.

The eugeosyncline sedimentation was followed by orogenic stage I, in the course of which crustal movements produced a rift that can be traced through Finland in a SE—NW direction from Lake Ladoga to the Gulf of Bothia and perhaps still farther into Sweden. Depressions and horsts were formed in this rift zone, a good example of which in the Kiuruvesi area is the depression at Sulkavanjärvi—Niemisjärvi (Figs 30 and 32 II).

In the depression the anatectic melting and recrystallisation of the Early Precambrian basement and the overlying volcanic and sedimentary layers gave rise to hypersthene-bearing quartz diorites and diorites under conditions of the pyroxene gabbro-granulite facies. The margins of the Sulkavanjärvi—Niemisjärvi block were intruded by granite magma, which thus formed hypersthene-bearing pyroxene granites and pyroxene granodiorites. The heat from the intrusive material (mixed magma) flowed into the surrounding volcanites and sedimentary gneisses, which show evidence of contact metamorphic alterations due to the rise in temperature. At the same time shear movements gave rise to dislocation or cataclastic metamorphism in the contact. The outcome of contact and dislocation metamorphism combined was the formation along the margins of the granite mass of cordierite-bearing rocks as alteration products of volcanic and sedimentary rocks. Contact-dislocation metamorphism is probably the best term for describing the metamorphism that produced the cordierite-bearing rocks.

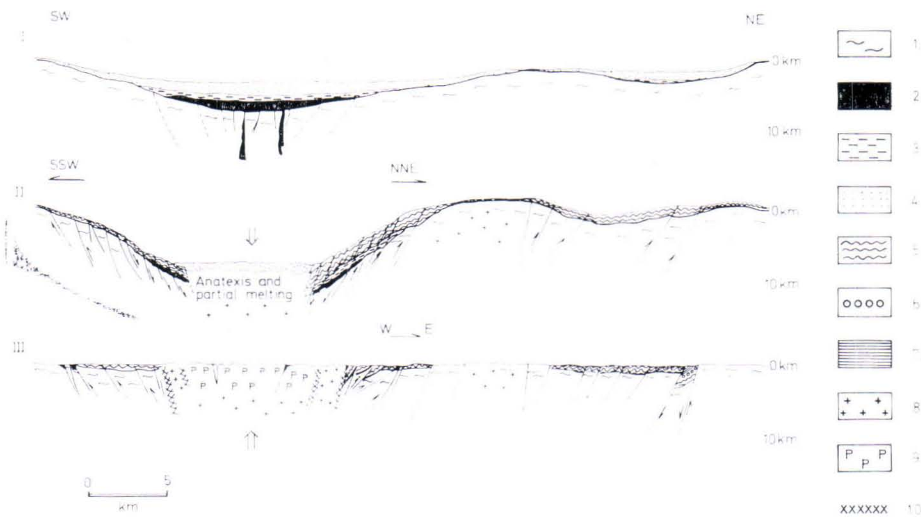

Fig. 32. The geologic evolution of the Kiuruvesi area. A cross section from Laukkala to Haajainen. Legend: 1. basement gneiss, 2. basic and intermediate volcanite, 3. tuffaceous and tuffite beds 4. sediments, 5. gneisses, 6. conglomerate, 7. mica schist, 8. granite, 9. pyroxene-bearing rocks, and 10. breccia.

in the marginal zones, since in contact metamorphism the prime factor is temperature and in dislacation or cataclastic metamorphism shear or directed pressure (Turner and Verhoogen 1960, p. 462; Sparks 1971, p. 136; Stanton 1972, p. 613). The mixed magma and the granitic and granodioritic fluid that were squeezed out when the cordierite-bearing rocks were formed produced intense migmatisation in the rocks of supracrustal origin in the environment of the block. The diabases in the Sulkavanjärvi—Niemisjärvi block intruded the joints formed in the crust during orogeny, and ophitic gabbros penetrated the sediments concordantly. The formation of the rift was followed by erosion, and the weathering products were deposited upon sedimentary mica gneisses in the fracture depressions. Volcanism was practically at a standstill during this event. The miogeosyncline in the Vieremä-Haajainen area began to fill, starting from the east, with the products of metamorphism from the volcanic and sedimentary deposits in the environment and from the para- and orthogneisses in the Early Precambrian basement. The conglomerate-greywacke-pelite beds deposited in the syncline underwent such intense metamorphism during the movements of the second orogenic stage that they are visible today as the Vieremä—Haajainen conglomerate-schist formation (Fig. 32 III).

The orogenies in the Kiuruvesi area were accompanied by several stages of crustal fault and shear movements as well as by metamorphic processes, all of which combined to enrich the ore fluids formed in the volcanic beds and to open feeders for them northwest of Kalliojärvi, at Hallaperä, in the environment of Koivujärvi, and elsewhere in the area for smaller ore deposits that are currently being investigated. Of special interest in the Fe-Cu-Zn-Pb sulphides is their association in this area with volcanism, cordierite-bearing rocks and shear movements.

The pegmatite and aplite dykes were formed during the first and second orogenic stage. Seismic measurements and the presence of young faults indicate that the dislocation of the bedrock is still going on along the Raahe—Ladoga line.

Facies conditions

Facies conditions in the Kiuruvesi area vary from regional to contact and dislocation metamorphic. Regional metamorphism is represented by supracrustal rocks of the amphibolite facies. These are 1. the young Vieremä—Haajainen conglomerate-schist formation with augen schists that have undergone later cataclastic metamorphism, and 2. volcanic-sedimentary series composed of a) acid and basic volcanites, and b) migmatised mica and hornblende gneisses. Pyroxene-bearing diorites and quartz diorites that crystallised from the anatectic melts in the Sulkavanjärvi—Niemisjärvi block represent the pyroxene gabbro-granulite facies of regional metamorphism.

Dislocation metamorphism has taken place along long and relatively narrow translation zones trending in various directions. In these fracture lines, which might have reached the mantle (cf. p. 69), the temperature could have risen well above that in the environment. The P-T conditions in the dislocation zones presumably approached those of the contact metamorphic hornfels facies. Shear stress often exerts a catalytic effect on the dislocation zones, and it is along these zones that volatiles migrate readily.

Under conditions of the hornblende-hornfels facies, contact-dislocation metamorphism produced a) cordierite-garnet-biotite rocks from pelitic-volcanic sediments, and b) cordierite-garnet-anthophyllite rocks from sediments of basic volcanic affinity. Some of these rocks may also be attributed to dislocation metamorphism. Under conditions of the pyroxene-hornfels facies, dislocation metamorphism produced within the Sulkavanjärvi—Niemisjärvi block a) cordierite-garnet-hypersthene rocks deriving from basic volcanites, whose SiO_2-deficient horizons are represented by the sapphirine-bearing parageneses at Kalliojärvi, and b) diopside-scapolite skarns that refer to the lime-rich beds. Retrogressive dislocation metamorphism is manifest locally northwest of Kalliojärvi, where the grade of metamorphism decreased in narrow shear zones from the pyroxene-hornfels facies (probably granulite facies) to the green schist facies (cf. sapphirine-bearing rocks p. 50).

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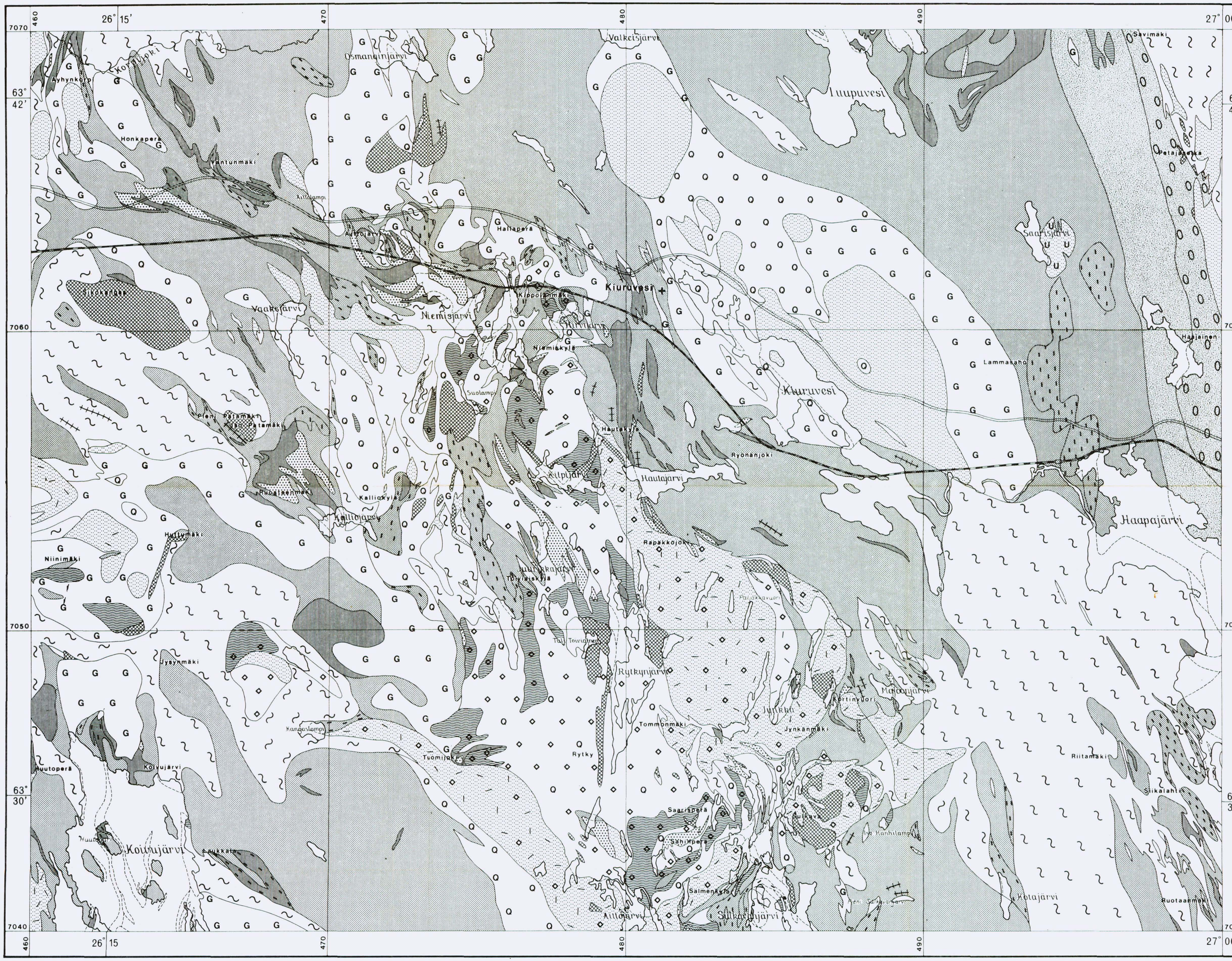
APPENDIX 1



PETROLOGICAL MAP

of the

KIURUVESI AREA

by

Erkki Marttila

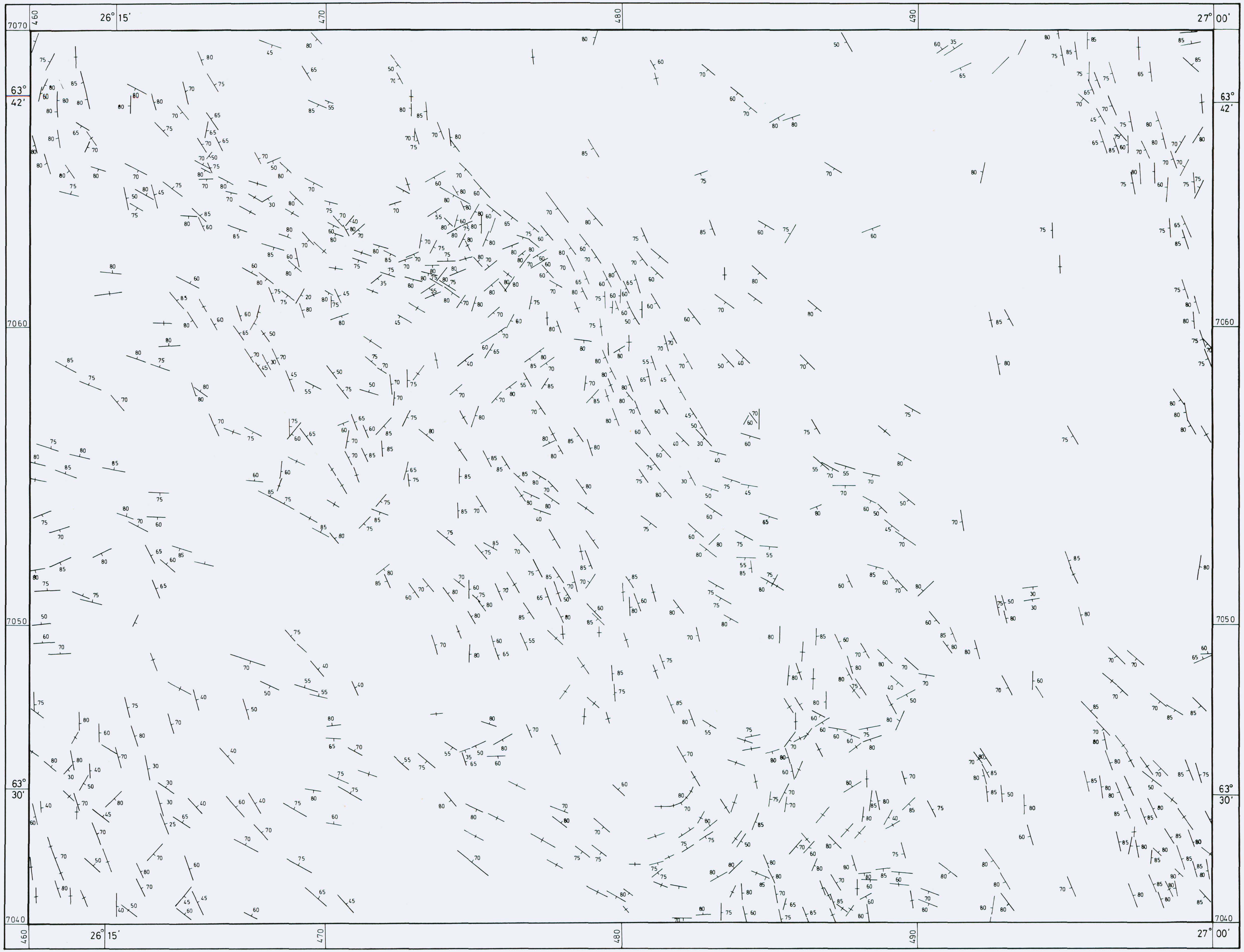
1975

- Basic and intermediate volcanite / Uralite-porphyrite
- Acid tuff- and tuffiteschist-leptite / Intercalations of skarn
- Mica gneiss / Hornblende gneiss
- Mica schist
- Conglomerate
- Cordierite-bearing rock
- Peridotite, gabbro and diabase
- Diorite
- Quartz diorite
- Granodiorite
- Granite
- Epidote-bearing granite-unakite / Porphyritic granite
- Strongly granitic basement gneiss
- Black schist and graphite-bearing gneiss
- Pyroxene (mainly orthopyroxene)

0 1 2 3 4 5 km

Geological Survey of Finland
Bulletin 283

Appendix 2



SCHISTOSITY in the KIURUVESI AREA

by

Erkki Marttila

1975

60 Strike and dip of schistosity

Vertical schistosity

0 1 2 3 4 5 km

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