SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 709 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 69 NR 1

TIBOR PARÁK

THE ORIGIN OF THE KIRUNA IRON ORES

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View of a part of Kiirunavaara's open pit with a foot-wall of "conglomerate" in the foreground. Photo B. Rönnberg.

CONTENTS

PREFACE

The present paper renders an account of the results of a survey covering the Kiruna area. The survey has been carried out by the author since 1965. Complementary data have at first hand been collected in Lapland, an area which the author is most familiar with through his work as a prospecting and mining geologist.

I am greatly indebted to several persons who have assisted me in my work.

I am very grateful to Professor Sven Gavelin who's encouragement and advice has been a great support throughout this study. I also want to express my sincere thanks to Professors Per Geijer, Olof Ödman and Sture Landergren for their help and constructive discussions.

My colleagues at Luossavaara-Kiirunavaara AB (LKAB), Dr. Sven Ljunggren, Dr. Paul Forsell and Dr. Jan v. Feilitzen have been very helpful to me. In particular, I would like to acknowledge Dr. Paul Forsell for his constructive criticism and for our close cooperation. I would also like to thank Dr. Ulf Hallgren, SGU, for his critical reading of the text. I am grateful to Mr. Per-Lennart Karlsson who assisted me with advice on the statistical treatment of the data, and to Messrs. Georg Patzauer, Sven Israelsson, Gerhard Nilsson and Stig Järlstig for their laboratory work.

A collection of samples from the Tuolluvaara ore has been made available to the author owing to Mr. P. V. Villner, TGA.

I owe a great debt of gratitude to my company LKAB which made the publication of this survey possible.

ABSTRACT

It was more than 50 years ago that Geijer described the rocks and iron ores of the Kiruna field. From the information available at that time he concluded that the ores had been formed by magmatic differentiation processes. Geijer introduced the theory of the magmatic-intrusive emplacement for these ores in 1919 (1919a). Originally, he had considered them to be extrusive (1910).

Over the past ten years considerable changes have taken place in the character of mining techniques. Underground mining has replaced open-pit mining. This has led to increased possibilities for studying the geology of the ores and wall rocks. In the author's opinion, the new geological observations and geochemical data are in contradiction with the magmatic-intrusive theory of the origin of the ores.

A few examples of some of the observations that contradict the magmatic-intrusive theory are as follows:

1. Ore fragments (xenoliths) and pebbles of different types of Kiruna ore are found in large quantities in the hanging wall rock of the main ore — the quartz-bearing porphyry. This phenomenon was observed also by Geijer (1910, 1968), who interpreted the fragments as being derived from some older, now unknown ores. The author interprets the ore fragments as being related to the Luossavaara-Kiirunavaara ores and the quartz-bearing porphyry. Consequently, they are younger than the Kiirunavaara ore. The quartz-bearing porphyry was formed later than the main ores. Thus, an intrusion of the main ore between the syenite-porphyry and the quartz-bearing porphyry cannot have taken place. It is improbable that the ore fragments have been derived from older ores. The Kiruna type of iron ore has not been found in any rock older than the Kiruna porphyries.
2. The results of the geochemical survey do not support the theory of magmatic differentiation.
3. The structure of the ores indicates that they were formed by sedimentation in connection with volcanism.
4. A conglomerate containing numerous ore pebbles of Kiruna type has been noted in the hanging wall of the main ore body at Luossavaara.
5. "Offshoots" observed at Kiirunavaara are interpreted to be wedges formed by faults or deformations of the main ore by intrusion of dike-porphyries.
6. The "ore breccias" of the Luossavaara foot-wall — which actually are not breccias in the usual sense, but consist of dike-like bodies in syenite-porphyry — have chemical compositions (and grain sizes) which differ from those of the main ore.
7. Frequently, the ores described by Geijer show a successive transition upwards into a quartz-banded type of ore.
8. The chemical composition of the wall-rocks indicates that the ores were formed in a volcanic environment.

INTRODUCTION

In view of the fact that there exist several descriptions of the geology of the Kiruna district, it seems quite unnecessary to repeat what has already been published in detail. Only a short summary of the petrography of the rocks is presented here, including several new observations. In addition, the results of about 100 rock and mineral analyses, and about 70 ore analyses from the Kiruna field are reported. For the first time, chemical analysis of the boulders in the Kurravaara conglomerate are reported, as well as analyses of the syenite-porphyry of Hauki type, sericite quartzite, greywacke, phyllite, and quartzite-sandstone.

Rock units are described in the same order as used by Geijer (from west to east): Kiruna greenstone and Kurravaara conglomerate, the Kiruna porphyries, the Lower Hauki rocks and the Vakko sedimentary rocks. A short presentation of the ores follows the description of the rocks.

PETROLOGY

ROCK UNITS

The most important relevant literature is: Lundbohm (1898, 1898A), Geijer (1910, 1916, 1927, 1931, 1931b, 1950, 1968), Sundius (1912, 1915), Ödman (1957) Offerberg (1967).

The north-western part of the map shows a type of granite described by Offerberg (1967) as younger granite. This rock is not dealt with in the present study.

KIRUNA GREENSTONES

The oldest part of the Kiruna greenstones is composed of dark grey, fine grained basaltic greenstones and a chlorite-actinolite rock. Other parts consist of a series of spilitic lavas with intercalations of clastic and chemical sediments. The greenstones are greyish-green on fresh surfaces and light green on weathered surfaces. They are fine-grained and often amygdaloidal. A large proportion of the greenstone show primary structures, such as pillows. They are also schistose in places. This is the case at Valkeasiipivaara and in the district west of Syväjärvi, where strongly schistose calcite-veined greenstones were found in some drill holes.

Judging from the material of the cores, these schistose greenstones include deformed pebbles consisting of polymict material. It is not unusual to find pebbles rich in magnetite (up to 30 % Fe) amongst the pebble material that consists exclusively of fine-grained vulcanites. Rock types directly comparable

to Kiruna vulcanites have not, so far, been found in pebble material. Occasional pebbles of red, fine-grained quartzitic-sandstone have been found in the schistose greenstone. The biggest pebble was 6—7 cm long, 3—4 cm wide and moderately rounded. The microscope shows that the pebbles consist mainly of quartz-grains, arranged in fine and medium grained layers. Besides quartz, small grains of hematite are also to be found. They are more highly concentrated in the fine-grained layers.

The greenstones are very frequently scapolitized. Scapolite is often observed in the form of "pearl necklaces" along cracks or in a dotted pattern.

The mineral composition of the greenstones is as follows: hornblende, plagioclase, epidote, scapolite, biotite, chlorite, and to a lesser extent calcite, leucoxene, sericite, magnetite, titanomagnetite, apatite, pyrite, and quartz.

Three chemical analyses were carried out on greenstones from the drill hole (Dh 402, 477) near the Kurravaara road and three on the schistose type of greenstone from the area west of Syväjärvi (Table 1).

The sediments, which may also be found together with lavas in Kiruna greenstones, were classified by Sundius into fine and coarse-grained categories and also agglomerates and limestones. The fine type often shows bedding in places. Cross-bedding also occurs. It consists mainly of amphibole and plagioclase. The fine type forms the matrix in the coarsergrained sediment, which consists of small fragments of greenstones and/or albit rocks. Well-preserved graded bedding occurs in places in the coarser type of sediment, showing that the upper surface of the series faces eastwards. Agglomerates consisting of large and small angular fragments of greenstones are less common in the greenstone than in the sediments.

Limestones intercalated in the greenstones are often impure and besides calcite, include light green actinolite and titanite. The thickest layer of carbonate rock — 14 m thick — was intersected by drilling in the greenstone by the Kurravaara road. It is a fairly pure dolomite with 24.9 % CaO and 17.4 % MgO, according to the results of the analyses.

In the greenstone west of Valkeasiipivaara (Dh 318), a 24 m thick bank of graphitic schist was found intercalated with fine-grained sediments showing graded bedding. The total thickness of the sedimentary section is several hundred metres at this point, making it thicker than earlier observed sediments in these greenstones. In connection with the graphitic schist, copper, zinc and some lead mineralizations have been found.

In addition to the sediments in the greenstones mentioned above, magnetic ores have been found at Kojuvaara, Pahtosvaara and Suolojåkk (Fig. 1). Judging from the results of geophysical measurements and diamond drilling, these ore bodies are several hundred metres long and attain thicknesses of about 20 m. Analyses of the drill core from a drill hole at Suolojåkk show an average of over 20 % Fe in a 12 m section, of which 6 m averaged

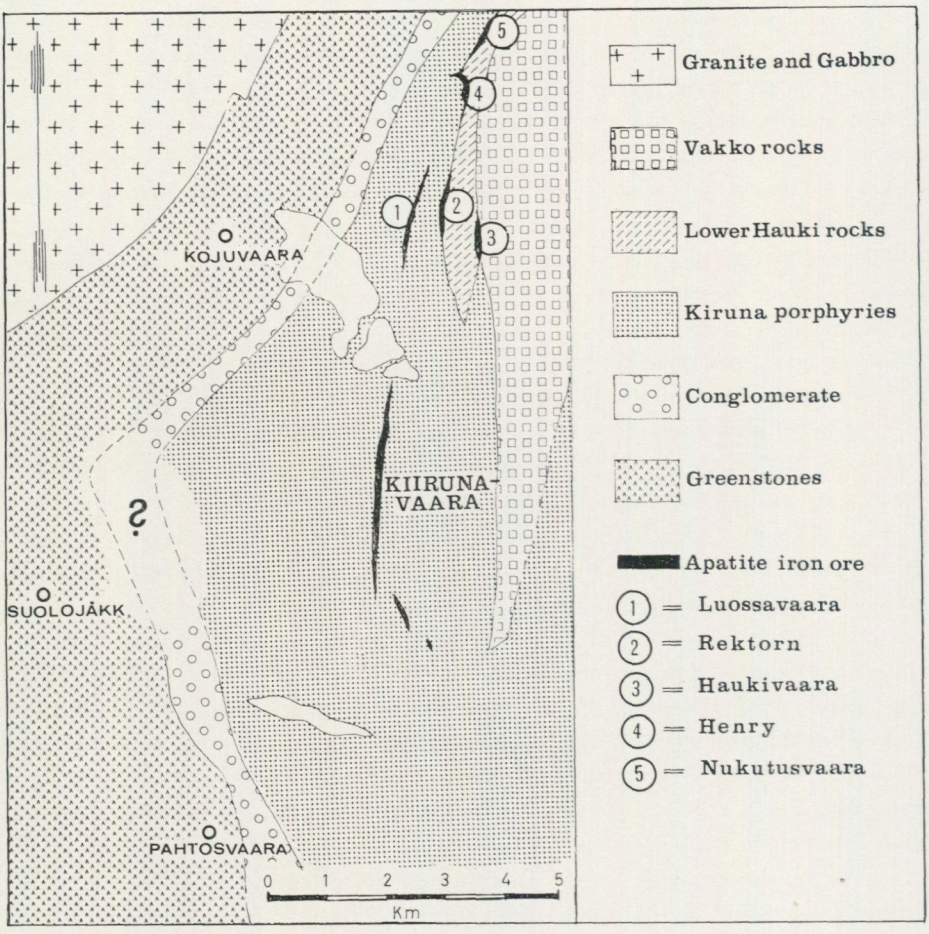

Fig. 1. Simplified map showing location of Kojuvaara, Suolojåkk and Pahtosvaara iron ore deposits in relation to the apatite iron ores.

over 50 % Fe. One of the analyses showed 0.24 % P. The chemical composition of the ore from Suolojåkk, together with three chemical analyses of the magnetite-rich pebbles from the schistose greenstone are shown in Table 2.

KURRAVAARA CONGLOMERATE

According to earlier descriptions, the Kurravaara conglomerate rests conformally on Kiruna greenstones. Subsequent investigations (Parák, 1971) have shown that at places there exists a discordance of about 30° between these two units. Cores from drilling west of Syväjärvi have not provided a clearer picture of the contact between the greenstone and the conglomerate.

The pebble material is polymictic. Beds rich in pebbles alternate with pebble-free layers. The latter often show cross-bedding. The pebble material usually consists of salic rocks, although greenstones are also found.

Pebbles rich in magnetite, known as magnetite-syenite-porphyry pebbles, occur more commonly in the Kurravaara district (and Pahtosvaara) than around Valkeasiipivaara or west of Syväjärvi. Pebbles of limestone, red jaspilite, banded sediments and quartz can also be found. The red, fine-grained phenocryst-free felsite pebbles, several decimetres in size, which are found near Kurravaara, are almost entirely absent from the southernmost part of the conglomerate.

Samples of 12 pebbles of the most common rock types were chemically analysed (Table 3). Six of these pebbles show structures similar to Kiruna porphyries (albitophyre). In all six samples the matrix is darker than the albite phenocrysts. The chemical analyses show these pebbles composed of a soda-dominant material. Na_2O — and K_2O contents agree with those contents mentioned by Sundius for a pebble free layer ($Na_2O = 8.24$ % and $K_2O = 0.50$ %). Three pebbles represent a fine-grained rock similar to the syentite-porphyry of Kiirunavaara's foot-wall, though they lack phenocrysts. Three pebble samples show a phenocryst-free, porous, skarn rock.

Ten pebbles of magnetite-syenite-porphyry of the type described by Sundius (and discussed by Geijer and Ödman) have been chemically analysed and the trace elements determined. Although this type of pebble has been important in previous discussions concerning the stratigraphic position of the Kurravaara conglomerate, no chemical analyses whatsoever have been carried out previously. These 10 pebbles are all soda-rich. The chemical composition of these pebbles resembles that of the syenite- porphyries and the greenstones (Table 4).

The Fe-content in the analysed pebbles varies between 16.0 and 36.3 %. The Ti-content is usually around 0.15 %. In one case it is 0.71 %. The distribution of trace elements in the magnetite of the pebbles differs, however, from the Kiruna ore-field's other magnetites.

Magnetite ore is less common in the pebble material, but appears occasionally as fragments up to a few centimetres in size. Magnetite fragments from outcrops of conglomerates and drill cores show only ores with low phosphorous content. The determination was carried out by the "Kimo-test" method in the field. The fragments of the ore are always fine-grained (0.2—0.5 mm). On the other hand, relatively coarse-grained magnetite (1 mm) is found in the matrix of the conglomerate. This magnetite is usually seen as narrow winding veins or as small round concentrations surrounded by green hornblende.

The matrix of the conglomerate is composed of small fragments of albite-rich rocks and grains of plagioclase, uralite, magnetite, quartz, calcite and apatite. Sometimes a trace of chalcopyrite can be seen.

KIRUNA PORPHYRIES

The term "Kiruna porphyries" includes rock types that elsewhere are usually known as keratophyre and quartz-keratophyre. In the present study, however, the terms syentite-porphyry and quartz-bearing porphyry are employed, as they have long been used in descriptions of the geology of this field.

The most detailed petrographic-minerological description of these rocks was made by Geijer in 1910. As far as the chemical composition of these rocks is concerned, only those analyses carried out after 1967 are reported in the present study. Earlier chemical analyses have been collected and published by Offerberg (1967).

Syenite-porphyry

Geijer (1931, p. 23) classified these rocks into different categories. By "Syenite-porphyry" he meant rocks containing alkaline feldspar and varying amounts of dark minerals, but not more than 5 % quartz. The term albitophyre was used when the porphyry "consists almost entirely of sodic feldspar". The quartz-free, usually biotite-rich, type was called "basic syentite-porphyry".

Within the mapped area the syenite-porphyry is seen to overlie the Kurravaara conglomerate. Contacts between the Kurravaara conglomerate and the porphyries are sharp. The drill cores from holes west of Syväjärvi are fractured in the vicinity of the contact. The part of the syenite-porphyry that lies nearest the contact is skarn-bearing and slightly schistose. Drill cores from Kiirunavuoma (just off the map) show neither fractures nor alteration at the contact.

During the past few years, the district west of Kiirunavaara has been surveyed by diamond drilling. Altogether, 500 m of drill cores from holes west of the syenite (Dh 466, 1810 within the map area) consist of fine-grained intermediate rocks. Besides several types of syenite-porphyry already known to exist in the Kiruna district, other rocks occur, often lacking porphyric texture, that are very similar to those found in the Kurravaara conglomerate's pebble material. Macroscopically, the darkest type of rock resembles certain Kiruna greenstones. Under the microscope it is seen that the darker colour is usually caused by a relatively high magnetite content.

The following chemical analyses have been carried out on rocks found west of the syenites:

	Fe^{tot}	Fe^{2+}	SiO_2	Na_2O	K_2O
1. Grey syenite-porphyry	2.15	0.10	67.6	7.18	1.80
2. Grey syenite-porphyry with veins of calcite	6.78	0.85	55.6	7.09	1.04
3. Grey syenite-porphyry with veins of calcite	9.50	1.70	55.6	7.83	0.85
4. Light grey non-porphyric rock	4.38	0.70	66.7	5.98	3.69
5. Reddish felsitic rock	0.63	0.20	68.5	8.90	2.41
6. Reddish felsitic rock	1.22	0.40	65.6	8.82	2.80

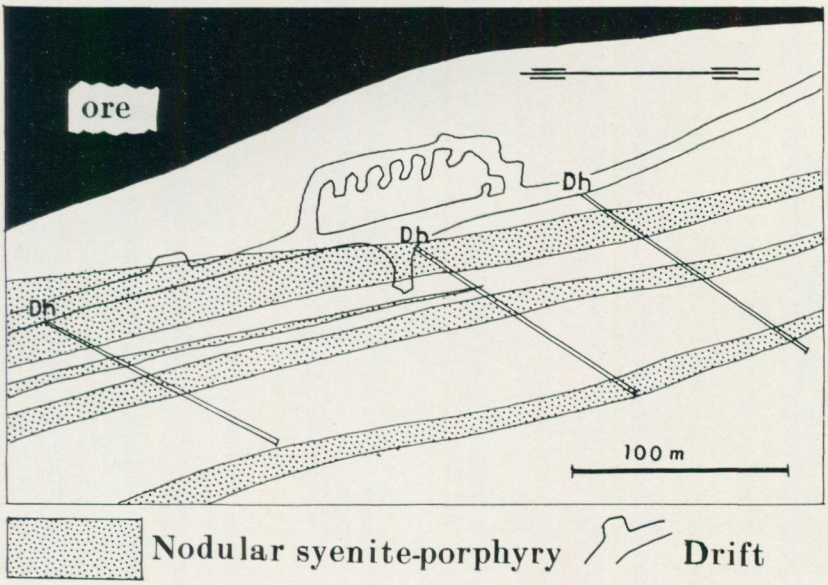

Fig. 2. Beds of nodular syenite-porphyry in foot-wall porphyry. Kiirunavaara. (Dh = Drill holes.)

Further north, on a level with Syväjärvi, several holes have been drilled in the syenite-porphyry, the colour of which varies, between red and grey. In some places it is phenocryst-free, in others it shows an amygdaloidal structure. Magnetite-rich varieties are common here. In a diamond drill hole (Dh 1373) between Hopukka and Kurravaara, syenite-porphyry which was partly amygdaloid-bearing and partly magnetite-impregnated was found under the Lower Hauki rocks.

Drillings showed distinct amygdaloidal lava beds in the foot-wall of the Kiirunavaara-Luossavaara ore. Here nodular syenite-porphyry occurs at the contact with the porphyry beds (Fig. 2). The amygdules consist of actinolite, apatite, titanite, magnetite and occasionally zircon.

Six chemical analyses of syenite-porphyries have been carried out (Table 6).

Tuffitic layers, as well as layers of jaspilite and small lenses of banded magnetite-albite ore were found. In the foot-wall of the Kiirunavaara ore several distinctly banded layers of tuffites up to 2 m thick were observed (Fig. 3). These show an angle of disconformity of about 30—35° to the foot-wall contact. One of the tuffitic layers shows a relatively rich impregnation of pyrite.

Magnetic-rich syenite-porphyry occur in the mapped area in the proximity of the Henry ore, west of Syväjärvi, and on Mount Hopukka. The rock consists mainly of albite and magnetite.

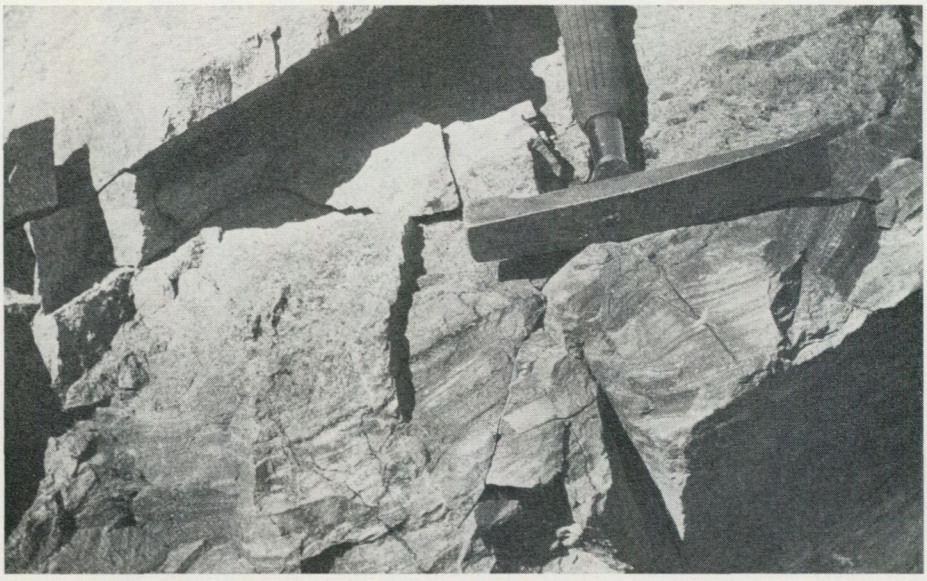

Fig. 3. Layered tuff bed in syenite-porphyry. Kiirunavaara.

Fig. 4. Pebbles of syenite-porphyry and nodular syenite-porphyry in a matrix of magnetite in the foot-wall contact in Kiirunavaara. Photo B. Rönnberg.

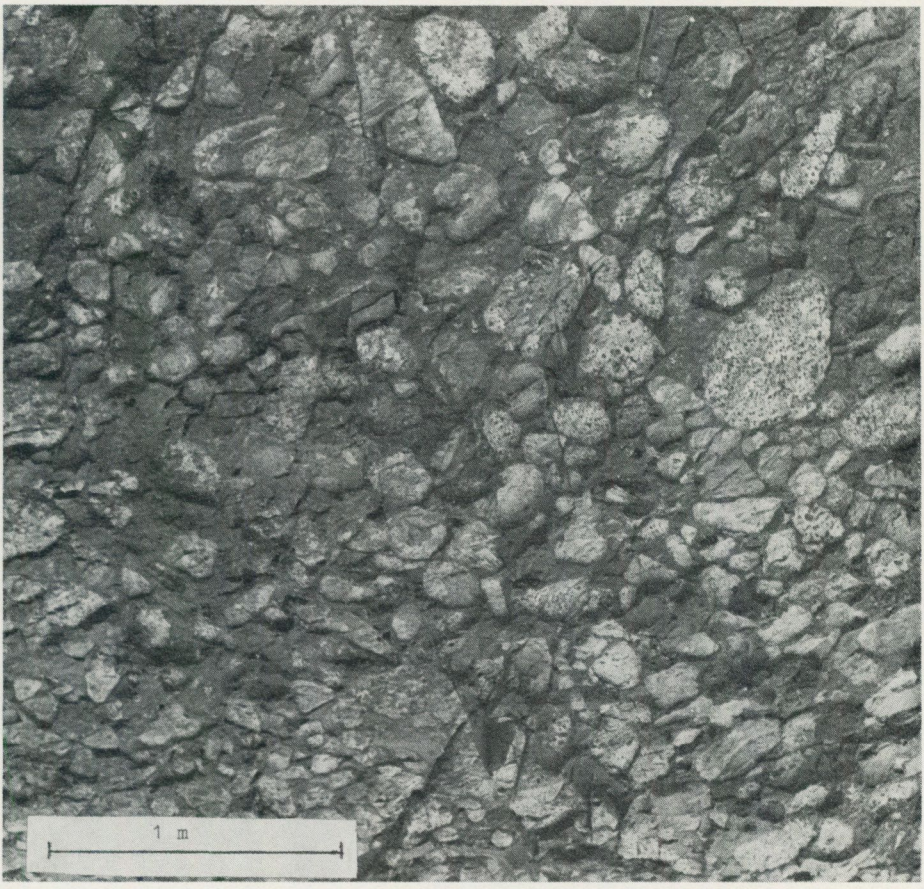

Fig. 5. Pebbles of syenite-porphyry and nodular syenite-porphyry in a matrix of magnetite in the foot-wall contact in Kiirunavaara. Photo B. Rönnberg.

This variety of syenite-porphyry was described in detail by Geijer (1910, 1916), who gave it the name *magnetite-syenite-porphyry*. It often exhibits feldspar phenocrysts and nodules consisting of albite and magnetite. Titanite nodules are less common. Magnetite occurs here in the form of veinlets and fragments of magnetite, as well as fine-grained impregnations of magnetite in the porphyry. The chemical composition of the magnetite-syenite-porphyry is given in Table 5.

At the foot-wall contact in the southern part of the Kiirunavaara open pit, about 150 m below O-point, a conglomerat-like formation occurs. It consists of a magnetite matrix with angular to well rounded pebbles of the surrounding foot-wall porphyries (Figs. 4 and 5). This particular formation is about 30 m long and 8—10 m wide. According to P. Forsell, a similar formation has been observed in the northern part of the Kiirunavaara ore's foot-wall.

The pebbles consist of syenite-porphyries and nodular syenite-porphyries. They vary in size from a few centimetres to about half a metre. These two types are mingled in an irregular fashion, although a certain grading according to pebble size is discernable. The pebbles show no rim alterations.

A remarkable rock contact has been observed west of the Henry ore, which most nearly resembles an eroded surface of the syenite-porphyry. The syenite-porphyry is fractured near the contact. The matrix consists af a very lean magnetite ore with both angular and rounded fragments of porphyric rocks. The material consists mainly of syenite-porphyries, although other less easily defineable rocks are also included.

Further north, in the western part of the Henry Ore's open pit, the syenite-porphyry alternates between schistose and amygdaloidal with veinlets of magnetite and quartz. The schistose type is often rich in chlorite. A magnetite ore, very rich in calcite and nearly 10 m thick, was found in the amygdaloidal rock. This is the thickest of the ore-veins, most of which are not more than a few centimetres thick. This part of the field most nearly resembles the Luossavaara "ore breccia".

Syenite

Syenite, which was formerly considered to constitute the lowest part of the syenite-porphyry massif, has been shown by recent surveys to occur in the central part of the syenite-porphyry west of Kiirunavaara. Both red and grey varieties of this rock are to be found. They show a plutonic rock structure, in contrast to the volcanic rock structure of the porphyries. The transition between syenite and syenite-porphyry is continuous.

The mineralogical composition of the syenite is similar to that of the syenite-porphyry, consisting of soda-rich perthitic feldspar, pyroxene, epidote, magnetite, titanite, apatite, and occasionally quartz.

Quartz-bearing porphyry

Quartz-bearing porphyry forms the hanging wall of the ore bodies of Kiirunavaara, Luossavaara and Luossajärvi, and rests directly on the syenite-porphyry in the central part of the field. The rock formation decreases in thickness towards the north. On the southern slope of mount Hopukka, the quartz-bearing porphyry is interrupted by displacements. It reappears north of Hopukka. This has been noted in several out-crops. The exact delimitation of the quartz-bearing porphyry towards the north has not been determined.

Quartz-bearing porphyry has been found in cores from holes in Lower Hauki rock near Haukivaara, and also in drill holes near the Kurravaara road, east of Nukutusvaara. At the latter site, porphyry is found in a position that would

seem to indicate that it occurs as sheets in basic rocks. The quartz-bearing porphyry also covers a large area in the eastern part of the map.

The quartz-bearing porphyry, in contrast to the syenite-porphyry, seldom exhibits distinct volcanic structures. The rock does, however, present a wide colour scale, of which the reds are dominant. Feldspar phenocrysts are common, although at Tuolluvaara the rock has a phenocryst-free, leptitic structure (Geijer, 1920). Sakkaravaaras quartz-bearing porphyry often includes light-coloured mica. This is also true of the quartz-bearing porphyry that was found in a drill hole near the Kurravaara road. Geijer (1910) reports fluorite (CaF_2) in the quartz-bearing porphyry from Sakkaravaara.

Microscopic examination of the matrix of the quartz-bearing porphyry shows it to be micropoikilitic. The rock consists mainly of quartz, microcline and plagioclase, and magnetite, apatite, and occasionally zircon, calcite and tourmaline. The phenocrysts have been shown to be perthite. Quartz phenocrysts are rare.

Ljunggren (1956) described alterations of the quartz-bearing porphyry between the Luossavaara and Rektorn ore bodies. These alterations, which include silification, sericitization and carbonatization, are strongest at Rektorn.

Kaolinization of the quartz-bearing porphyry at the ore contact is not unusual. This zone of alteration varies in thickness from 0.1 to 1.5 m.

In a drift situated at the 540 m level in the middle of Kiirunavaara ore body, an unusual development in the hanging wall has been found. There is a transition zone, consisting of skarn-banded and skarn-spotted rocks. Within this zone, there is a skarn-rich ore with inclusions of the surrounding skarn-spotted rock type. One part of the skarn-banded rock is folded. It is of interest to note that inclusions resembling the rock type of the main ore occur in the skarn-bearing slightly folded rock (Fig. 6).

Opposite the above mentioned site (in the same drift), the hanging wall rock is skarn-banded towards the ore body (Fig. 7). The banded rock is separated from the typical quartz-bearing porphyry by a 10—20 cm thick band of skarn.

The most apparent characteristics of the area of quartz-bearing porphyry are beds of agglomerates and conglomerates, as well as lenses and fragments of iron ore.

The agglomerate zone on the eastern slope of Luossavaara and a similar formation about 1 500 m north of Luossavaara have been described by Geijer (1910). While the agglomerate at the former site lies east of Luossavaara's main ore body, the agglomerate north of Luossavaara rests directly on syenite-porphyry. This has been proved by recent examinations which show that it is difficult to draw an exact boundary between these two rock types. The syenite-porphyry is itself broken up at the contact zone. A thin agglomerate unit only a few metres wide has recently been found about 60 m west of the agglomerate zone that occurs north of Luossavaara.

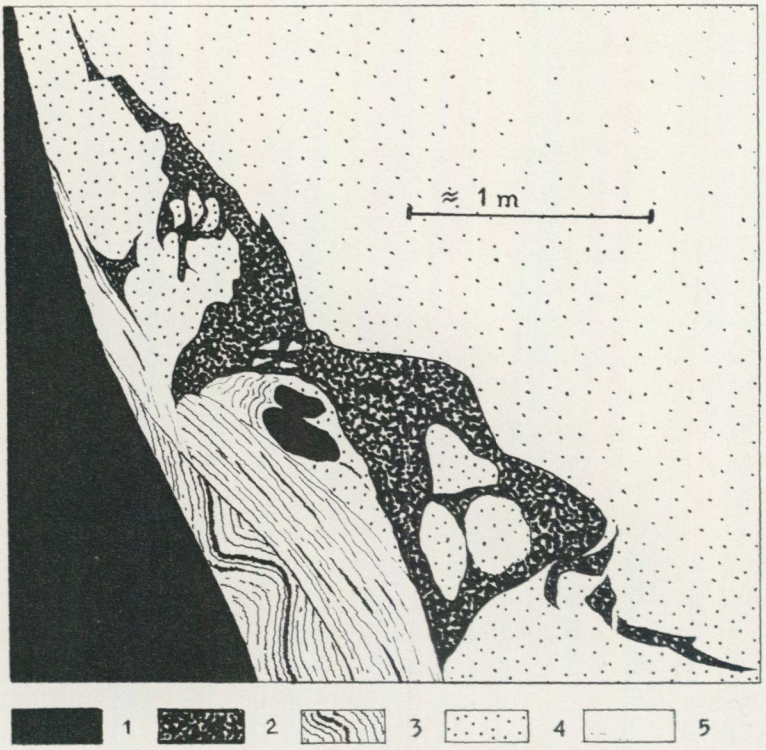

Fig. 6. Detail of the hanging wall of Kiirunavaara ore body. 1 = Main ore body, 2 = Iron ore, rich in skarn, 3 = Skarn-banded rock, 4 = Skarn-spotted quartz-bearing porphyry, 5 = Quartz-bearing porphyry.

These agglomerates consist mainly of fragments of syenite-porphyry, quartz-bearing porphyry and magnetite-syenite-porphyry. The last type occurs most frequently in the agglomerate that lies north of Luossavaara (Fig. 8). The rock material in some of these fragments is identical with rocks known from the Lower Hauki series (Stutzer, 1907). In recent years fragments of a magnetite ore showing partial alteration to hematite have also been found in the agglomerate north of Luossavaara. Furthermore, small disintegrated fragments of malachite have been observed amongst the porphyry fragments in the agglomerate. An agglomeration bed that was found between Luossavaara and the Rektor ore included a large number of ore pebbles which are similar in composition to that of the main ore bodies.

Geijer (1910, p. 135) mentions that in the agglomerate zone situated on the eastern slope of Luossavaara the rocks are composed almost entirely of fragments, with very little matrix. The rocks have the appearance of a normal conglomerate. The pebbles are arranged with their longer axes parallel to the strike of the bed.

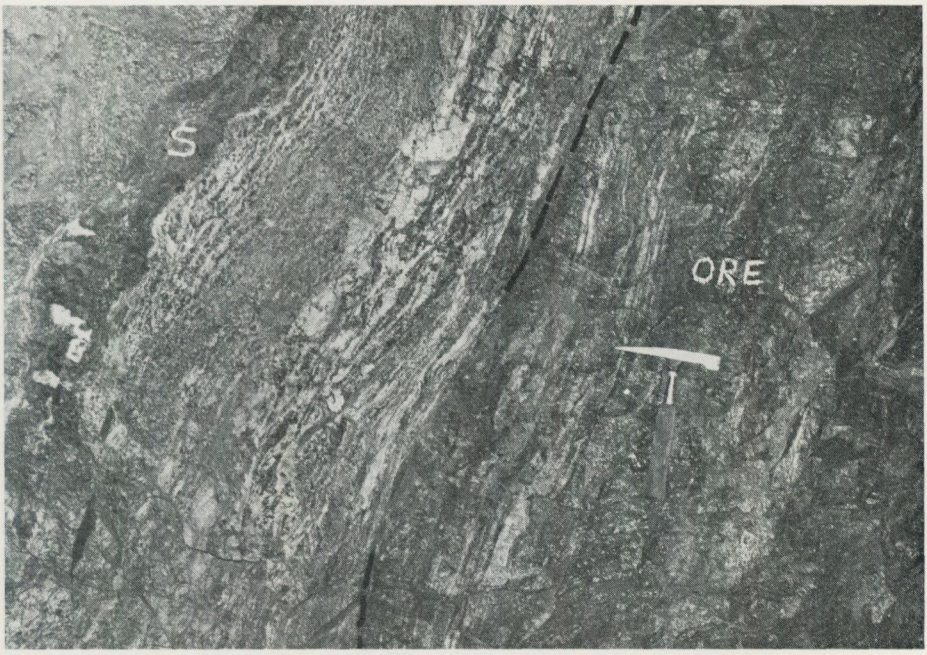

Fig. 7. Detail of the hanging wall of Kiirunavaara ore body. The uppermost part of the ore body, with a width of one metre, shows veins and treaky lences of a white to light-red rock composed of quartz and albite. The nearest part of the hanging wall is composed of a skarn-banded rock. The rock to the left of a band of skarn (S) consists of quartz-bearing porphyry.

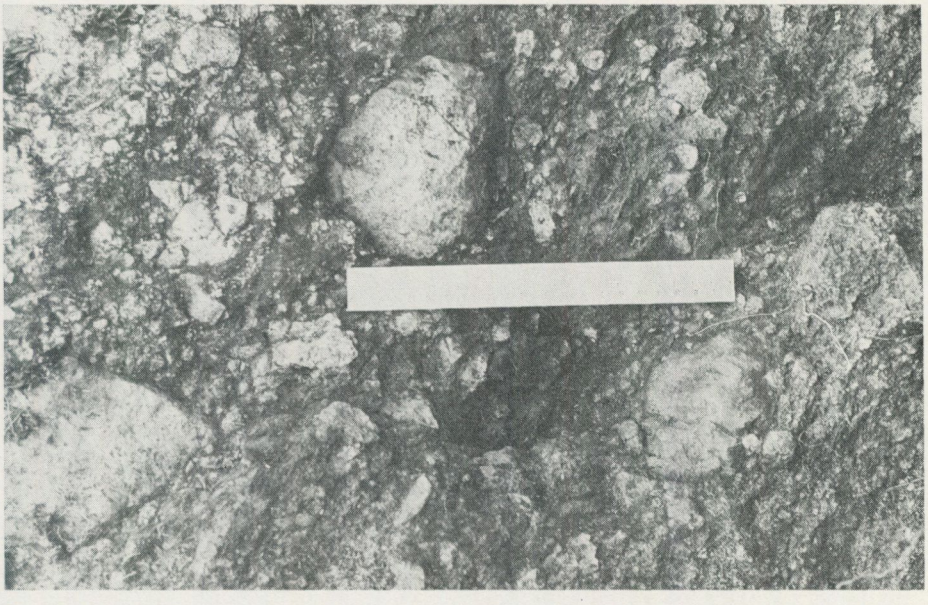

Fig. 8. Agglomerate in the quartz-bearing porphyry, N of Luossavaara. Length of scale 205 mm.

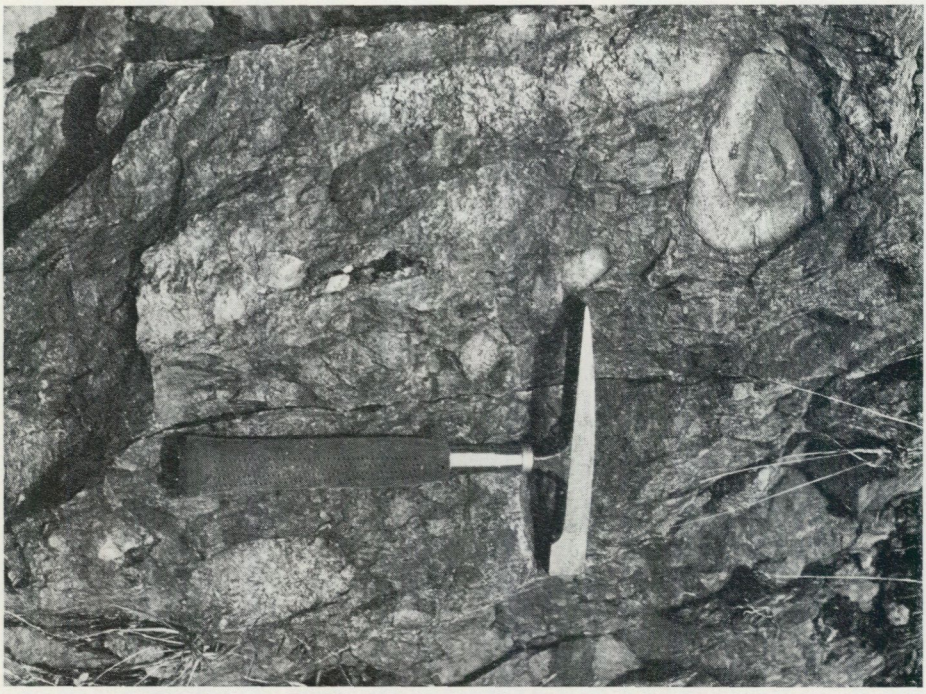

Fig. 9. Conglomerate in the hanging wall porphyry of Luossavaara.

Although these agglomerates and/or conglomerates are now covered by waste rock, at this locality there is an entrance to a gallery driven towards the top of Luossavaara. The accessible part of the gallery shows an ordinary conglomerate at least 30 m thick. The pebble material of the conglomerates includes syenite-porphyry, quartz-bearing porphyry, some fine-grained rock pebbles with altered rims, magnetite ore and quartz (Fig. 9). The pebbles can be 50 m in diameter. The biggest, well-rounded magnetite ore fragment that was found measures about 70 x 30 cm. The oval pebbles lie parallel to the dip of the main ore body. Angular fragments occur in minor quantities.

Partial analysis of one of the most usual rock types among the pebbles showed the following content:

$SiO_2 = 63.4$, $Fe^{tot} = 1.38$, $Al_2O_3 = 14.9$, $MgO = 0.85$, $CaO = 1.22$
$Ti_2O = 1.34$, $V_2O_5 = 0.02$, $Na_2O = 6.05$, $K_2O = 0.66$

The matrix of the conglomerate consists of a greyish-green, fine-grained material that macroscopically resembles phenocryst-free porphyry. The matrix is sometimes schistose around the pebbles. Unfortunately, the part of the conglomerate lying nearest to the Luossavaara ore body contact could not be studied because of a rock-fall.

Fig. 10. Fragments of rocks and iron ores in a matrix essentially composed of apatite and magnetite.

The quartz-bearing porphyry is often schistose. The colour becomes greyish near the contact with the Lower Hauki rocks. The contact surface, which can be studied in numerous outcrops and drill holes, dips eastwards at an angle of 55° at a level with Nukutusvaara. Quartz-bearing porphyry lying near the contact often includes iron ores which can be up to several metres thick. These ore sheets generally run parallel to the contact surface. Small fissures filled with hematite or quartz can be seen in the quartz-bearing porphyry near the contact. These fissures decrease in number away from the contact.

The quartz-bearing porphyry in the Rektorn open pit includes a rock with unusual structure in the vicinity of the ore contact. Rounded and angular porphyric and/or phenocryst-free fragments occur in a generally darker apatite-magnetite-hematite-rich matrix. The degree of rounding in the pebbles varies. They are usually highly elongated in the direction of the strike. They vary in size from a few centimetres up to several decimetres. The pebble material is at places monomict, consisting of quartz-bearing porphyry, although transitions to more polymict compositions are common (Fig. 10). Thus rounded or angular fragments of hematite and magnetite ore and also pebbles of phenocryst-free and other types of porphyry occur (Figs. 11 and 12). The porphyry pebbles (or fragments) usually show altered rims (Fig. 13).

Fig. 11. Polymictic fragments in the quartz-bearing porphyry, near to the ore contact. Rektorn.

Fig. 12. Pebbles of porphyry and hematite ore in the quartz-bearing porphyry, near to the ore contact. Rektorn.

Fig. 13. Xenoliths of porphyry, with alterations at the margins, in the quartz-bearing porphyry. Foot-wall of the Rektorn ore body.

Partial chemical analyses for three of the pebbles are as follows:

	SiO_2	Na_2O	K_2O
1.	71.0	4.32	3.10
2.	52.5	2.31	4.16
3.	58.0	2.59	5.31

At places, the matrix is fine-grained and often porphyric. In general, the matrix contains corroded phenocrysts similar to those found in the pebbles and fragments. Another type of matrix, consisting mostly of apatite, magnetite, hematite, calcite and sericite, shows banding. In the southernmost part of the Rektorn open pit, graded bedding is seen which is in keeping with the normal upside-down position (Fig. 14). The apatite-banded ore which here rests on the mechanical sediments is often folded (Fig. 15). In some places the apatite-banded ore lies directly on the quartz-bearing porphyry.

Fragments of magnetite ores and rocks of a porphyric character in the quartz-bearing porphyry are important in the discussion of ore genesis (Figs. 16 and 17). Geijer has discussed the nature of iron ore xenoliths in several publications, so that any description of them here would be superfluous. It can be

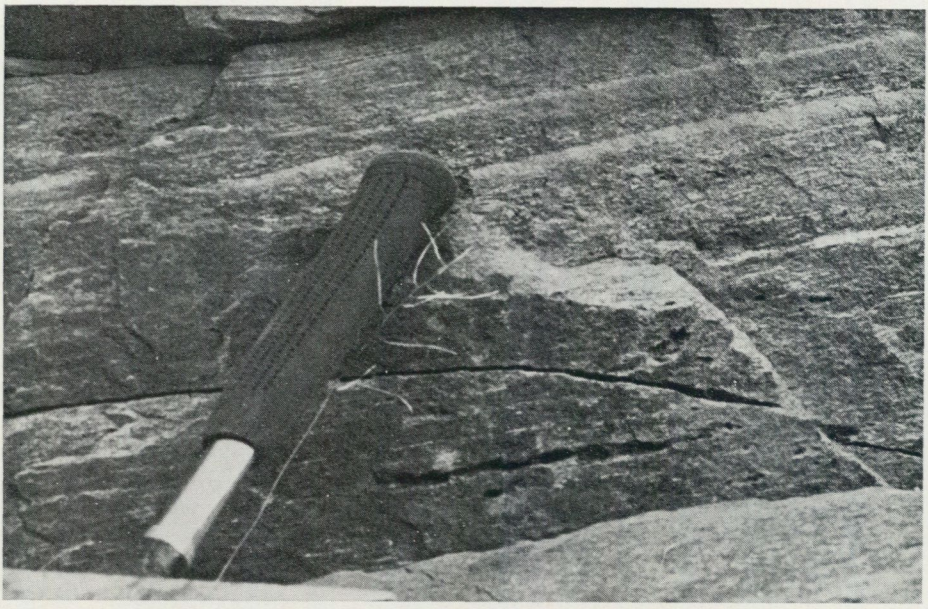

Fig. 14. Graded bedding in the weathering breccia, between the ore body and the quartz-bearing porphyry. Rektorn.

Fig. 15. Folded apatite-banded ore. Rektorn.

Fig. 16. Fragments of magnetite ore in the quartz-bearing porphyry. Luossavaara.

Fig. 17. Fragments of porphyry in the quartz-bearing porphyry. Luossavaara.

Fig. 18. Pebble of P-poor magnetite ore in a fragment of P-rich magnetite ore from the hanging wall porphyry. Luossavaara.

mentioned that xenoliths of magnetite ore rich in apatite, with enclosed rounded pebbles of apatite-free magnetite ore, were found during recent investigations east of the main ore body at Luossavaara (Fig. 18).

The distribution of the iron ore xenoliths has been proved to be greater than indicated by Geijer (1968). Fragments of magnetite ore occur even north of Luossavaara. Small fragments of magnetite ore were thus found just north of Luossavaara's open pit, in the foot-wall of the Rektorn ore and at several places west of drill hole 142 and drill hole 226 (see map). The most northerly observation was made only a few metres from the foot-wall contact of the Henry ore body.

In conjunction with the largest iron-ore fragment to be found north of Luossavaara (Fig. 19), fragments of a type of magnetite-syenite-porphyry and porphyric rock occur. These fragments lie parallel to the general direction of

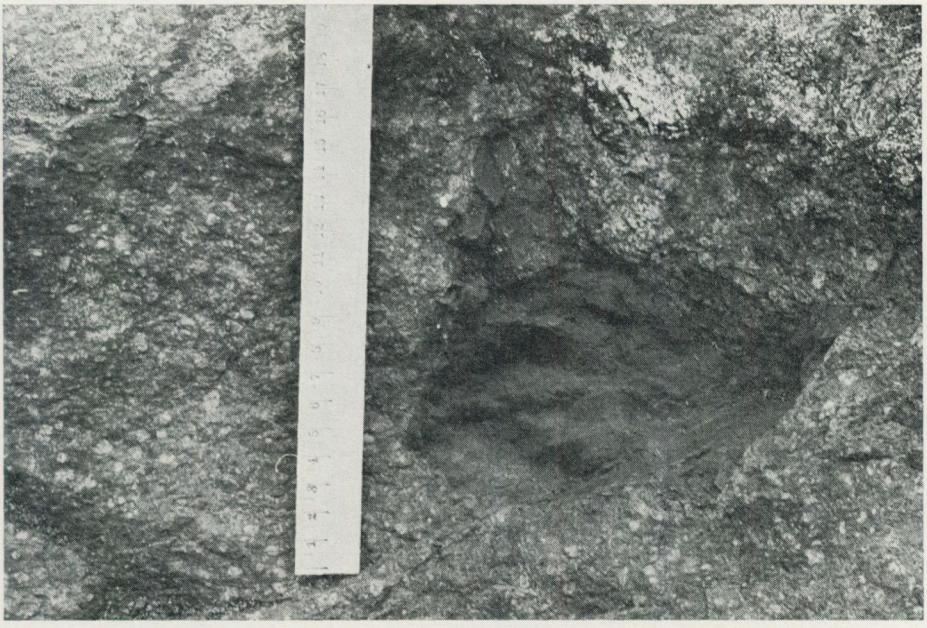

Fig. 19. Fragment of magnetite ore in the quartz-bearing porphyry, N of Luossavaara. Length of scale 201 mm.

the strike. Similar phenomena have been observed at other local outcrops north of Luossavaara. It should be noted here that a certain schistosity and change in colour are usually connected with these "fragment strips".

A zone of smaller magnetite ores in the quartz-bearing porphyry can be traced on the magnetic map. The small magnetic anomalies found east of the southern part of the Luossavaara represent a chain of small magnetite ores parallel to the main ore body (Carlheim-Gyllensköld, 1910). Geijer (1924) had already noted similar phenomena in his description of drill cores from deep drilling holes in Kiirunavaara's hanging wall porphyry. Thus, he states that several breccia zones, and even an ore zone (drill hole Luossajärvi I), occur in this hanging wall porphyry.

The largest magnetite ore (Neptunus) in the quartz-bearing porphyry between the Rektorn ore and the Luossavaara ore, was discovered by drilling, but was later also exposed by stripping at the surface. This ore lies about 200 m east of the Luossavaara ore and parallel to it in an agglomerate. The total area of the ore (which is not entirely exposed) is about 200 m^2. The area is 6—7 m thick at its thickest point.

In 1910 Geijer stated that small occurrences of magnetite ore (some rich in apatite) were to be found in a belt on the eastern slope of Kiirunavaara. Geijer's comments on these magnetite ores (1968), which he described as "small, to a

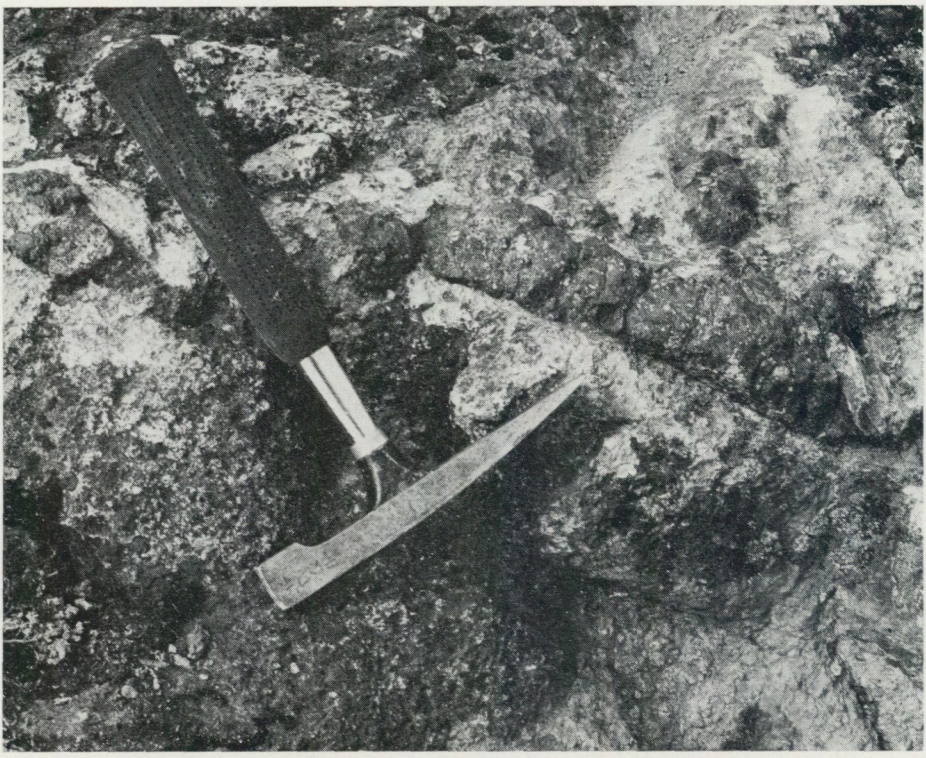

Fig. 20. Fragments of quartz-rich hematite ore in the quartz-bearing porphyry. (About 100 metres W of the northernmost part of the Rektorn. Analysis: Table 7, sample 1.) Photo B. Bihagen.

large extent ordinary, similar for example to Kiirunavaara's" ores, reads as follows: "The phenomenon as a whole has no known equivalence either within the Kiruna district or in other places where apatite iron ores occur, and no plausible explanation can be offered" (translated from Swedish).

One ore body, the so-called "Päron" ore — which on the basis of mapping has a cross-section of about 300 m^2 — was found in the quartz-bearing porphyry at the hanging wall of Kiirunavaara ore body. It was stripped in 1926 and has since been worked out (see map).

Fragments of hematite ore have recently been found in the upper part of the quartz-bearing porphyry. They have been observed within 100 m of the Lower Hauki rocks' contact. Thus, there occur, west of the Rektorn ore's northern tip, fragments consisting of quartz-rich, slightly magnetic hematite ore poor in apatite (Fig. 20). West of the drill hole 189, xenoliths of apatite-banded hematite ore up to about 1 metre in size have been found in several places. Several of these fragments lie in an apatite matrix that fills the fissures in the fractured, red, quartz-bearing porphyry (Fig. 21). In most cases the apatite

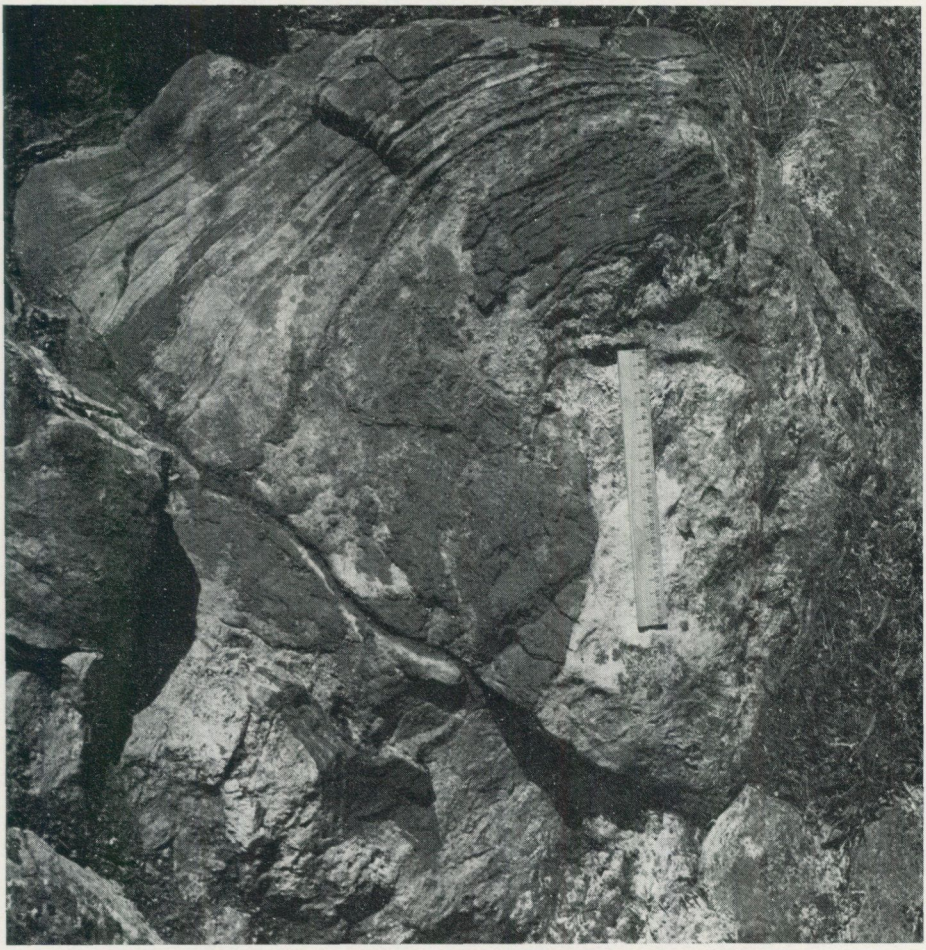

Fig. 21. Xenoliths of apatite-banded hematite ore, surrounded by apatite, in the quartz-bearing porphyry. (Analysis: Table 7, sample 3.) Photo B. Bihagen.

bands in the ore xenoliths grade into the surrounding apatite mass without any noticeable structural change (Fig. 21). Chemical analyses of ore fragments from the site west of the Rektorn ore (sample 1), west of the drill hole 189 (sample 2), and the apatite mass (sample 3) are given in Table 7.

The quartz-bearing porphyry is "apatite brecciated" over an area of about 10 000 m². Just north of this area, which stretches west of Henry's most southerly point, the quartz-bearing porphyry is rich in glassy quartz veins.

During the construction of Bolags School in the town of Kiruna, lenses of apatite up to 20 cm thick were found in the quartz-bearing porphyry. Their exact length could not be determined. They strike more or less north—south.

One drill core (E of Luossajärvi) showed 5 m of light reddish-grey anhydrite

in the quartz-bearing porphyry. The anhydrite was diffusely banded. The zone near the contact was "brecciated" and enclosed fragments of magnetite ore and quartz-bearing porphyry. Pyrite and chalcopyrite impregnations could also be seen. Contacts between the anhydrite and the quartz-bearing porphyry were distinct. The chemical composition of the anhydrite is shown in Table 8.

During the last few years radioactivity measurements have been made of the Kiruna area. Radioactivity anomalies have been detected in the quartz-bearing porphyry. In most cases they represent surfaces, up to 1 m^2, with a maximum of a few hundred micro-roentgens (R). The strongest indication was measured in a drill hole near Nukutusvaara. The drill core material, consisting of grey schistose quartz-bearing porphyry, was examined in the laboratory. 3000 ppm thorium could be noted in a core section 25 cm long.

Vulcanites of andesitic character (now appearing as amphibolites) occur in the quartz-bearing porphyry in the eastern part of the field. Identification of the rocks is difficult, because the rock is scapolitized in certain places, or exhibits a porphyric structure closely resembling schistose quartz-bearing porphyry. As it is difficult to say where the boundary lies between the above named rocks and the quartz-bearing porphyry, both types are represented by the same colour on the enclosed map.

Ten new analyses of quartz-bearing porphyry are reported in Table 9.

Dike porphyries

Dikes of syenite-porphyry. Dikes of syenite-porphyry cross-cut both the syenite-porphyry and Kiirunavaara's ore body. Up to the present time none of these dikes — about 10 in number — has been observed in the quartz-bearing porphyry. The dikes show a composition and texture similar to the other Kiruna porphyries.

Dikes of syenite-porphyry have, however, been reported from Tuolluvaara. Geijer (1920) states that "Syenite-porphyry forms dikes in the light red, quartz-bearing porphyry and in the ore. It is thus even younger than the formation of the ore" (translated from Swedish). Geijer reports that in places syenite-porphyry-dikes show a flow-structure and possess relatively high iron and phosphorus contents. Furthermore, he pints out that scapolitization of feldspar occurs in these dikes.

Geijer (1910, p. 41) states that dikes of a fine-grained syenite are found in the syenite which run parallel to the general direction of the strike.

Dark grey, fine-grained *dikes of meta-dolerite* (meta-diabase) up to several metres in width occur in the syenite-porphyry west of Kiirunavaara, in Zenobia (i.e. the northern part of the Kiirunavaara ore body) and also in the agglomerate east of Luossavaara. Circumstances do not permit mapping of the trend and

length of these dikes. A dolerite dike east of Luossavaara's ore body can be seen in an outcrop as well as in a nearby drill hole. This dike, which is a little over 1 m thick, strikes in a southwesterly direction and dips eastward at an angle of 55°. A chemical analysis of this dike is given in Table 10. The analysis shows that the iron content is relatively high. The iron content varies between meta-dolerite dikes in the field. Variations in the iron content are present even within the same dike.

Dikes of quartz-bearing porphyry in Kiirunavaara are known through Geijer (1910). His monograph contains a detailed petrographic description of these dikes. The dikes often show a granophyric structure. The longest quartz-bearing porphyry dike is about 2 500 m long.

It intersects the syenite, the syenite-porphyry, the ore and even the quartz-bearing porphyry. Construction work west of Kiirunavaara has recently revealed several similar dikes. These dikes run parallel to each other.

LOWER HAUKI ROCKS

From the centre of the town of Kiruna northwards, to a point west of Mount Kurravaara, an altered iron-ore-bearing rock suite occurs. For the most part, these rocks rest on the quartz-bearing porphyry. At the northernmost point, on the other hand, the Lower Hauki rock series rests directly on the syenite-porphyry. This has been confirmed by diamond drilling (Dh 1373). The dip of this rock series varies, with a minimum slope at its southern end of about 50° and a maximum of about 70° at the northern end.

"Detritus of porphyry"

In earlier publications, this rock was known as "Rektor-porphyry". According to Geijer (1950) "The term "porphyry" really is a misnomer, as a large partion of the rock body is not porphyritic at all and the rest not in a typical way, but it seems the only label that can be used without introducing either an entirely new term, or one containing an uncertain genetic interpretation".

This rock is in fact composed of two quite different types. One of them, which usually lies directly on the quartz-bearing porphyry or on the Per Geijer ores, is grey in colour and resembles sandstone, showing cross-bedding (Fig. 22). Similar cross-bedded structures have been observed in the Rektorn, Haukivaara, and Henry ore's open pits. Magnetite and hematite that occur in this detritus are often concentrated in more or less continuous horizons (Fig. 23). Fragments of iron ore of the Per Geijer ore type can often be seen in the rock. In some places the sandstone-like type does grade into the other type, a red more homo-

Fig. 22. Cross-bedding in detritus of porphyry. Rektorn.

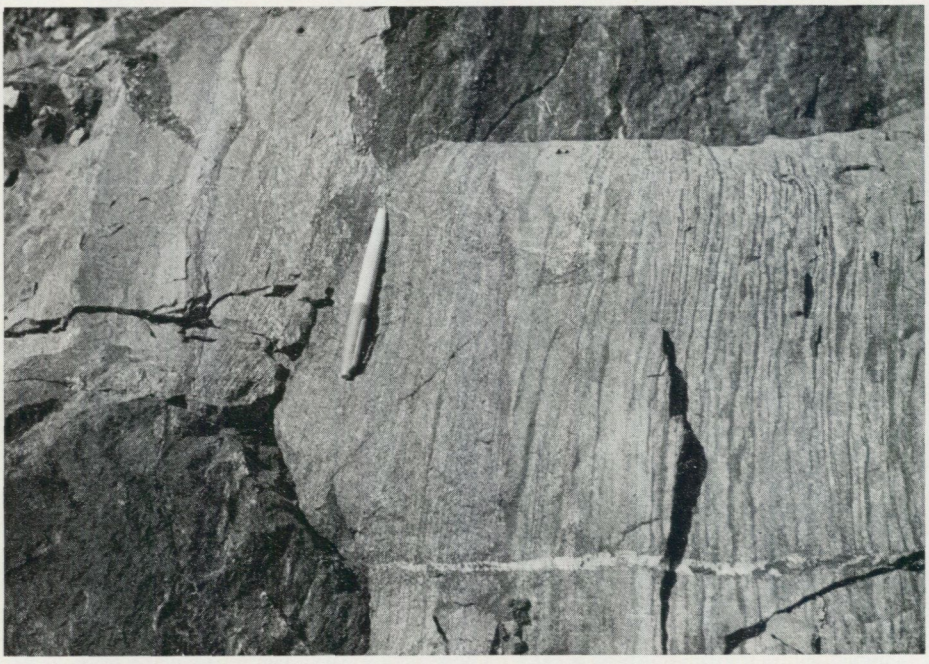

Fig. 23. Detritus of porphyry with thin horizons of hematite. Rektorn.

genous one. In this rock, "spherolites" can be observed under the microscope. (This type of rock could be equivalent to that which Geijer called "Rektor-porphyry".)

Detritus of porphyry (including the red type of rock) stretches from just south of the Rektorn ore to just north of Syväjärvi. Drilling has shown the existence of these rocks also in the deeper parts of the Lower Hauki rock series. It should be added that inclusions of sericite-quartzite are also to be found.

Microscopic examination shows that the rock consists mainly of potash-feldspar, quartz, and to a lesser extent calcite, sericite, albite, hematite and magnetite. Barite, tourmaline, zircon, ankerite and orthite have also been observed. Chemical analyses of the detritus of porphyry are given in Table 11.

Furthermore, numerous pegmatite veins, up to a few decimetres thick, occur in the detritus of porphyry. They consist mainly of quartz, ankerite, hematite, calcite and plagioclase. These veins cross-cut both the detritus of porphyry and the ores, which indicates that the veins are younger.

Recent investigations with a Geiger-Müller detector have shown scattered radioactive patches in the detritus of porphyry. No identification of the radioactive mineral has been made so far. The possibility of a connection between the zircon-orthite content of the detritus of porphyry (see below) and its radioactive patches should not be discounted.

In his monogram, Geijer (1910) mentions a type of porphyry from the Nukutusvaara field occurring in the Lower Hauki rocks which "is accordingly structurally different from the great mass Kiirunavaara—Nokutusjärvi, which occupies a lower level. It is more siliceous. It is quite identical with that found by Zenzén between Luossavaara and Haukivaara. This type of porphyry may be called the Nokutus type." This "Nokutus" type porphyry is found in Nukutusvaara. It resembles the quartz-bearing porphyry. This rock lies in the horizon of detritus of porphyry.

Syenite-porphyry of Hauki type

This rock is generally grey, with lighter and darker variations. It is fine-grained, in some parts massive and schistose in other parts. The rock forms structures varying between amygdaloidal and phenocryst-free types. Numerous veins of calcite occur in the rock.

The Hauki type of syenite-porphyry also contains polymictic fragments (often shows typical agglomerate) which are most common in the hanging wall part of the rock. The syenite-porphyry is up to over 100 m thick. The rock is impregnated with magnetite and hematite, which sometimes can form ore layers.

The syenite-porphyry of Hauki type is composed of albite, quartz, muscovite, sericite, biotite, and hematite. Some orthite, zircon, tourmaline and apatite are

also found. In places, the rock is impregnated with sulphide minerals (pyrite, chalcopyrite, bornite) and copper carbonates (malachite, azurite). The chemical composition of the rock is shown in Table 12.

Sericite quartzite

This rock is also known as sericite schist. It occurs among the Lower Hauki rocks both in the form of light grey-light green very schistose layers, which can be over 10 m thick, and in the form of layers which lack distinct boundaries. Sericite quartzite sometimes shows a blueish-dark grey colour depending on the dissemination of hematite and, to a lesser extent, magnetite in it. It is difficult, often even impossible, to trace the boundaries where the sericite-rich variety of this rock grades into the detritus of porphyry and the syenite-porphyry of Hauki type. In its most usual form the rock's primary minerals are quartz and sericite, the components next in importance being iron oxide (usually hematite) and potash-feldspar. Microscopic examination shows some calcite, tourmaline, bornite, ankerite, and rarely titanite, fluorite, orthite and zirkon. Biotite can be observed in thin sections of sericite schists. In sections from Nukutusvaara, chlorite is often seen.

The chemical composition of the rock is given in Table 13.

VAKKO ROCKS

These rocks are composed of mechanical sediments (Geijer 1931, p. 110) namely: greywacke, phyllitic slate and quartzitic sandstone (with conglomerate layers). Within the mapped area, the Vakko rocks rest on the Lower Hauki rocks partly concordantly and partly with boundaries of a tectonic nature. Tectonic contact has been proved to exist in the southern part of the field (south of the Rektorn ore) and north of Nukutusvaara. The eastern boundary of the Vakko rocks is marked by a line of dislocation.

Greywacke

The basal units of the Vakko sediments are composed of greywacke which often is conglomeratic in appearance. This rock, which occurs from Haukivaara in the south to Hopukka in the north, is often 50 m thick, as has been proved by drilling.

The pebble material varies both in size and composition. Most common are pebbles a few centimetres long. The matrix of the greywacke is sometimes impregnated with hematite and magnetite. Graded bedding shows that the most easterly layers are the youngest. Intercalation in the greywacke of coarse-

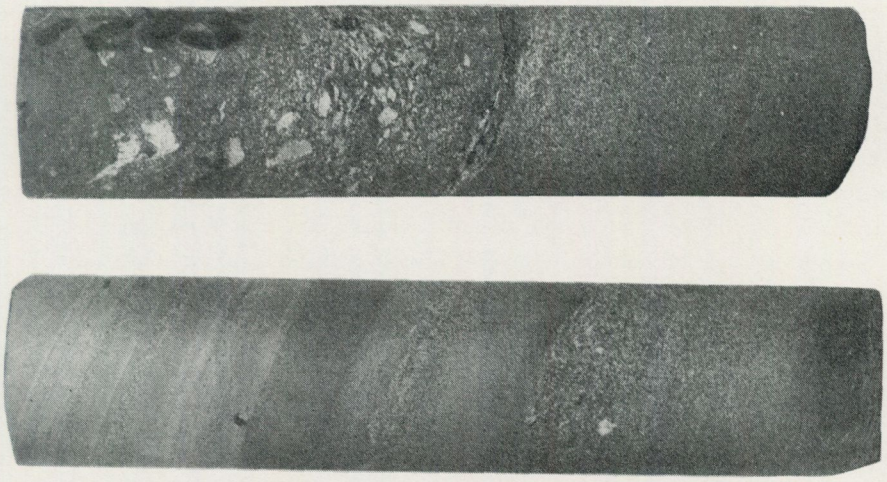

Fig. 24. Graded bedding in the greywacke. Above: drill hole 1286, below: drill hole 1283.

grained sandy materials showing cross-bedding and graded bedding occurs in places (Fig. 24). The polymic pebbles usually consist of hematite ore (also, though more seldom, found mixed with magnetite). Most of the pebbles are composed of fine-grained grey phyllite. A few pebbles resembling quartz-bearing porphyry have also been found.

The drill core material from the greywacke in which ore pebbles occur most sparsely was subjected to chemical analyses. The results are shown in Table 14.

Phyllite

This rock and the greywacke are conformable. Often, they appear to grade into each other. Judging from drillings, the phyllite is sometimes over 50 m thick.

The phyllite is grey-green in colour. Its pronounced schistosity is shown by biotite-rich intercalations up to 1 cm thick. Fine-grained impregnations of hematite and magnetite are arranged parallel to the schistosity of the phyllite. The phyllite often shows small folds. The occurrence of numerous quartz veinlets is characteristic. These veinlets appear in the same way as the calcite veinlets in the syenite-porphyry of Hauki type. Veinlets and lenses of calcite, often together with quartz which in turn is impregnated with chalcopyrite, are also characteristic of the phyllite. Small disseminated grains of pyrite can be noted in places. They are distributed along the schistosity planes.

At Haukivaara the phyllite rests directly on the (Per Geijer) ore. Strong fault tectonics in this area are indicated by wedges of phyllite in the Lower Hauki rocks. (See profile Fig. 37.) The chemical composition of the phyllite is given in Table 15.

Quartzitic sandstone

The youngest member of the Vakko rocks consists of quartzitic sandstone with several conglomerate beds. The quartzitic sandstone is mostly pale grey in colour, though in places round, rust-coloured patches of weathered feldspar or narrow dark bands of iron oxides can be observed. These dark bands often disclose cross-bedding in the quartzitic sandstone. The size of the quartz grains varies. About 60 % are smaller than 0.1 mm. Lenses of mudstone are usual.

Conglomerate beds occur at several levels in the quartzitic sandstone. Their thickness varies and can often be over 50 m. The pebble material consists almost exclusively of red quartz-bearing porphyries. Fragments of grey, fine-grained phyllite rocks are quite frequently to be found in the basal parts of the quartzitic sandstone. Pebbles of hematite, sometimes banded, have been observed. Quartzitic sandstone is mined in the Nukutusvaara open pit. Table 16 shows the chemical composition of this rock.

DESCRIPTION OF THE ORES

MAIN ORE BODIES

Kiirunavaara

The Kiirunavaara ore deposit is about 4 000 m long and has an average width of 90 m. The ore has been proven by drilling to have a depth of about 1 000 m. But magnetic measurements would seem to indicate the existence of a continuous ore body extending to a depth of at least 1 500 m.

Luossavaara

The Luossavaara ore is 1 200 m long, with an average width of 23 m. Judging from the results of drilling, the wedge-shaped ore body extends to about 300—400 m below the surface where it diminishes in width to a sheet generally not more than a few metres wide.

Luossajärvi

The Luossajärvi ore body has, during recent diamond drilling, been shown to form a direct continuation to the north of the deeper parts of the Kiirunavaara ore. The top of this ore body lies about 500 m under the surface of the lake. Its length is estimated to about 1 000 m and its average width to 60 m.

The Kiirunavaara, Luossavaara and Luossajärvi ores lie between syenite-porphyry and quartz-bearing porphyry. The ore-bodies strike NNE and generally dip about 50—60° towards the east. The contacts between the ores and the porphyries are sharp and often marked by actinolite-skarn. Both at Kiiruna-

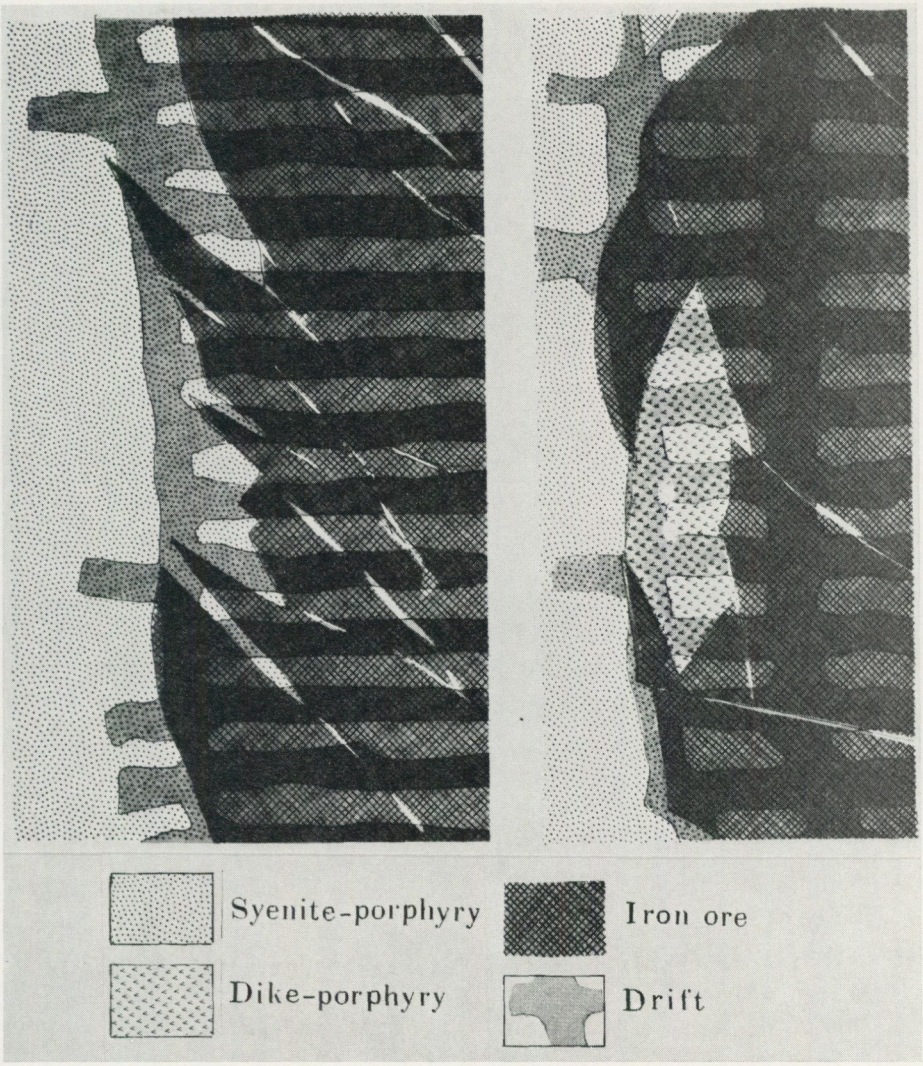

Fig. 25. "Offshoots"-resembling ore wedges in the foot-wall contact, Kiirunavaara. (From the mine-map.)

vaara and at Luossavaara, "ore breccias" occur in the syenite-porphyry (and to a lesser degree in the quartz-bearing porphyry as is also the case at Tuolluvaara).

The contact relations between ore and syenite-porphyry show that the phenomena which previously were interpreted as "offshoots" are the result of tectonic deformations or the intrusion of younger dike porphyries parallel to and near the ore contact (Fig. 25).

Investigations at Luossavaara in conjunction with mining operations have

not been able to prove the existence of these "offshoots". In this deposit the main ore is always separated from the "ore breccia" by a zone of skarn which is distinct enough to be used as a cut off boundary when mining the main ore body. The thickness of this border zone varies from a few centimetres to several metres. Sometimes a light red feldspar rock occurs between this skarn and the "ore breccia".

The dominating ore mineral in all these deposits is magnetite. Drilling, however, proves that hematite also occurs in the Kiirunavaara and Luossajärvi ores.

Within the Kiirunavaara magnetite ore, a hematite ore up to 25 m thick with a very low magnetite content has been found. Judging from drilling (mostly carried out at the 370 and 500 m levels), it seems that hematite occurs along the entire length of the magnetite ore. In most cases, however, the ore in question is only a few decimetres thick. Geijer (1910) pointed out the presence of hematite ore at the surface on the southern slope of Kiirunavaara. Drilling at deeper levels in the Kiirunavaara ore (at the 800—1 000 m level) has not resulted in the discovery of any hematite ores. In the Luossajärvi ore body, hematite ore makes up 1/3 of the entire thickness of the ore in one drill hole and constitutes the central part of the ore body. The boundaries are not sharp. The hematite usually shows a low magnetite content.

Microscopic examination shows that the hematites of the Kiruna field have an identical occurrence. With the exception, as Geijer (1910) pointed out, of the martitization of the upper part of the Kiirunavaara ore, no evidence of martitization has hitherto been found in these ores.

The grain size of the ores varies somewhat, the Kiirunavaara ore being, by and large, finer-grained than the Luossavaara and Tuolluvaara ores.

The predominant gangue mineral in these ores is fluorine-apatite with about 2.5 % F and 0.6 % rare-earth metals. Data on this topic is to be found in Geijer (1910, 1967) and Parák (1973). The grain size of the apatite is about 0.08 mm. There usually is a sharp boundary between the apatite-rich and the apatite-poor ores.

The apatite-rich ores show a richly varied structure, such as apatite bands, or lamination of apatite (lamination can, however, occur in apatite-poor ores too), skeleton ore, and apatite spotted ore.

The apatite-rich ore diminishes with depth in the Kiirunavaara ore body. Except in the southern part of the deposit, the Luossavaara ore is apatite-poor. The Luossajärvi ore body is made up of about 50 % apatite-rich ore.

Besides apatite, hornblende (actinolite) is the most common gangue mineral found in these ores. Calcite, biotite, quartz, titanite, diopside, talc and albite are also present, but in lesser quantities. Zircon, orthite and monazite occur as accessory minerals, usually in conjunction with apatite. In the apatite-banded ore, in the southern part of Kiirunavaara, small red lenses up to 15 mm long were found by P. Forsell. They consisted mainly of monazite and a little albite.

These lenses are parallel with the apatite-banding. Sulphide minerals are rare. Their occurrence can generally be associated with faultzones.

At one place on the 540 m level, in a drift at the middle of the ore body, the ore encloses a white, light-red, albite-quartz rock as veins and lenses. These inclusions are oriented parallel with the borders of the ore. (See Fig. 7.)

Dark green, strongly schistose bands of chloritized altered rock, a few centimetres thick, running parallel to the ore foot-wall contact, have been observed in the Luossavaara ore only a few metres from the ore contact.

These bands could be traced for several metres, although mining operations made it impossible to determine their extent. Similar bands have been found in two of the thicker "ore veins" west of the main ore body (see p. 51). The chemical composition of these ores is shown in Table 17.

TUOLLUVAARA

The Tuolluvaara ore deposit lies 4 km east of Kiirunavaara. In contrast to the Kiirunavaara, Luossavaara, and Luossajärvi ores, its foot- and hanging walls consist of the quartz-bearing porphyry. The ore deposit is made up of several ore bodies that were probably continuous originally, but have since been broken up and displaced by faulting. A large part of the deposit consists of breccia ores. The contacts between the ores and the wall-rocks are always sharp.

Geijer (1920) mentions that hematite occurs to a lesser degree in the Tuolluvaara magnetite ores. This hematite is described as consisting of coarse lumps (Fig. 26), which are seldom more than a few centimetres in diameter. The

Fig. 26. Hematite (grey white) in magnetite ore. Tuolluvaara. Photo B. Rönnberg.

hematite is described as a secondary formation. Recent drilling operations have established the existence of a larger, probably isolated, hematite ore a couple of hundred metres below the surface (Vietnam ore, with P = appr. 2 %).

In general, the Tuolluvaara ores are characterized by a low phosphorus content, although magnetite ore rich in phosporus occurs in places (Bråkmalmen).

According to Geijer (1920) the magnetite is fine-crystallized with a grain-size of about 0.10—0.15 mm. The grain-size of the apatites varies between 0.5—1.0 mm. Other minerals which occur in the ore are: hornblende, (asbestos), biotite, serpentine and, less frequently, zircon and quartz. The chemical composition of the ore is shown in Table 17 a.

THE "PER GEIJER" ORES

"Per Geijer" ores is a collective name for the Haukivaara, Rektorn, Henry and Nukutusvaara deposits and the Lappmalmen ore.

With the exception of Haukivaara, these ores form a more or less continuous ore layer lying on the quartz-bearing porphyry. According to investigations carried out so far, the layer extends from the town of Kiruna to Syväjärvi.

Four of the Per Geijer ores, namely Haukivaara, Rektorn, Henry and Nukutusvaara appear at the surface and are, or have been, in production. The fifth — the Lappmalmen ore — lies about 700 m below the surface and is still in its exploration phase.

In places, this ore layer is deformed by faults. A similar deformation has been noted in the southern part of the Lappmalmen ore, which is broken up into several blocks. Faulting has resulted in a strong lifting of this part of the ore. Other Per Geijer ores have also been affected by tectonic movements. The northwest crescent-shaped part of the Henry ore body is probably formed by a series of displacements of a folded ore layer.

The "Per Geijer" ores consist of both magnetite and hematite. The ores are characterized by high apatite contents (Tables 18—22).

As mentioned above, the foot-wall of the "Per Geijer" ores consists of quartz-bearing porphyry. The Haukivaara ore, however, lies adjacent to the eastern border of the Lower Hauki rock series. The contacts between the ores and the quartz-bearing porphyry are usually sharp and well defined.

It is more difficult to observe the contact in cases where the reddish, "sugar-grained" apatite or detritus of porphyry lies directly on the quartz-bearing porphyry. In most cases the phosphorus-rich magnetite lies nearest the foot-wall and the phosphorus-rich hematite nearest the hanging wall.

The horizon of the apatite iron ore is associated with a variety of ore-impregnated rocks such as detritus of porphyry, syenite-porphyry of Hauki type,

sericite quartzite, Hauki hematite and its fragment-bearing or quartz-banded varieties. The latter rock is less common than the others.

It has been noticed in both the magnetite and hematite ores that the basal part of the Per Geijer ores contains small fragments of apatite-poor ore in a matrix of apatite-rich ore.

The main characteristics of the Per Geijer ores are:

a. The ore is made up of magnetite and hematite. The latter can even be predominant in some deposits.

b. Apatite generally makes up between 15—20 % of the volume of the ore, irrespective of whether it is magnetite or hematite.

c. Calcite and quartz are the next most important gangue minerals (besides apatite).

Chemical analyses show that potassium dominates over sodium in the Per Geijer ores, as is also the case in the Kiirunavaara—Luossavaara ores.

The grain size of magnetite and hematite is usually 0.02—0.1 mm, hematite grains often being larger than the grains of magnetite. Apatite has a grain size of about 0.1 mm. Rim martitization has been observed in samples from the Rektorn ore, Haukivaara and the Lappmalmen ores.

The apatite is not always pure fluorine-apatite. The rare-earths metal content of the apatite is generally lower than that found in the Kiruna apatites.

The following summary of the individual Per Geijer ores is based on the works of Geijer (1910, 1919, 1919a, 1950), Ljunggren (1956), and Parák (1969).

HAUKIVAARA

This deposit has a special position in realtion to the other Per Geijer ores. The tectonic movements (thrust-faults, wrench-faults and small folding) which determined the present position of the ore also affected the minerology of the deposit and paved the way for chemical alteration. This is true for both the ores and the wall-rocks. In the fissures (fracture zones) secondary minerals such as uranium-bearing mica are found which are otherwise unknown in the Kiruna ore-field.

Several completely or partially unconnected ore bodies occur in the deposit. The ore is composed almost entirely of hematite. Diamond drilling shows that the proportion of magnetite increases with depth.

In the upper 10 m of the deposits apatite and the silicates are almost completely leached out.

The contacts of the ores with the wall-rocks are generally sharp. The wall-rocks of the ore bodies consist of detritus of porphyry, syenite-porphyry of the Hauki type, agglomerate, sericite quartzite, phyllite and quartzitic sandstone.

Alteration processes include silicification, sericitization of the wall-rocks and martitization of the ore. The dip of the ore bodies is generally easterly at about 50°. The chemical composition of the ore is shown in Table 18.

Rektorn

This deposit has a simpler shape than that of the Haukivaara ore. The ore is situated between a foot-wall of quartz-bearing porphyry and a hanging wall of detritus of porphyry. In the proximity of the foot-wall the ore consists almost exclusively of magnetite. Near the hanging wall the dominant ore mineral is hematite in which martitization has been found on a small scale.

In the southern part of the deposit, cross-bedding can be seen in the apatite-banded ore (Fig. 27). Furthermore, the apatite-rich magnetite ore in the central part of the deposit shows a marked "plane-schistosity". Flat surfaces of as much as several square metres can easily be cut into thin slices, often less than 1 cm thick (Fig. 28).

The ore presents the highest SiO_2-content of all the Per Geijer ores. This SiO_2-content decreases with depth. The ore and the wall-rock of the hanging

Fig. 27. Cross-bedding in apatite-banded ore. Rektorn.

Fig. 28. Plane schistosity in magnetite ore. Rektorn.

wall are cross-cut by veins a few decimetres wide consisting mainly of quartz, ankerite, hematite (specularite), calcite and albite.

The wall-rock of the ore has been silificed, sericitized and carbonatized, although to a lesser extent than in Haukivaara. The dip is easterly at about 50°. The chemical composition of the ore is shown in Table 19.

Henry

This deposit occupies a special position owing to the fact that the ore body in its northern part curves westward, and that both the foot-wall and hanging wall in this part are composed of quartz-bearing porphyry. This position has been proved by the latest investigations to have been caused by a series of displacements.

The ore consists mainly of hematite. Magnetite occurs in the northwestern part of the deposit. The transition between magnetite and hematite ores is continuous. Both are phosphorus-rich. In the magnetite-predominant ore a somewhat higher carbonate content is sometimes noted. Sometimes, near the foot-wall, apatite lumps can be observed in the ore. They can cover several

square metres. Hematite ore fragments are included in these apatite masses. (These inclusions often show beautiful apatite banding.)

The foot-wall of the ore consists mainly of quartz-bearing porphyry and to a lesser extent of syenite-porphyry to the west. The main constituent of the hanging wall is detritus of porphyry, ore fragments, phosphorus-poor Hauki hematite, and to a lesser degree, the Hauki type of syenite-porphyry. The ore dips eastwards at about 60°. The chemical composition of the ore is given in Table 20.

Nukutusvaara

The deposit constitutes a direct continuation of the Henry ore to the north. It is characterized by NW—SE and nearly N—S faults. The ore, which originally formed a single layer, has been displaced by faulting, which caused the western parts to sink in relation to the eastern parts. The ore is composed of magnetite and hematite. Magnetite is predominant in the north and hematite in the south. In addition, the Nukutusvaara ore is characterized by a high apatite content. Apatite is often found in well-defined layers. Magnetite sometimes shows stratification according to grain size, conform with the apatite bands (Fig. 29).

The general dip is eastwards at about 70°. The Nukutusvaara ore continues northwards, diminishing in thickness, under Lake Syväjärvi.

Fig. 29. Stratified magnetite ore. Nukutusvaara.

The foot-wall consists of quartz-bearing porphyry. It is often altered near the ore contact and appears as a grey-green schistose phenocryst-poor variety. A relatively high thorium content (3 000 ppm) was noted in a drill hole in the schistose quartz-bearing porphyry. The main constituents of the hanging wall are detritus of porphyry, quartz-bearing porphyry, and syenite-porphyry of the Hauki type. To a lesser extent, Hauki hematite is present.

Besides seritization and silicification, chloritization on a large scale is fund in the hanging wall-rock of the ore. The chemical composition of the ore is shown in Table 21.

Lappmalmen

The first indications of the existence of this ore were obtained by magnetic surveys. The ore constitutes the partly continuous and partly faulted deep-lying parts of the other Per Geijer ores which are all exposed at the surface. The top of the ore body, where it has been displaced by faults, lies 700 m below ground level. The ore is at least 2 500 m long and its area about 150 000 m^2 just beneath the top level. It seems to increase with depth. The southern part of the Lappmalmen ore has been disturbed tectonically. It is abruptly truncated west of the Haukivaara deposit. No investigation of how far the ore extends north of the Henry deposit has as yet been carried out.

The Lappmalmen ore can reach very great thicknesses. In one drill hole a 250 m long section of ore was found, containing an average of 44.2 % Fe, 4.3 % P and 5 % SiO_2. An examination of drill core material did not reveal any repetition of the ore layers. Fine-grained almost phyllitic intercalations a few centimetres wide can be noted parallel to the apatite banding.

The ore minerals consist of hematite (20—30 m in the proximity of the hanging wall) and magnetite. The ore is characterized by a higher P-content and lower SiO_2 content than the other Per Geijer ores.

The foot-wall is consistently composed of quartz-bearing porphyry. The hanging wall contains hematite impregnated detritus of porphyry, schistose syenite-porphyry of the Hauki type, and quartz-banded or fragmented ore. The ore dips eastwards at 55—70°.

Three drill holes have shown that the transition between the apatite-rich ore and the overlying quartz-banded ore is continuous.

Quartz-bands up to 2 cm wide occur here even in the apatite-banded ore. The quartz- and the apatite-banded ores are conformable. Neither displacementplanes nor any other signs of tectonic deformation were seen in the drill core material from this contact-zone. In the other drill holes, where the quartz-banded ore lies directly on the apatite-rich Per Geijer ores, the boundaries between the two types are easily established.

In the drill holes mentioned above, detritus of porphyry is absent. In those

cases where this arkosic rock occurs, it always appears between the apatite-rich and the quartz-banded ores. The transitions, however, are often successive.

The Lappmalmen ore has been affected by alterations, though to a lesser degree than the other Per Geijer ores. A weak martitization of the magnetite, and sericitization and silicification of the wall-rock have been observed. The chemical composition of the ore is given in Table 22.

QUARTZ-BANDED ORE

This type of ore has not previously been described in the Kiruna field because the regions in which it has been found have hardly been investigated at all. Although a few of these ores had been found previously, they were at that time considered to be Hauki hematites. A white to light grey-glassy, or flint-like,

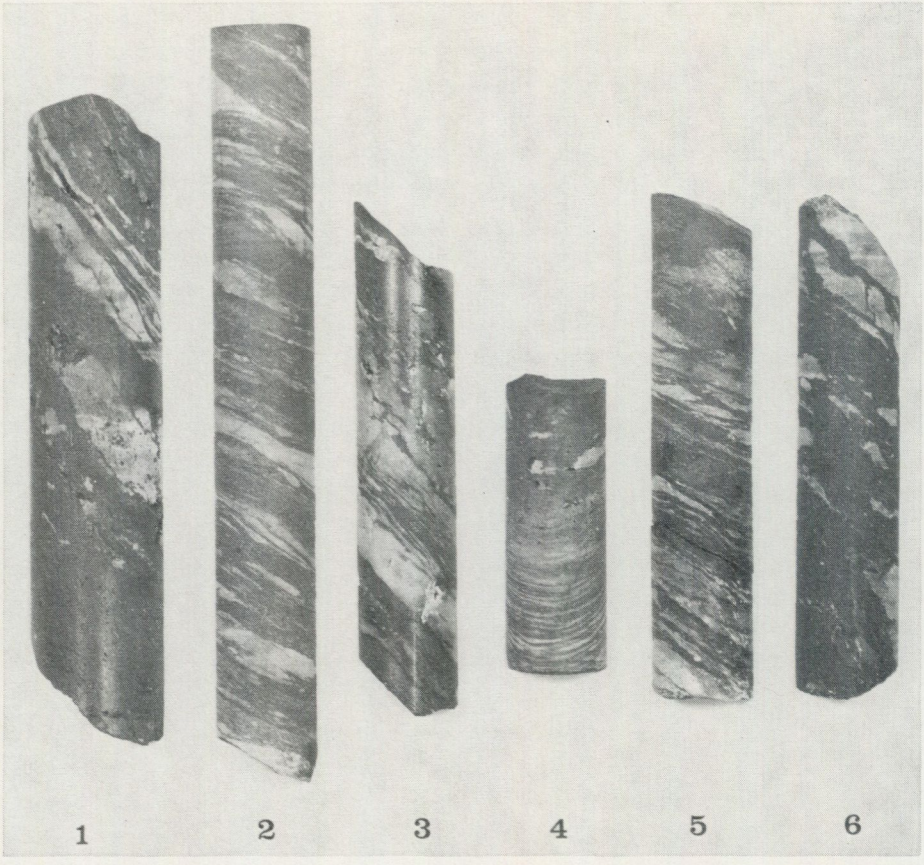

Fig. 30. Quartz-banded iron ores from the Kiruna area. 1=drill hole 1137, hemetite and quartz; 2=drill hole 1369, hematite magnetite and quartz; 3=drill hole 370, magnetite and quartz; 4=drill hole 370, hematite and quartz; 5=drill hole 1228, hematite and quartz; 6=drill hole 1284, magnetite and quartz.

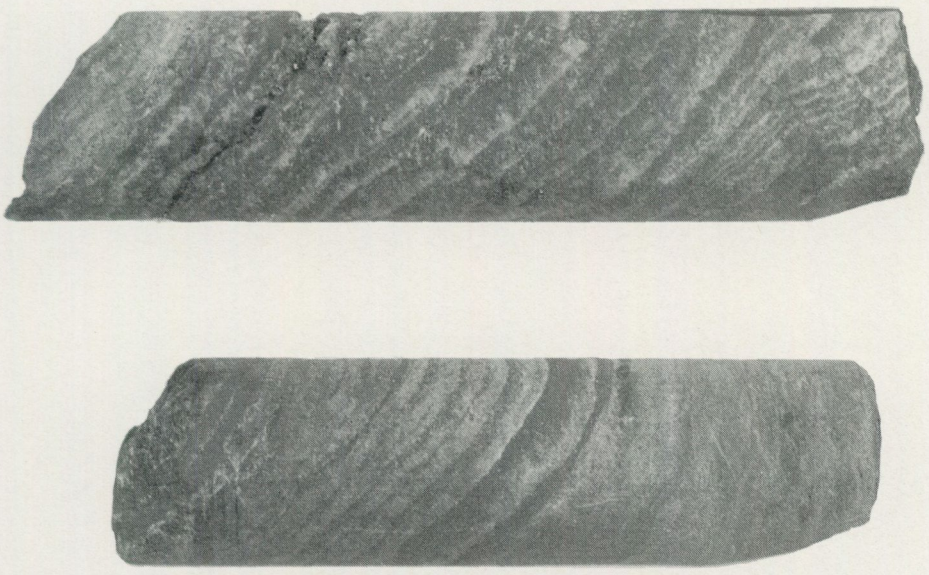

Fig. 31. Photos showing the continuous transition from pure quartz to pure hematite in the bands, from drill hole 1364.

quartz in layers, alternating with hematite or magnetite ores was found during diamond drilling in the so-called Lower Hauki rocks (Fig. 30). In at least three cases (Dh 1284, 370 and 1368) a direct transition from Per Geijer ores to a quartz-banded ore was noted. Like the apatite-banding in Per Geijer ores, the quartz bands in quartz-banded ore, which is relatively poor in iron, follow the general directions of the strike and dip. Chemical analysis shows that the quartz-bands in the iron ore have a SiO_2-content of over 98 %. Of the iron minerals, hematite is predominant in this type of ore.

Quartz and hematite (magnetite) bands occur mostly with sharp contacts, although continual grading of iron oxide and quartz has been noted in certain bands (Fig. 31). The bands are usually a few centimetres wide.

Quartz has also been found in a different form both in drill holes and in exposures. The quartz occurs in the form of lenses and lumps in a fairly pure iron ore (Fig. 32).

The thickest quartz-banded iron ore deposit was intersected by drilling between the Rektorn and Henry ores and attains a thickness of 60 m. In most of the drill holes the typical quartz-banded ores are not more than a few metres thick. They can, however, occur several times in the same drill hole. Transitions to both schistose and fragment-bearing hematite of the Hauki type have also been found.

In drill hole 333, the quartz-banded ore, Hauki hematite (along with fragment-bearing types) accompanied by intercalated bands of sericite quartzite,

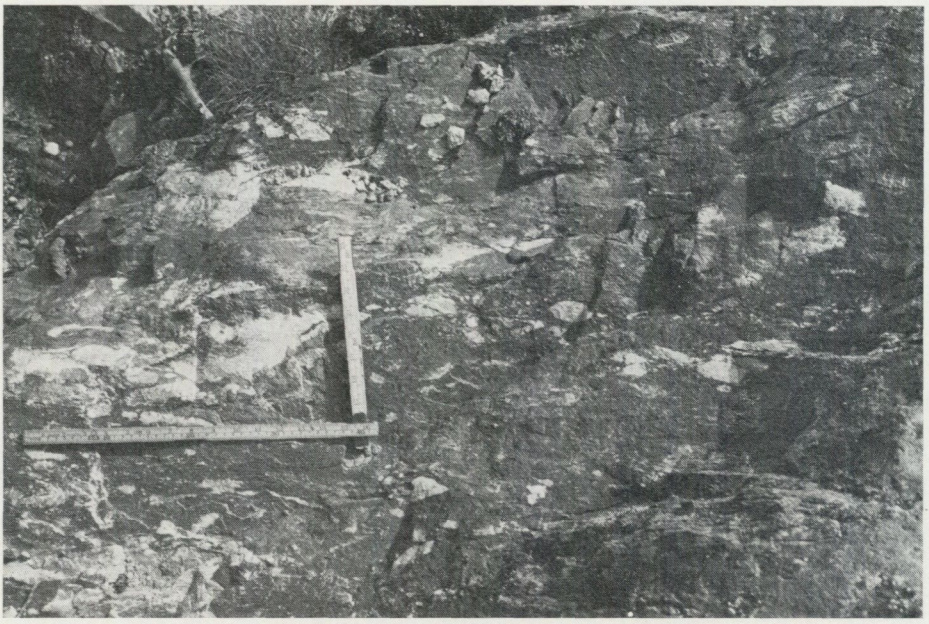

Fig. 32. Lenticles of quartz in hematite ore between Rektorn and Henry deposits.

reaches a thickness of over 200 m. The following contents were observed in these rock formations: Fe = 20—30 %, P = 0.5 % and SiO_2 = 15—45 %. This thick zone overlies the detritus of porphyry (with winding bands of hematite), which in turn rest on the 250 m thick Lappmalmen ore (the upper 20—30 m consist of apatite-rich hematite ore, the rest being apatite-banded magnetite ore). Thus, the total thickness of the Lappmalmen ore, and the ore-bearing rocks, is about 450 m in this part of the field.

HAUKI HEMATITE

Amongst the Lower Hauki rocks, schistose, shiny, fine-scaled hematite ores occur. They differ considerably in texture and composition from the Per Geijer ores and the quartz-banded ores. Hauki hematites always lie above the Per Geijer ores.

The ore mineral consists almost entirely of hematite. Magnetite is found only in minor quantities. Microscopic examination shows the presence of quartz, sericite, chlorite, and barite. Zircon, orthite and tourmaline occur more seldom.

A formation similar to the quartz-banded ores, though containing a large amount of sericite quartzite, is found north of Syväjärvi. These variations between the different types of rocks from sericite quartzite to Hauki hematite are

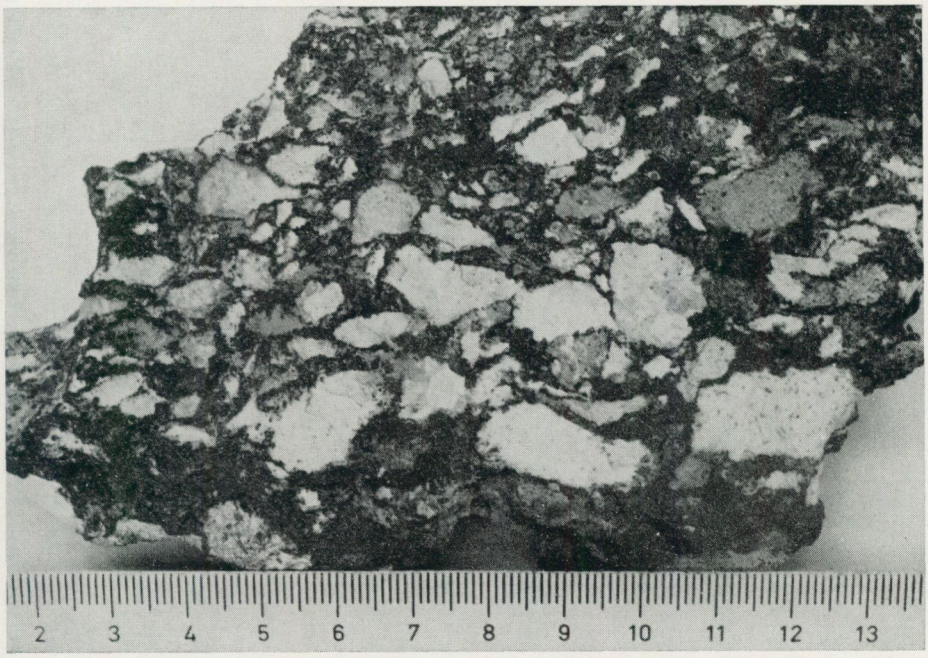

Fig. 33. Fragments in hematite ore Syväjärvi. Scale in cm.

illustrated by the following analyses (samples taken from west to east at intervals of about 3 m):

No.	1	2	3	4	5	6	7	8	9	10	11
SiO_2 %	90.3	37.6	51.3	53.5	79.5	64.0	53.5	38.5	79.9	66.8	51.9
Fe %	9.7	44.2	30.6	25.5	15.9	23.4	33.7	39.4	12.9	22.2	36.7
P %	0.005	0.080	0.030	0.030	0.030	0.030	0.070	0.050	0.030	0.090	0.02
K_2O %	0.043	0.18	0.13	0.31	0.23	0.11	0.063	0.096	0.58	0.019	0.01
Na_2O %	0.007	0.013	0.013	0.016	0.034	0.013	0.013	0.040	0.086	0.007	0.00

The Hauki hematites are often fragment-bearing, for which reason they are often called fragment-ore. The fragments usually consist of white and red silicified rocks (Fig. 33).

It is worth noting that these ores often show high barium-contents. Several per cent barium are included in the iron-poor Hauki hematite which is sometimes found in the sericite quartzite at Syväjärvi. The chemical composition of the Hauki hematites is shown in Table 23.

"ORE BRECCIAS" [1]

The so-called "ore breccias" which occur in the Kiruna field can be divided into three groups, namely:

1. Vein (or dike)- like ore bodies. These form networks here and there.
2. Different types of ore impregnations in the wall-rock (including magnetite-syenite-porphyry).
3. Ore breccia in which angular fragments of wall-rock lie in an ore matrix.

Ore veins (sometimes as banding) occur in the proximity of the Luossavaara's and to a lesser extent the Kiirunavaara's foot-wall (syenite-porphyry). They are also found west of the Henry ore body.

These ore veins at the main ore's foot-wall contacts consist mainly of vein (or dike)- like bodies varying from a few millimetres to 5 m in thickness, and forming "trellises" in places. By and large, these ore veins (the name "veins or dikes" refers only to their geometry, and not to their origin) lie parallel to one another at an angle of 20—30° to the strike of the main ore body (Fig. 34). The ore in these veins is poor in phosphorus, but often relatively high in carbonate. Cross sections of these ore veins of the Luossavaara "ore breccia" are cross-cut in several places by younger ore dikes up to 15 cm thick (Fig. 35). The magnetite in the veins is coarser grained than in the main ore body.

An up to ten centimetres thick, grey-green, chloritized, schistose layer of

[1] In this context the following ought to be pointed out. Technically, all the rocks which contain over 20—25 % Fe are treated as ore breccia by the LKAB company, regardless of geological considerations.

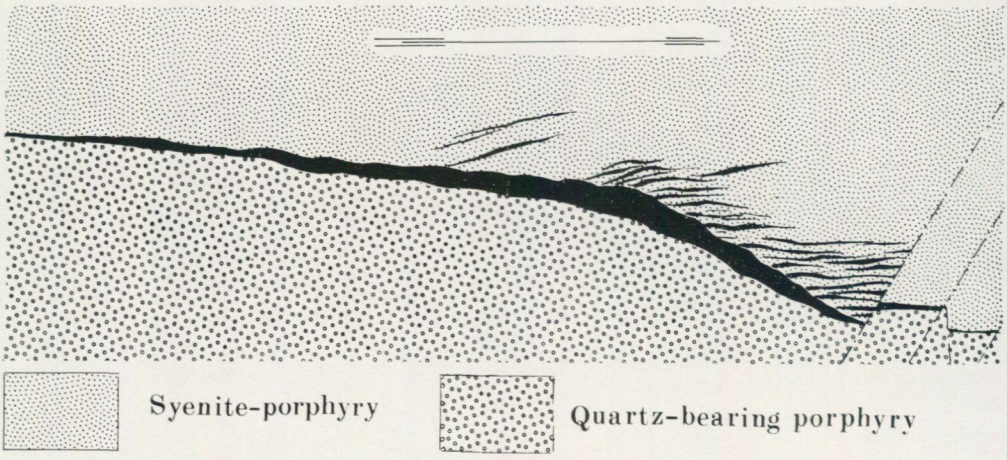

Fig. 34. Drawing showing the relationship between the Luossavaara ore body and the ore veins of the syenite-prophyry, "the Luossavaara breccia".

Fig. 35. A young vein of magnetite ore cuts a syenite-porphyry with magnetite schlieren. Luossavaara.

altered rock has been observed in each of the two thicker "ore veins". These layers are conform with the "ore veins". A chemical analysis of the layers gave the following results:

Fe = 14.25 %, CaO = 1.10 %, Al_2O_3 = 19.6 %, TiO_2 = 0.82 %, Na_2O = 0.22 %
P = 0.29 %, MgO = 24.4 %, SiO_2 = 28.3 %, V_2O_5 = 0.04 %, K_2O = 0.66 %

Besides veins and veinlets, the magnetite ore occurs in places in the form of xenoliths in the syenite-porphyry (Fig. 36).

Ore impregnations (type 2) are known in the largest extensions west of the Henry ore, and west of Syväjärvi, and to a lesser extent west of Luossavaara main ore body, in the quartz-bearing porphyry, and in the Lower Hauki rocks.

Ore breccias (type 3) are known from Tuolluvaara (Geijer, 1920), and on a smaller scale at Kiirunavaara and Luossavaara. West of the Henry ore body,

Fig. 36. Xenolith of magnetite ore with veins of calcite. Luossavaara.

west of Syväjärvi, and in some places in the Lower Hauki rocks, they are found in conjunction with the ore impregnations.

As the map shows, the impregnations and the ore breccia which occur in the syenite-porphyry are not always connected to the main ore bodies. This is the case to the west of Henry and to a greater extent west of Syväjärvi.

In the Kiirunavaara ore body (to a small extent, which is why it is not marked on the map) and at Luossavaara, where both forms of ore accumulation are present, the contacts between them are marked by a chlorite-rich skarn zone. This "boundary-zone" is so general that it is used as the ore boundary mark in mining. There is thus no direct continuous ore transition here between the ore breccias and the bulk of the ore bodies.

TECTONIC FEATURES OF THE KIRUNA FIELD

It is not the author's intention to discuss here the tectonic elements of the Kiruna field in detail. For this reason, the main tectonic elements shown by geophysical measurements and diamond drilling will only be mentioned briefly. (The tectonics of the Kiruna field can be studied with the help of the map.)

The tectonics have been treated in earlier studies. The most important are those by Sundius, Geijer and Ödman. The first two writers consider the Kiruna field to be a monoclinal rocksuite. Ödman regarded the Kiruna porphyries as overthrusting the younger Kiruna greenstone.

Many rock contacts in the Kiruna field are determined by faults which can be divided into three groups: faults (and overthrusts) striking north or which conform to the strike of the ore bodies; faults striking NNW; and those which strike NE—SW. It should be pointed out, however, that planes of movement have been shown to exist which strike E—W. Mining operations have brought to light relatively small faults which deviate from the directions mentioned above. The plane of dislocation running nearly N—S is one of the largest occurring within the map area. Another important fault zone forms the boundary between the eastern Kiruna greenstones or the quartz-bearing porphyry and the Vakko sediments.

Several new investigation trenches exposing the contact of the quartz-bearing porphyry with the Lower Hauki rocks in the area between the Henry and Rektorn ore bodies show clearly a fault direction striking about N 20°E, above which the Hauki hematites lie directly on the quartz-bearing porphyry. Mining operations have shown small folds with gently plunging axes.

ANALYSIS OF TRACE ELEMENTS IN MAGNETITE AND HEMATITE FROM THE KIRUNA FIELD

INTRODUCTION

335 samples were collected of various ore- and rock types from boreholes. One ore sample was hand-picked. In addition, 10 magnetite-rich pebbles were sampled from rock exposures in the Kurravaara conglomerate.

An additional 44 samples were taken from three diamond boreholes (a section through Rektorn—Lappmalmen) in which the trace element content was investigated in enriched ore samples (Fig. 37).

Sections of core approximately 20 cm long were generally chosen. Pieces 3—4 times larger were taken in cases where the amount of sample was insufficient for analysis, owing to poor magnetite and/or hematite dissemination. The size of the prepared conglomerate pebbles varied between 5—15 cm.

The collection of samples represents 16 different groups of ore and rocks (referred to below as 'sample group') according to the place from which the samples were taken. Kiirunavaara is divided in a higher (320 m level) and a lower (800 m level) level (Fig. 38).

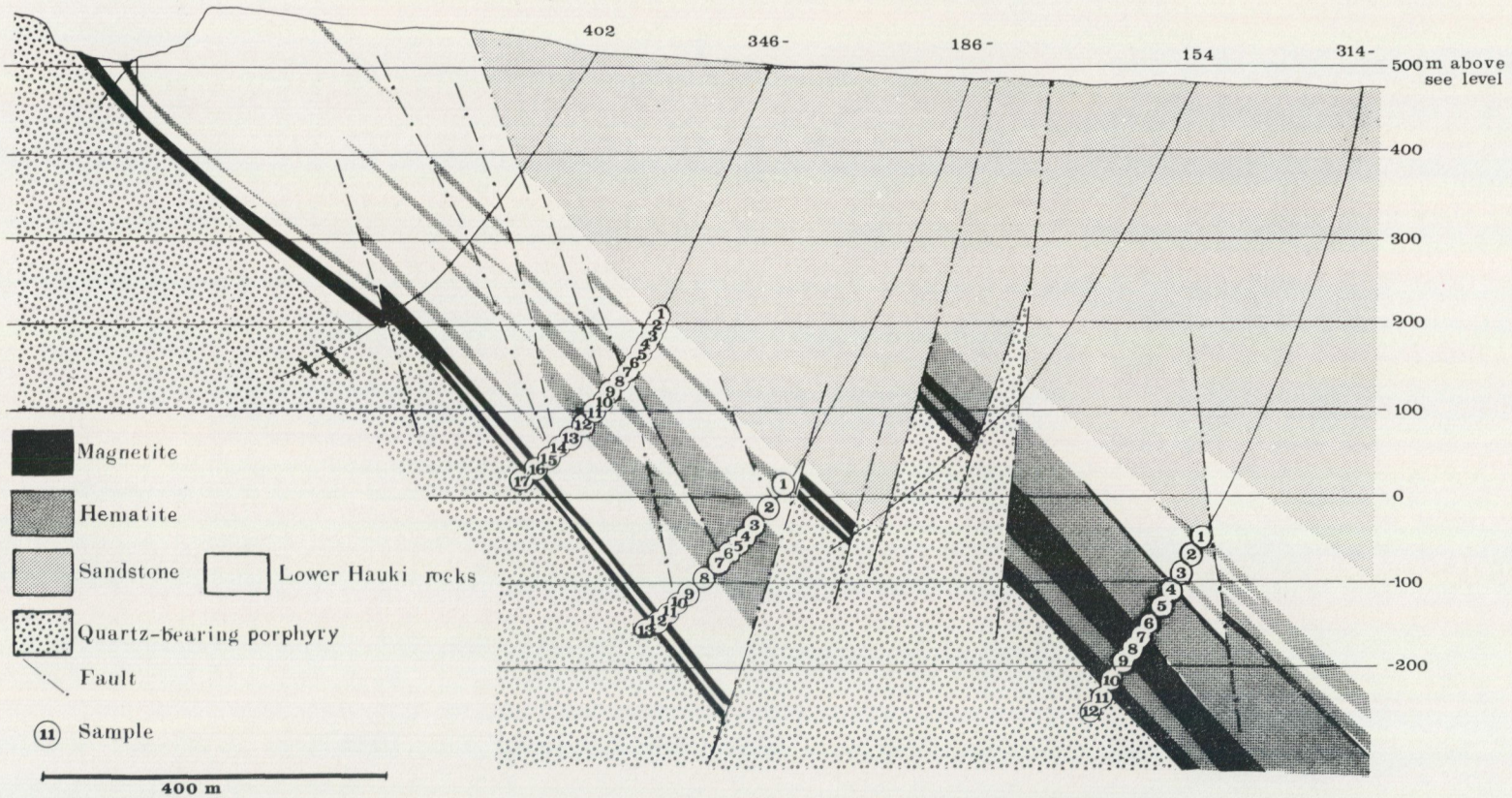

Fig. 37. Location of samples in the cross section through the Rektorn ore and the Lappmalmen ore. (Determinations in Table 40.)

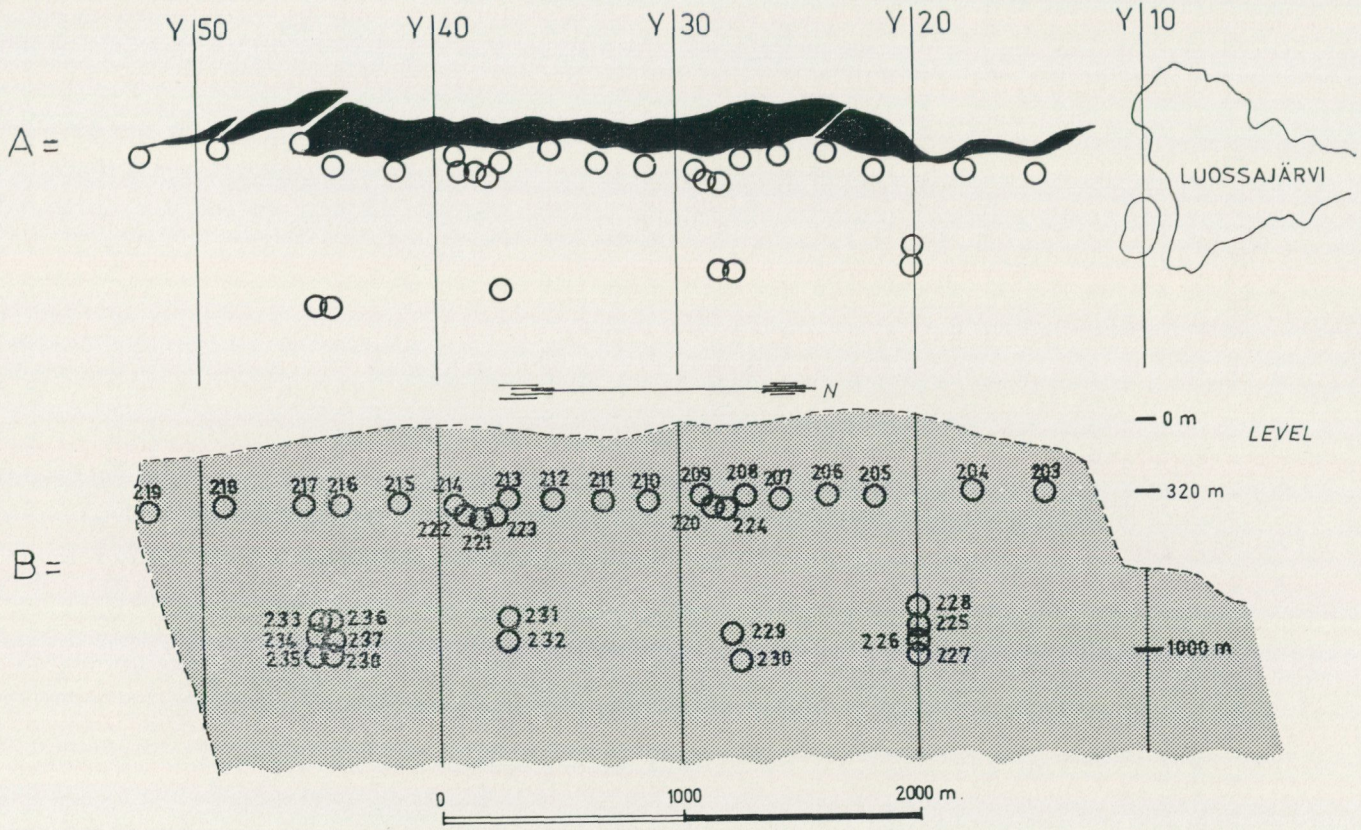

Fig. 38. Sampling of specimens in Kiirunavaara. A = horizontal section, B = longitudinal section.

SAMPLE PREPARATION

As the purity of the samples is very important, it is desirable that a microscopic examination precedes the crushing of the samples in order to decide the most suitable particle size. For this purpose, more than two hundred thin sections and one hundred polished sections from the Kiruna field were examined.

The procedure after the microscopic examinations was as follows: The samples were washed in demineralized water. After drying, the samples were crushed and pulverized in an agate-mill. They were then sieved and separated by a magnet. In order to decide whether or not more grinding was necessary, the enriched samples were examined under a binocular microscope. The material which remained after the above mentioned separation was placed in beakers filled with demineralized water. The magnetic part was separated with the help of a weak electric magnet. The separation was repeated 10—15 times, every time in fresh demineralized water. During this process a control of the degree of purity was done by the binocular microscope. When the desired purity was obtained, the samples were dried for 20 hours at 95°C, after which they were placed in plastic vials. If the controlled degree of purity was not satisfactory (98 %), the process was repeated.

The average grain-size distribution of the magnetic samples obtained was as follows: 16 % = 0.06—0.04 mm, 31 % = 0.04—0.025 mm, 43 % = 0.025—0.013 mm, 5 % = 0.013—0.007 mm. The same equipment was used for each sample preparation. Between each sample the equipment was washed in alcohol. Nylon bolting cloth was used for sieving.

Another test of the degree of purity was done on selected samples chosen at random. They were spectographically analysed for Si. With the exception of one sample — No. 341 — where the calculated SiO_2 content was 1.14 %, the limit of SiO_2 was under 1 % and in most cases under 0.2 %.

In this connection we can refer to Ekström (1967) who states that silicon in the magnetites from Kiirunavaara really is situated in the magnetite structure. Ekström determined the SiO_2 content to 0.09 % using geoscan.

REDUCTION OF HEMATITE

A number of samples consist of hematite. An equality regarding the degree of purity between hematites and magnetites was desired. At first the hematite was separated using heavy (Clerici's) liquids. This method, however, is very lengthy. Therefore, the hematite was reduced to magnetite and separated like the magnetite. Testing of this method — regarding the examined trace elements —

did not show any difference with respect to the gravitation separation by heavy liquids.

The method used for reducing the hematite to magnetite was as follows:

Pieces of hematite were washed in demineralized water, crushed and pulverized. The resulting powder was divided into 2 g portions and placed in porcelaincrucibles. These were heated for 5 minutes at 500°C. Hydrogen gas streams were coupled 2 x 2 minutes through the kiln. After the first two minutes the material was taken out of the kiln and cooled. Following this treatment, the reduced small parts of the samples were put together into complete samples.

ANALYTICAL METHODS AND NUMBER OF ANALYSES

The analytical determinations, apart from zinc, were carried out spectographically. Zinc determinations and control analyses for copper, titanium, vanadium and manganese were carried out by the atomatic absorption method. After producing a standard sample, each determination was carried out three times. The copper, zinc, titanium, zirconium, vanadium, chromium, molybdenum, manganese, cobalt, nickel, aluminium and magnesium determinations are distributed as follows:

Sample group	Sample	Magnetite	Hematite	Co-exist. Ma+He	Determination
1	Vakko sedimentary rocks	10	21	7	372
2	Hauki hematite	—	4	—	48
3	Sericite quartzite	3	9	3	144
4	Syenite-porphyry of Hauki type	11	9	6	240
5	Detritus of porphyry	22	14	11	432
6	Per Geijer ores	44	30	22	888
7	Quartz-bearing porphyry	20	5	3	300
8	Kiirunavaara ore	31	5	—	432
9	Luossavaara ore	22	—	—	264
10	Luossajärvi ore	18	5	5	276
11	Tuolluvaara ores	13	5	3	216
12	Syenite-porphyry	15	—	—	180
13	Magnetite-syenite porphyry	9	—	—	108
14	Kurravaara conglomerate, matrix	8	—	—	96
15	Kurravaara conglomerate, pebbles	10	—	—	120
16	Kiruna greenstone	3	—	—	36
		239	107	60	4152

The lowest values which could be determined are as follows (all in ppm):

Cu = 5, Zn = 5, Ti = 5, Zr = 50, V = 10, Cr = 5
Mo = 25, Mn = 10, Co = 10, Ni = 10, Al = 100, Mg = 25

The laboratories at Malmberget and Kiruna report the following errors in their determinations:

between 1— 5 ppm = 0.3 ppm		between 100— 500 ppm = 60 ppm	
between 5— 10 ppm = 5 ppm		between 500— 1000 ppm = 150 ppm	
between 10— 50 ppm = 10 ppm		between 1000— 5000 ppm = 600 ppm	
between 50—100 ppm = 20 ppm		between 5000—10000 ppm = 1000 ppm	

INSTRUMENT

LKAB Laboratory, Malmberget

To determine copper, titanium, zircon, vanadium, chronium, molybdenum, manganese, cobalt, nickel, aluminium and magnesium, the Hilger automatic quartz spectograph E 742—301 (Hilger & Watts Ltd) was used. Focal length = 1 700 mm, dispersion = 5 Å mm at 3 000 Å. Spectral region and length = 1 910—8 000 Å (75 cm).

Optical system: Reflector — Lins system F 1083. Source unit (Hilger & Watts Ltd.). BNF Source Unit FS 131. DC arc 13 Å. Hilger & Watts Ltd non-recording photometer (L 451) and a 'Galvoscale' FR 300 galvanometer for the non-recording microphotometer were also used.

LKAB Laboratory, Kiruna

Zinc analyses and control measurements on copper, titanium, vanadium and manganese were carried out by means of atomic absorption instruments, type Techtron AA5, Techtron AA-120 with recorder, digital read-out and printer.

STATISTICAL PROCESSING OF THE SPECTROGRAPHIC ANALYSES

The present paper covers the determination of Cu, Zn, Ti, Zr, V, Cr, Mo, Mn, Co, Ni, Al and Mg in 346 samples taken from 16 different rock types or ore sample groups. The total number of determinations is thus 4152 (Table 48).

The arithmetic mean has often been the most usual method of indicating an average. In geological publications in which chemical analysis data has been presented, it quite simply has been called the mean.

Some determinations, however, produce values which show a marked deviation from the others. The average is influenced by such extremely high or extremely low values. The effect of such values is reduced if the *median* is used. The median values have therefore been used in this paper as the average content for the various rock species and ore groups.

The very high-grade samples from the Rektorn—Lappmalmen section have not been treated statistically and are used only for purposes of comparison.

GEOCHEMISTRY OF TRACE ELEMENTS IN MAGNETITE AND HEMATITE FROM THE KIRUNA FIELD

INTRODUCTION

In this section the results of investigations into the content of the twelve above mentioned elements in magnetites and hematites from the Kiruna field are presented. Each element will be dealt with in a separate section.

With regard to the trace element content of the magnetites and hematites from the Kiruna field, reference may be made to three publications, namely Landergren (1948), Hegemann and Albrecht (1954) and Frietsch (1970).

Landergren analysed seven magnetites from the Kiruna field.

Hegemann and Albrecht used the trace element distribution in magnetites and hematites for comparison of the Kiruna iron ores with a number of other ores. Unfortunately, the basic material was largely published diagrammatically, so that comparisons with the new analysis material are only possible to a limited extent.

Of the analyses presented by Frietsch, 15 are of magnetite, 3 magnetite ore, 6 hematite, 2 hematite ore of the apatite iron type and 2 hematite and 1 Hauki hematite samples from the Kiruna field. Frietsch's material also included a hematite analysis of conglomerate (hematite pellet) from Doktors kulle.

Frietsch (1970, Table 34) presented a comparison between trace elements in magnetites from apatite ores and from ores of the Hauki type in the Kiruna district on one side and hematites from southeastern Missouri (from Kisvarsányi & Proctor, 1967) on the other. The medians of the analyses from the present investigation and Frietsch's table are shown below. The trace element distribution presented in the table is used by Frietsch as evidence of ore genesis through magnetic differentiation. The new and different results can scarcely support the same hypothesis of ore genesis. The discrepancies between the values and the consequences for genetical considerations will be discussed in a later chapter.

District	Magnetite, apatite iron ore, ppm of										
	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Mo	Mg	Al
1. SE Missouri	3560	1060	20	1700	41	49	4	119	3	930	710
1. N Sweden	1500	1300	10	70	120	220	40	100	7	1900	1590
2. Kiruna field	600	1100	0	365	85	250	14	40	0	500	200

District	Hematite, iron ore of the Hauki type, ppm of										
	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Mo	Mg	Al
1. SE Missouri	480	3	1	22	11	6	1	150	30	42	4570
1. N Sweden	700	80	<20	<200	<20	<20	60	<50	<30	<3000	>3700
2. Kiruna field	1950	110	50	10	0	20	60	50	0	0	600

1. = According to Frietsch
2. = According to Parák

Cu, Zn, Ti, Zr, V, Cr, Mo, Mn, Co, Ni, Al AND Mg IN MAGNETITE AND HEMATITE

COPPER

According to Rankama and Sahama (1950) "It is probable that small amounts of copper may replace ferrous iron in mineral structures in the absence of an appropriate supply of sulfur owing either to oxidation or to previous crystallization". Cornwall and Rose (1957) reported that the Cu is usual in the magnetites from the Keweenawan lavas (Michigan). They report up to 880 ppm Cu in the magnetite. The same authors state that "Cu^{2+} should replace Fe^{2+} because of their similar ionic size, and the fact that copper is most abundant in the minerals that contain Fe^{2+} suggests that Fe^{2+} has been replaced". According to Ringwood (1955), Cu^{2+} "does not enter crystals as readily as Na^{1+} and Fe^{2+} and is therefore concentrated in residual magmas until a concentration is reached which is sufficient to precipitate $CuFeS_2$".

The average Cu content of igneous rocks is the following (Sandell and Goldish, 1943): Basic igneous rocks 149 g/ton, intermediary igneous rocks 38 g/ton and acidic igneous rock 16 g/ton.

As regards the Cu contents in the different iron ores, Hegemann and Albrecht (1954) show that high Cu contents are common in volcanic-sedimentary, in the contact-metamorph and the intra magmatic types. According to the same authors, the Cu content in hydrothermal ore is $\sim$ 350 ppm. The lowest Cu content is found in sedimentary iron ore types.

According to Kisvarsányi and Proctor (1967), the Cu content in magnetites and hematites from Pea Ridge, Iron Mountain and Bourbon varies from 1 to 8 ppm, while hematite from Cedar Hill contains 1 ppm Cu.

As can be seen from table (Annersten and Ekström, 1971), the Cu content in the magnetites varies from 8 to 53 ppm and in the hematites from 5 to 11 ppm (samples from Grängesberg).

Copper analyses for magnetites and hematites of the Kiruna field included in the present investigation are given in Table 24.

The most striking feature at Kiirunavaara is the difference in the copper content between various levels. The 14 samples which represent Kiirunavaara

ore from the 800 m level show relatively little scatter of the values. All lie between 8—20 ppm. Magnetite samples (17) from the upper level (320 m), with the exception of three values (250, 70 and 190 ppm, all in ore with a low phosphorus content) show a copper content between 20 and 50 ppm. Discounting the extreme values, there is no change in the tendency of the copper distribution to decrease with increasing depth. Kiirunavaara hematites (320 m level) show a markedly higher copper content than the magnetites. Luossavaara magnetites have a lower copper content compared with the Kiirunavaara magnetites. The values are often below the limit of sensitivity of the instrument (5 ppm).

Copper could be detected only in 3 out of 9 magnetite samples from magnetite-syenite-porphyry in the northern part of the area (6, 10 and 20 ppm). The copper content of magnetites from quartz-bearing porphyry is distributed in such a way that the samples taken from the zone in contact with Per Geijer ores show a substantially higher copper content than the samples taken near the contact with Kiirunavaara and Luossavaara ores. Copper values vary widely in magnetites from Per Geijer ores. The highest values were obtained from Haukivaara and Nukutusvaara. Henry magnetites contain from 5 to 58 ppm Cu. The lowest copper values (between 0—15 ppm) in Per Geijer ores were found in the magnetites from Lappmalmen.

Magnetite samples from the Vakko rocks are remarkably high in copper. Out of 7 analysed samples 4 contained between 260 and 540 ppm Cu.

The hematites of the Kiruna field were found to have a higher copper content than the magnetites. Samples from the Vakko rocks constitute an exception.

ZINC

According to Rankama and Sahama (1950), "The manner of occurrence of zinc is determined by its property of diadochically replacing ferrous iron and magnesium in mineral structures. The radii of these ions are: r $Zn^{2+} = 0.83$ kX; r $F^{2+} = 0.83$ kX; r $Mg^{2+} = 0.78$ kX. This similarity causes the presence of zinc in magnetite and ilmenite and explains the fact that early magmatic oxide ores are actually weakly zinciferous".

According to Wedepohl (1953), Zn enters into the pyroxene and magnetite of basic rocks and into biotite and amphibole in acid rocks. Zlobin and Gorshkova (1961) did not find any correlation between the concentrations of Zn, Mg and Fe in the alkaline Sandyk massif. According to Vincent and Phillips (1954), magnetites in gabbro from the Skaergaard-intrusion, W. Greenland, contain between 1 000 and 2 000 ppm Zn.

Kisvarsányi and Proctor (1967) found an average Zn content of 119 ppm in magnetite ore from Pea Ridge and Bourbon and in magnetite-hematite ore from Iron Mountain. The same authors report 100 ppm Zn in magnetite-hematite ore from Pilot Knob and 200 ppm Zn in hematite ore from Cedar Hill.

According to Annersten and Ekström (1971), the Zn-content varied from 23 to 297 ppm in magnetites and from 16 to 36 ppm in hematites from Grängesberg.

From the Kiruna field, Frietsch (1970) reported the following Zn contents (in ppm):

Apatite iron ore; magnetite from 50 (Rektorn, Nukutusvaara) to 350 (Tuolluvaara)

Apatite iron ore; hematite from <50 (Haukivaara, Rektorn) to 300 (Henry)

Iron ore of Hauki type; hematite <50 (Haukivaara)

Conglomerate (unknown origin); hematite 150 (Doktors Kulle)

Zinc analyses for Kiruna field magnetites and hematites are presented in Table 25.

Kiirunavaara magnetites show median Zn content which is much lower than the value reported previously. The analyses also show that the Zn content tends to decrease with depth in the Kiirunavaara ore body, despite three markedly differeing analysis values (100, 80 and 100 ppm) in the test material from the deeper level. According to the analyses, the average Zn content of the Luossavaara magnetites is slightly higher than in the Kiirunavaara magnetites. Magnetites in Kiirunavaara—Luossavaara wall-rock do not differ in Zn content from the magnetites in the ore bodies. Most of the Zn values for magnetites from the Per Geijer ore bodies lie between 20 and 50 ppm. Out of 44 samples, only two samples from Nukutusvaara (60 and 80 ppm), one from Lappmalmen (60 ppm) and one sample from Henry (60 ppm) show relatively high Zn contents.

Magnetites in the magnetite-rich pebbles from the Kurravaara conglomerate are remarkably high in Zn. Zinc was found in all the samples, the values ranging from 60 to 140 ppm.

The present analyses indicate that the hematites at Kiirunavaara and Luossajärvi contain less Zn than the magnetites in the same deposit. However, the opposite condition was found to exist in the other sample groups.

TITANIUM

Titanium is the most abundant trace element. It replaces iron in magnetite and hematite structures. Several publications deal with these problems. Examples include Ramdohr (1926), Sahama (1946), Vincent (1960), Deer et al. (1962), Buddington and Lindsley (1964) and Dasgupta (1967).

According to Rankama and Sahama (1950), the average content of Ti in the igneous rocks is 4400 ppm, in quartzites 960 ppm and the shales average (Minami) is 4300 ppm.

The highest Ti values are found in titaniferous iron ores. Landergren (1948) showed that the Ti content in this type of iron ore varied from 3.18 to 23.5 %.

According to the same author, the Ti content reaches 7.0 % in the magnetite and 2.0 % in the hematite in lateritic iron ores (Antrim, N. Ireland).

Landergren (1948, Table 56) reported 0.02 % Ti from iron ores in lime- and dolomite rocks and 0.02 % Ti in the skarn ore from central Sweden. The same table shows that the apatite ore from central Sweden contains 0.17 % Ti.

Between 4 800 and 3 300 ppm Ti were recorded by James and Dennen (1962) for magnetites of hydrothermal origin. According to Kisvarsányi and Proctor (1967), the Ti content in the iron ores of Missouri varies as follows:

Type	Ti content in ppm
Magnetite-hematite-apatite	1 050—6 340
Fe—Cu (Boss-Bixby)	1 000
Hematite	232—733

The analyses reported by Annersten and Ekström (1971) show that the Ti content in the magnetites from Grängesberg varied from 23 to 1 980 ppm and in the hematites from 71 to 4 740 ppm.

According to Frietsch (1970), the Ti content in the magnetites and hematites from the Kiruna field varies as follows (in ppm):
Apatite iron ore; magnetite = Kiirunavaara from 1 800 to 3 000, Rektorn 300, Tuolluvaara, Nukutusvaara 600
Apatite iron ore; hematite = from 600 (Haukivaara) to 4 800 (Rektorn)
Iron ore of Hauki type; hematite = <600 (Haukivaara)
Conglomerate (unknown origin); hematite = 6 000 ppm (Doktor Kulle)

Titanium analyses included in the present investigations are given in Table 26.

Table 26 shows that the Ti content varies considerably between magnetites and hematites in the various rock/ore groups.

The most striking point is that the Ti content of the Kiirunavaara—Luossavaara magnetites is considerably lower than was found in previous investigations (Frietsch, 1970). The explanation for this could be in the different degrees of purity of the test material. To elucidate this statement, the Ti content of pure separated magnetites (300—800 ppm) should be compared with those from unseparated magnetite ores from Kiirunavaara and Luossavaara. The average value in the later case is 3300 ppm Ti for apatite-poor magnetite ore and 1400 Ti for apatite-rich magnetite ore from Kiirunavaara and Luossavaara (yearly average of ores produced).

Kiirunavaara (320 m level) and Luossavaara magnetites have a substantially higher Ti content than the deep-lying (800 m level) magnetite ores. A calculation of the deep-lying part of the Per Geijer bodies (Lappmalmen) gives a median Ti content for magnetites of 700 ppm. There are large differences between the magnetite ores in the main or bodies and the wall-rock magnetites.

Magnetites from detritus of porphyry are an exception. A striking difference — as regards the Ti content — can also be noted between the magnetite of Vakko and Lower Hauki rock types on one hand and the other rock types (sample groups 13, 14, 15 and 16) on the other.

In most cases the Ti content of the hematites is greater than that of the magnetites. The Ti median for Lappmalmen hematites is 3 050 ppm. The high Ti content of the Tuolluvaara hematites in comparison with the Kiirunavaara and Luossajärvi hematites is also worth noting.

ZIRCONIUM

According to Taylor (1965), "Zr^{4+} may be expected to substitute to some extent for Ti^{4+}, and hence accompany that element in substituting for Fe^{3+}". Zr entering in magnetite or hematite structure is not known to the author.

The difference in the Zr contents of some classes of igneous rocks are illustrated by the table below (Hevesy and Würstlin, 1934a).

Peridotites, eclogites, dunites: 60 g/t
Gabbros: 140 g/t; diorites: 280 g/t
Granites: 460 g/t

There are few data on the Zr content of the iron ores. Frietsch (1970) states that Zr has only been determined for a small number of iron oxide samples. From the Kiruna field, Frietsch reports <300 ppm Zr in the apatite ores from Kiirunavaara and Rektorn. According to Geijer (1910), "The zircon occurs in almost all ore types, even in the "stratified" one, but it is nearly always enclosed in apatite".

Analyses of magnetites and hematites from the Kiruna field show Zr to be present in 39 out of 346 samples. The limit of detection of the instrument was 50 ppm. No Zr could be detected in samples from the Kiirunavaara, Luossajärvi and Tuolluvaara ores. Zirconium was found in only one sample out of 74 from the Per Geijer ores. Magnetite and hematite samples from the Hauki type syenite-porphyry produced no Zr values above the dectection limit of the instrument. Zirconium was detected in almost all the magnetite samples from magnetite-syenite-porphyry.

Out of 25 samples from the quartz-bearing porphyry, five contained Zr. The highest Zr value found was 1 100 ppm Zr. This value is approximately ten times greater than the Zr content of the other samples. It is assumed that this sample was contaninated by the mineral zircon, which can contain as much as 67 % Zr.

Of all the samples taken from the Lower Hauki rocks and the Vakko rocks, only a very small proportion showed a Zr content above the detection limit of the instrument. In this case, hematite samples were most abundant.

A summary of the analysis results is given in Table 27.

VANADIUM

Vanadium occurs mainly as V^{3+}. This element has almost the same ionic radii (0.74 Å) as Fe^{2+}. According to Wager and Mitchell (1951), V^{3+} preferably enters pyroxenes and the ore minerals, preferring magnetite ($FeO \cdot Fe_2O_3$) to ilmenite ($FeO \cdot TiO_2$). Vanadium was not detected in the Skaergaard olivines.

The V content and Cr/V ratio are thus useful indices for the fractionation of basic igneous rocks.

With the exception of Pilot Knob (3 ppm) and Cedar Hill (3 ppm), the V content in the iron ores of Missouri varies from 625 to 1 385 ppm (Kisvarsányi and Proctor, 1967).

According to Landergren (1948), "Among the sediments only the oolitic ores and the laterites show contents above the average value of the upper lithosphere! The highest content is found in the titaniferous ores and the apatite ores". The same author shows that the average V content in apatite iron ores from N Sweden is 1 300 ppm.

According to Annersten and Ekström (1971), the V content in magnetites from Grängesberg varies from 404 to 2 890 ppm and in the hematites from 394 to 2 160 ppm.

The V content in the hydrothermal type of ore from Mount Hope Mine varies from 160 to 500 ppm (James and Dennen, 1962).

As shown from the Kiruna field by Frietsch (1970), the V content in the magnetites from Kiirunavaara varies from 1 300 to 2 300 ppm, and in the magnetites from Luossavaara between 1 300 and 1 800 ppm. The same author (1970) reported further; "The V contents in hematites of apatite iron ore type varied from 1 000 (Haukivaara) to 1 700 (Rektorn) ppm. In the hematites of Hauki type the V content varied from <50 to 100 ppm".

A summary of the V content of magnetites and hematites from the Kiruna field as found in the present investigation is presented in Table 28.

Of the elements investigated, the V analyses show the least scatter. Of the ore deposits investigated within the Kiruna field, the Kiirunavaara and Luossavaara ore bodies show the highest V content. A decrease in the V content with increasing depth in the Kiirunavaara magnetites can be read from the table. It is interesting to see that a lower V content can be noted in the Luossajärvi magnetites and an even lower content in the Tuolluvaara magnetites. A decrease in the V content with increasing depth was also found in magnetites from the Per Geijer ore bodies, which have a lower V content than the Kiirunavaara magnetites. In the Lappmalmen magnetites, a V content median of 730 ppm was found.

Of the magnetites from the Kiruna field rock types, the samples from the Vakko rocks show the lowest V contents (sample group 1). There is a remarkably large difference in V content between the magnetites from quartz-bearing porphyry and syenite-porphyry.

In a number of cases, the average V content of the hematites exceeds that of the magnetites. It should be noted that the V content of hematites also shows a tendency to decrease with increasing depth. This also applies to hematites from the Per Geijer ore bodies. The Lappmalmen hematites have a median value of 970 ppm V. Hauki hematites are extremely low in V.

CHROMIUM

The average Cr content in various igneous rocks is as follows (Rankama and Sahama, 1950):

Peridotite (dunite)	3 400 g/t
Gabbro	340 g/t
Diorite	68 g/t
Granite	2 g/t
Nepheline syenite	0.7 g/t

These values show that Cr is enriched in the early crystallates. Taylor (1965) states that the Cr concentration is a useful indicator of basic and ultrabasic igneous rock parentage. Faust et al. (1956) used Cr as one of the index elements to distinguish serpentines derived from ultrabasic rocks rom those derived from the metamorphism of limestones and dolomites.

Ultrabasic and basic igneous rocks show the highest Cr contents. This fact implies that titaniferous ores which are associated with these rocks should be enrichment of Cr, compared to other iron ores. Iron ores of igneous origin are usually rich in chromium.

According to Landergren (1943, 1948), titaniferous iron ores show Cr content up to 5 500 g/t. In the iron ores of gabbros, the Cr content is 3 500 g/t. The same author mentions that the Cr content of apatite iron ores is less than 0.001 %.

As can be seen from a table by Fröhlich (1960, p. 234), the Cr content of the sedimentary (mesozoic) iron ores varies from 28 to 775 ppm Cr.

According to Kisvarsányi and Proctor (1967), the Cr content in the iron ores of Missouri reaches 4 ppm (with the exception of the Fe—Cu type of ore from Boss Bixby, which has a Cr content of 26 ppm). The reported Cr contents from Missouri do not show any differences between the magnetites and hematites.

Annersten and Ekström (1971) report that the Cr content in the magnetites from Grängesberg varies from 17 to 200 ppm and in the hematites between 14 and 107 ppm.

According to Frietsch (1970), the Cr content in the Kiirunavaara magnetites is less than 20 ppm and in the iron ores of Hauki type 20 ppm. The same author reported 20 ppm Cr in hematite from conglomerate (Doktors Kulle).

The new analysis results show the following picture for the distribution of

chromium (Table 29) in the Kiruna field: In only four cases (out of 31 samples) was the Cr content in magnetite from Kiirunavaara greater than 5 ppm, which is the dectection limit of the analytical method used. The Cr contents in these four samples were between 8—12 ppm Cr. All four samples were taken from the 320 m level. The Luossavaara magnetites (22 samples), on the other hand, contained Cr in 12 cases. Chromium occurs mostly in the ore veins W of the main ore body. There is no difference in the Cr content of magnetites from surface ores and deep-lying ores in Luossavaara. The 12 Cr analyses vary between 5—50 ppm.

Per Geijer ores show a higher Cr content than the Kiirunavaara ore. In 36 out of 74 samples, Cr analyses were found to vary between 5 and 40 ppm. In two samples (Nos. 168 and 169), values were found which differ considerably (600 and 210 ppm) from the Cr content of the other samples. In general terms it can be said that, while Cr is found in Haukivaara and Nukutusvaara, it is practically absent in the 4 km long ore bed which connects the Per Geijer ore bodies.

Remarkably high Cr contents were found in samples from the Kurravaara conglomerate. The magnetite test material was collected mainly from prepared pebbles (sample group 15 in Table 29) and intermediate material (sample group 14 in Table 29). Greenstone magnetite shows a very high content (1 400 ppm) Cr. This indicates a different mode of formation compared with the other magnetites.

The median for the Cr content in magnetite from syenite-porphyry is considerably lower than the arithmetic mean for the same analyses. The explanation lies in the fact that two samples (Nos. 313 and 314) have very different values (840 and 1 800 ppm respectively). These two samples come from syenite-porphyry that is tectonically disturbed and in which conglomerate-like inclusions occur. Even among the samples from magnetite-syenite-porphyry (sample group 13), there is one sample (No. 325) with a Cr content of 1 700 ppm, which therefore differs considerably from the other samples. Magnetites from the Vakko rocks often have relatively high Cr contents. This means that the median lies between the syenite-porphyry level and the magnetite-synite-porphyry level.

In the Kiruna field the Cr content of the hematites is usually slightly lower than that of the magnetites. Sericite quartzite (sample group 3) consitutes an exception.

MOLYBDENUM

Taylor (1965) states that the free Mo^{4+} ions will substitute for Ti^{4+}, Zr^{4+} and Fe^{3+} and may occur in magnetite and ilmenite.

According to Rankama and Sahama (1950), Mo is concentrated in the last differentiates during magmatic crystallization.

Thirteen ppm Mo was found in magnetite-ilmenite concentrates from Min-

nesota (Sandell and Goldish, 1943). Zies (1938) mentions that the Mo content in fumarolic magnetite from the Valley of Ten Thousand Smokes is 0.04 %. According to Kisvarsányi and Proctor (1967), the Mo contents in the magnetites and hematites from Missouri vary from 1 to 6 ppm, with the exception of hematites of Pilot Knob where the hematite contains an average of 59 ppm Mo. The same authors recorded a higher Mo content in the central part of the Boss Bixby ore deposit.

The Mo content in the magnetites from Grängesberg varies between 2 and 9 ppm.

In one case, Frietsch (1970) found 20 ppm Mo and in another 10 ppm Mo in the magnetites of Kiirunavaara. The same author reported 10 ppm Mo from the magnetites in the Rektorn deposit. The Mo content in the hematites from Haukivaara is 20 ppm Mo and 10 ppm from Henry (Frietsch, 1970).

The analysis reported here (with 25 ppm as the limit of sensitivity for the instrument used) reveals Mo in only six samples. One magnetite sample from Haukivaara (No. 1) showed 60 ppm Mo. The other five Mo values were fund in hematites. In one sample from a borehole (No. 95) between the Rektorn and Henry deposits, the hematite showed 30 ppm Mo. The other four Mo values found were to the north of Syväjärvi (Nos. 35, 46, 47 and 31). At this point they amounted to 70, 40, 100 and 40 ppm Mo respectively. In each case, the samples containing Mo were surrounded by schistose or altered rocks.

MANGANESE

According to Rankama and Sahama (1950, p. 645), ". . . the bipositive manganese iron is able to replace diadochically the following ions: Fe^{2+}, Mg^{2+}, Zn^{2+} and Ca^{2+}. The replacement of Fe^{2+} by Mn^{2+} is the most common and geochemically the most important among the various possibilities". The authors mention furthermore "In its behaviour during the magmatic crystallization, manganese differs markedly from chromium, for instance, which is very pronouncedly concentrated in the early crystallates" and (p. 649) "A comparison of the chemical behaviour of iron and manganese at different states of oxidation reveals that bivalent manganese, like bivalent iron, does posses relatively strong basic properties and consequently remains in aqueous solution even in the presence of weak and dilute acids, whereas tri- and quodrivalent manganese in analogy with trivalent iron, are so weakly basic that their compounds are largely or totally hydrolyzed in waters on the Earth's surface."

Generally speaking, basic rocks contain more manganese than acid rocks.

Rankama and Sahama (1950) report an average of 0.15 % MnO in gabbros, 0.09 % MnO in diorites and 0.05 % MnO in granites. According to Hevesy et al. (1934), the average Mn contents of the shales and phyllites are 890 g/t and in the red clay 1 770 g/t, respectively.

As regards the Mn content of iron ores, Landergren (1948) mentions 7.45 % Mn for bog ore, 0.16 % Mn for oolitic-siliceous ore and 0.26 % Mn for sideritic ore. In the same table (56), Landergren reports an average of 0.65 % Mn in titaniferous ore of N Sweden and 0.07 % Mn in apatite ore of N Sweden. According to the author, the quartz-banded ore of central Sweden contains 0.12 % Mn.

The iron ores from Missouri have the following Mn values: magnetite and hematite ores of Iron Mountain = 3 743 ppm. Fe—Cu type of ore from Boss Bixby = 2 920 ppm and the ores from Pie Ridge and Bourbon = 732 respectively 634 ppm (Kisvarsányi and Proctor, 1967).

According to Annersten and Ekström (1971), the Mn content in the magnetites varied from 112 to more than 3 000 ppm and in the hematites from Grängesberg between 4 and 165 ppm Mn.

Frietsch (1970) mentions that the Mn content in the magnetites varied from less than 200 to 1 800 ppm and in the hematites from less than 200 to 1 000 ppm from Lahn-Dill. The same author presents the following Mn values in apatite iron ores from the Kiruna field (in ppm):

Ore	Magnetite	Magnetite ore	Hematite	Hematite ore
Kiirunavaara	200—1200	200		
Luossavaara	200— 400			
Haukivaara			<200	78
Henry			<200	<200
Nukutusvaara	<200	400		
Rektorn	<200	650	1 000—<200	
Tuolluvaara	<200—200			

A hematite ore of Hauki type from Haukivaara has given 200 ppm Mn in hematite and 80 ppm Mn in hematite ore. According to the new analyses, the Mn content of the Kiruna field magnetites and hematites is distributed as indicated in Table 30.

Kiirunavaara ores show markedly higher Mn contents than the other ores. Especially low Mn contents were found in the magnetites from Luossavaara, Luossajärvi and Tuolluvaara. This applies to both the magnetites and the hematites. The Mn content in wall-rock magnetites and hematites shows a significant difference in comparison with the values of the magnetites and hematites in the ores collected.

The Mn content of magnetites and hematites from the Per Geijer ore bodies differs markedly from that of Kiirunavaara magnetites and hematites.

Of the magnetites from the Per Geijer ore bodies, Henrymalmen shows a higher and Lappmalmen a lower Mn content than the other ore bodies.

Of the other sample groups, the Kurravaara conglomerate pebbles (sample

group 15) have an exceptionally high Mn content. The median in this instance is even higher than in the magnetites of the collected ores.

The hematites show a markedly lower Mn content than the magnetites. Hematites from Kiirunavaara (320 m level) constitute an exception.

Analysis of one year's output of ores from the Kiruna field gives the following manganese values: phosphorus-poor magnetite ore 0.062 % and phosphorus-rich magnetite ore 0.069 %, from Kiirunavaara. The extremely phosphorus-rich hematite ores contain 0.54 % Mn (Per Geijer ore hematites from Henry and Haukivaara).

COBALT

Co^{2+} and also Ni^{2+} are intermediate in size between Mg^{2+} and Fe^{2+}. According to Sen et al. (1959), Co^{2+} substitutes the Fe^{2+} in the magnetites of norite. Cornwall and Rose JR (1957) mention that "Co^{2+} probably replaces Fe^{2+}, with which it is nearly identical in ionic size and electronegativity" in the lavas of greenstones from Michigan. In the titanomagnetites from the teschenite sill near Gunnedah, New South Wales, both Ni and Co are camouflaged by Fe^{2+} (Wilkinson, 1957).

Carr and Turekian (1961) report the following Co contents for some rocks (in ppm): Basaltic rocks = 48, granodiorites = 7, granites = 1, schists = 40, shales = 19, pure limestone = 0.1 and quartzite = 0.3. The Co content varies between 12—27 ppm in the magnetites of hydrothermal origin from Mount Hope and from N Jersey Highland (James and Dennen, 1962). According to Carr and Turekian (1961), the Co content in the limonite (Salisbury, Conn.) is 68 ppm and in the bog iron ore (Lake Saltonstall, E Haven, Conn.) only 4 ppm. The same authors reported the highest Co content in the magnetite from Furneau, Quebec (Table 15). The content in the hematites from Fayal Mines, Eveleth (Mesabi dist.) is 42 ppm. The hematites from Marquette (Mich.) contain only 5 ppm.

Landergren (1948) reports the following Co contents: titaniferous ores = 0.02 %; oolitic-siliceous ore = 0.02 %; sideritic ore = 0.03 %. Landergren mentions further that the Co content in the bog ore is 0.013 %; in the apatite ores of central Sweden 0.0026 % and in the apatite ore of north Sweden 0.0093 %.

Contact-pneumatholitic iron ores contain 0.15 % (Hegemann and Albrecht, 1954).

According to Annersten and Ekström (1971), Co in magnetites varies from 16 to 53 ppm and in hematites from Grängesberg from 7 to 11 ppm.

The Co content of the iron ores of the Kiruna field, according to Frietsch (1970), is as follows:

Apatite iron ores	
Magnetites (ppm Co)	Hematites (ppm Co)
Kiirunavaara: 130, 130, 130, 130, 60, 120	Haukivaara: <20 (and <10 in the ore)
Luossavaara: 100, 100, 110, 60	Henry: <20, 80, 40 (and 80 in the ore)
Nukutusvaara: 120 (and 60 in the ore)	Rektorn: 120, <20
Rektorn: 20 (and 50 in the ore)	
Tuolluvaara: 100, 190, 100	
Iron ores of Hauki type	Haukivaara: <20, <20 (and <10 in the ore)
	Conglomerate: 30 (Doktors Kulle)

Table 31 shows that the distribution of cobalt in the magnetite from the various Kiirunavaara levels (320 m and 800 m) does not vary, being 120 ppm. However, there is a difference in the Co content in the direction of strike of the ore. The Co content in the southern section of the Kiirunavaara ore body is in fact considerably higher than that of the northern part of the ore body. Exceptions to this are the two southernmost sampling points where the Co content is remarkably lower, namely 20 and 60 ppm. In comparison with the Kiirunavaara magnetites, the Luossavaara and Luossajärvi magnetites have a lower Co content. The Co content of the Tuolluvaara magnetites is even lower.

The median Co content for magnetites from the Per Geijer ore bodies is roughly the same as that of the Luossajärvi magnetites. The lower value of the median for Lappmalmen (70 ppm) indicates a certain decrease in Co content with increasing depth in the magnetites of the Per Geijer ore bodies.

Wall-rock magnetites usually have a lower Co content than the magnetites of the ores.

The magnetites taken from Kurravaara conglomerate pebbles have substantially higher Co contents than the magnetites of the other rock types.

Hematites from the Kiruna field always have a lower Co content than the magnetites.

NICKEL

In reference to Co and Ni, Taylor (1965) states "The geochemical behaviour of these two similar elements is diverse, and clearly displays the importance of rather small differences in properties. They are intermediate in size between Mg^{2+} and Fe^{2+} and, on the basis of size (Table 17), and melting point data for the oxides (Table 18), the sequence of entry into crystal lattices should be Mg^{2+}, Ni^{2+}, Co^{2+}, Fe^{2+}. Predictions based on electronegativity or ionization potential produce a less clear picture". The average content of Ni in the igneous rocks, according to Goldschmidt (1937a), is: dunite = 3 160 g/t, gabbro = 158 g/t, diorite = 40 g/t, granite and nepheline syenite = 2.4 g/t.

Relatively high Ni contents are reported by Faust et al. (1956) in serpentines of ultrabasic-volcanic origin (class A). The content of Ni in these rocks is in

all cases over 400 ppm. Serpentines of limestone-dolomite origin (class B) have a Ni content only reaching 20 ppm (op. cit.).

In the following, Ni contents from iron ores of different origins will be presented. Hydrothermal iron ores from Mount Hope Mine and the New Jersey Highland contain from 26 to 46 ppm Ni (James and Dennen 1962). According to Kisvarsányi and Proctor (1967), the Ni content in the iron ores varies from 37 to 57 ppm. Annersten and Ekström (1971) reported 26—142 ppm Ni in the magnetites and 12—19 ppm Ni in hematites from Grängesberg.

According to Landergren (1948), Ni has been enriched in the apatite ores of N Sweden (0.020 %) in the titaniferous iron ores (0.03 %) and — among the sediments — in the oolitic (0.02 %) and lateritic (0.018 %) ores. The Ni content in the other ores shows a deficiency compared to the upper lithosphere.

Frietsch (1970) reports almost the same Ni contents in the iron ores of the Kiruna field, namely 220 ppm as in the magnetites from the apatite iron ores, N Sweden. The mean of Ni content in the hematite of apatite iron ores from N Sweden is 70 ppm (Frietsch, 1970).

The distribution of Ni in various ore types from the Kiruna field, according to the new analyses, is given in Table 32.

In comparison with previous analysis results (Frietsch, 1970), these values show a higher Ni content in Kiirunavaara magnetites. A slight decrease in Ni content with increasing depth can be observed from the new results. The analyses also indicate Ni enrichment in the central section of the deposit (320 m level). The degree of scatter for these anlyses is low whilst the Ni content ($\sim$ 135 ppm) in Luossavaara magnetites is much lower than in Kiirunavaara magnetites. It is also lower than earlier indications for these ores. The Ni content in the magnetites of Kurravaara conglomerate pebbles varies between 70—250 ppm. The magnetites in the wall-rock of the Kiiruna-Luossavaara ore bodies show a markedly lower Ni content than the main ore body.

Most evident is the high Ni content of magnetites from the Per Geijer ore bodies. Examination of the analysis values for the material reveals Ni enrichment in the magnetites from the Haukivaara ore body (arithmetic mean = 860 ppm Ni with two determinations of 1 400 and 1 600 ppm Ni, respectively) and the Rektorn ore body (arithmetic mean = 550 ppm Ni). The highest Ni enrichment was found in magnetites from the Henry ore body (arithmetic mean $\sim$ 1 000 ppm Ni with two determinations, of 13 and 2 300 ppm Ni, and an additional four determinations of more than 1 000 ppm Ni). Nukutusvaara magnetites show slightly more than 220 ppm Ni, whilst the corresponding value for Lappmalmen magnetites is 190 ppm, (the lowest content among the Per Geijer ores). The Lower Hauki rock magnetites show a very much higher Ni content than the other magnetites.

The Ni content of the hematites is always very low. Most analyses indicate a Ni content between 20—40 ppm. The highest Ni values were found in the

hematites from Kiirunavaara. A few high values were nevertheless obtained from sample group 4 (No. 61 = 200 ppm, No. 53 = 180 ppm), sample group 5 (No. 70 = 310 ppm), sample group 6 (No. 105 = 100 ppm, No. 136 = 130 ppm, No. 138 = 150 ppm, No. 155 = 110 ppm and No. 157 = 100 ppm) and sample group 7 (No. 194 = 160 ppm).

ALUMINIUM

According to Rankama and Sahama (1950) Al^{3+} can replace Si^{4+} and also Mg^{2+} and Fe^{2+} in the silicate phase. Information on the possibility of aluminium replacing iron in the magnetite or hematite lattice is however not known.

Kisvarsányi and Proctor (1967) report 708 ppm Al in magnetite and hematite from the Pea Ridge, Iron Mountain and the Bourbon iron ore deposits of Missouri. According to the same authors, the Al content in the hematites from Cedar Hill is 646 ppm and from Pilot Knob 8 500 ppm.

The aluminium content of iron ores generally is reported as Al_2O_3. Such analyses usually apply to iron ores and not to iron minerals. The present author therefore shares Frietsch's view (1970) on this matter: ".... no conclusions regarding the distribution of aluminium in the iron oxides in the different kinds of ore and rock can be drawn as it is not certain if the aluminium is sited in the lattice of the iron oxides or if it occurs as impurities in the form of feldspar or other aluminium-bearing minerals". The same author (1970) states that the magnetite and magnetite ore from Kiirunavaara—Luossavaara and Tuolluvaara contains less than 1 % Al_2O_3. Frietsch also reports an Al_2O_3 content of 0.4 % for hematite ore and 0.3—0.2 % for hematite from Henry.

(If Al_2O_3 values are multiplied by 0.5291, the actual Al content is obtained, which can be compared with the Al values which follow. In this respect the Al analyses can also provide information on the degree of purity of the test material.)

The results of analysis of the Al content in magnetites and hematites from the Kiruna field are presented in Table 33.

Kiirunavaara—Luossavaara magnetites show a considerably lower Al content (after conversion of Al_2O_3 to Al) than has been indicated previously. Test material from the deeper levels (Kiirunavaara 800 m level and Luossajärvi ore) contains less Al than material from the higher levels. The Al content in Tuolluvaara magnetites differs substantially from the Al content in magnetites from the Kiirunavaara—Luossavaara and also the Per Geijer ore bodies. The Per Geijer magnetites have an Al content which lies between the values for magnetite from the Kiirunavaara—Luossavaara and Tuolluvaara ore bodies. An increased Al content can be noted with increasing depth in magnetites from the Per Geijer ore bodies (the Lappmalmen Al value = 1 100 ppm). Magnetites from the wall-rock show higher Al contents than magnetites in the ores. According to the analyses, magnetites from the Vakko rocks (sample group 1) have a higher Al

content than magnetites from the Lower Hauki rocks. The highest Al content is found in the magnetite from the Kurravaara conglomerate.

The Al content of the hematites is higher than that of the magnetites. Exceptions in this respect are the hematites from the Hauki type syenite-porphyry, sericite quartzite and the Tuolluvaara ores.

MAGNESIUM

Nockolds (1954) reports the following MgO values as average in igneous rock: dunite 43.16 %, gabbro 8.06 %, andesite 4.36 %, dacite 2.12 %, granodiorite 1.57 % and nepheline-syenite 0.57 %.

Magnesium, usually reported as MgO, is generally included in the analyses of iron ores. These analyses often include silicates which co-exist with iron minerals. The quantity of Mg contained in magnetite or hematite is therefore not disclosed by such information. For this to be possible, the degree of purity of the test material must be so high that it precludes impurities such as inclusions and silicate minerals which have grown together. Microprobe analyses are of great help in avoiding such difficulties. Investigations into the Mg content in the magnetite lattice have recently been carried out at the Mineralogical — Geological Institute of Uppsala University and at the laboratories of the Swedish Geological Survey. The results are given in papers by Annersten (1968) and Frietsch (1970). Annersten summarizes his examination of a sulphide-bearing magnetite ore deposit (Stora Sahavaara, Northern Sweden) as follows: "Sulphurization of magnetite is assumed to be responsible to the introduction of Mg into the magnetite structure".

The content of Mg in some types of iron ores, as reported by Frietsch (1970), is as follows:

Type of ore		Spectrochemical analysis		Microprobe analysis
Skarn iron ore	MgO %	5.0	MgO %	4.3
Skarn iron ore		4.5		5.3—6.2
Skarn iron ore		4.5		3.8
Skarn iron ore		8.5		5.7—8.5
Stratified iron ore		3.5		5.9
Iron ore of unknown origin		2.9		5.6

Frietsch (1970) states that the values found by spectrochemical analysis represent Mg that is really sited in the magnetite and are not due to contaminations of magnesium-bearing silicates.

The new determinations of the Mg content in magnetites and hematites from the Kiruna field are presented in Table 34.

Among the ores, the Tuolluvaara magnetites have an exceptionally high Mg content. Relatively high Mg contents were also recorded in the Kiirunavaara and Luossajärvi magnetites. A substantially lower Mg content was found in the Luossavaara magnetites.

A notably lower Mg content was recorded in magnetites from the Per Geijer ore bodies. The relatively high Mg content in Lappmalmen (900 ppm) means that the Mg content of the other Per Geijer ore bodies is lower than shown in the table. There is a difference between the Mg content of the wall-rock magnetites and the magnetites of the ore bodies and also between the different magnetites from the wall-rocks.

The content of Mg in the hematite was with one exception (the detritus of porphyry) lower than the same content in the magnetite.

COMPARISON BETWEEN PHOSPHORUS-RICH AND PHOSPHORUS-POOR ORES WITH RESPECT TO TRACE ELEMENT CONTENT IN MAGNETITE AND HEMATITE

After magnetite and hematite, apatite is the most important mineral in the ores of the Kiruna district. The phosphorus content of the ores is determined entirely by the apatite. Other phosphorus minerals occur only in extremely small quantities.

Apatite or apatite aggregates are usually light grey in colour, sometimes reddish or greenish. The type of apatite is flour-apatite. However, a few analyses show chlorine contents which are almost as high as the fluorine content. The apatites of the Kiruna field also contain rare earth metals (incl. Y) more than 5 000 ppm, strontium = 120—440 ppm, thorium = 10—100 ppm, uranium = 0—10 ppm and arsenic = 0—250 ppm.

It has been established that there is a difference between the apatites in the different deposits (Parák, 1973). These differences are slight, however, within the phosphorus-rich ores and do not appreciably affect the results obtained in this investigation.

The ratio of magnetite (hematite) to apatite varies between the deposits and even within the same deposit. With regard to Kiirunavaara the phosphorus-poor ore has had a smaller areal extension at the surface compared to the phosphorus-rich ore, at the same time as the phosphorus content in the phosphorus-rich type of ore increases with increasing depth.

Both types of ore form distinct beds, which usually run parallel to the sheet-like ore body and can be distinguished without difficulty (Fig. 39). Since the two types of ore adjoin each other with sharp contacts, substantial differences are also noted in respect of the ore body in these types.

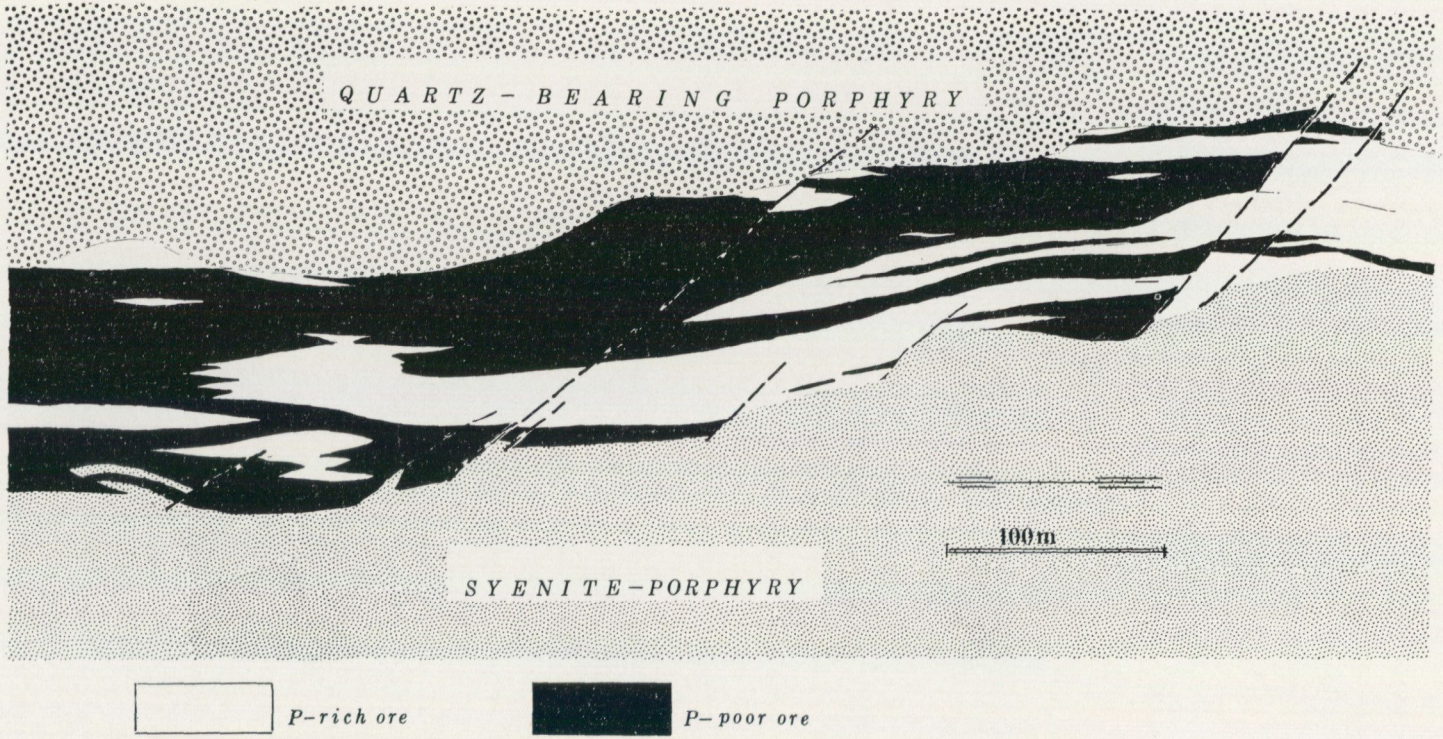

Fig. 39. Distribution of P-rich and P-poor ore in Kiirunavaara. (After P. Forsell.)

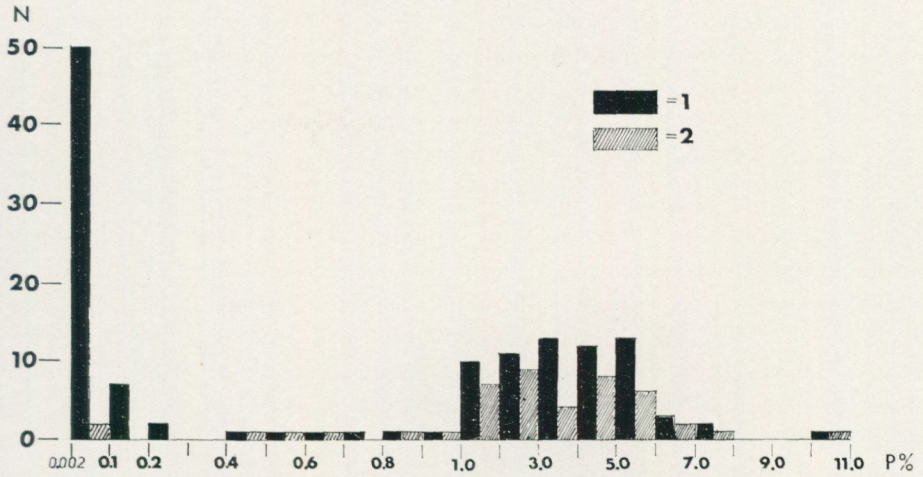

Fig. 40. Distribution of P in the samples. 1 = magnetite, 2 = hematite.

In his description of the Tuolluvaara deposit, Geijer (1920, p. 32) concludes that the relations between phosphorus-rich and phosphorus-poor ores indicates that the injection of the ore took place during two different, although fairly closely connected, stages. He also presents other examples from Swedish and foreign deposits where similar conditions occur.

If these conclusions hold true, it is obvious that a knowledge of trace element characteristics could contribute to a better understanding of the geologic development.

The presence of two types of ore led to a trace element investigation related to the phosphorus content. The investigation was based on 173 samples, all taken from the magnetite and hematite ores of the Kiruna field. As can be seen from Table 47, the phosphorus content of the samples varies greatly. The borderline (cut off) between phosphorus-rich and phosphorus-poor ores was drawn at 1 % P. An ore with this phosphorus content is normally regarded as a phosphorus-rich ore. However, the purpose was to bring out any significant factors (or at least trends) which apply to all the main ore bodies in the Kiruna field, as regards the trace element distribution. Only one phosphorus-rich sample from Luossavaara is included in the collected material, which is why this deposit is only represented by phosphorus-poor ore in the table.

The phosphorus content, as found in the above-mentioned distribution, is shown in Fig. 40.

As can be seen from this presentation, there seems to exist quantitatively a certain gap between phosphorus-rich and phosphorus-poor ore types.

Median values for the trace element content, classified according to phosphorus content, are given in Tables 35—38.

Brief comments on the tables are given below. Zirconium, chromium and molybdenum are not included in the tables, since only a few samples were found to contain these elements.

COPPER

Table 35 clearly indicates a decrease in copper with increasing depth in the Kiirunavaara ore body. The same table shows a remarkably high copper content in the phosphorus-poor samples from the Per Geijer ore bodies. This copper is found to be associated entirely with the Per Geijer ore magnetites, as indicated in Table 36. There are a few analyses of this magnetite with a high copper content. However, this cannot change the picture presented by Table 37, which shows that when all the analyses are combined, the hematite phase in both ore types has a higher copper content.

Table 38 shows that there is no difference between the two types of ore when all the copper values are studied, i.e. the differences which can be indicated when the individual groups are considered are evened out when the phosphorus-rich and phosphorus-poor ores are combined.

ZINC

As is the case with copper, the zinc median indicates a decrease in zinc with increasing depth in the Kiirunavaara ore body. This conclusion is reached when both the phosphorus-rich and phosphorus-poor types are dealt with jointly. Table 35 shows that the decrease in zinc is considerably greater in the phosphorus-rich ore than in the phosphorus-poor ore. The latter type of ore is richer in copper on the whole.

In the other ores of the Kiruna field, however, the opposite is found to apply. The Tuolluvaara samples constitute an exception, since in this instance the zinc content is equally high in both types of ore. Whilst the Per Geijer ores show zinc enrichment in the hematites according to Table 36, on combining all the samples we find that the hematite has a higher zinc content only in the phosphorus-rich ore.

A study of all the samples shows zinc enrichment in the phosphorus-rich type of ore (Table 38).

TITANIUM

Table 35 shows a decrease in titanium content with increasing depth in Kiirunavaara. This applies to both the phosphorus-rich and phosphorus-poor ores. As can be seen from Table 35, the Kiirunavaara, Luossajärvi and Per Geijer ores show a remarkable titanium enrichment in the phosphorus-poor ore type. The difference in titanium distribution for Tuolluvaara should be noted. How-

ever, it must be remembered that the hematites in the Tuolluvaara ores contain 1 400 ppm Ti as opposed to 300 ppm Ti for the magnetites. In addition, 4 out or 5 hematite samples are of the phosphorus-rich type. With regard to the titanium distribution, the hematite has a considerably higher titanium content in both the phosphorus-rich and phosphorus-poor ores. This is apparent from Tables 36 and 37.

When all the samples are combined, titanium shows enrichment in the phosphorus-rich ore.

ZIRCONIUM

Zirconium was detected in only four of the 173 samples examined. All four (three from Luossavaara ore veins W of the main ore body and one from Per Geijer ores) belong to the phosphorus-poor type of magnetite ore.

VANADIUM

Vanadium is enriched in the phosphorus-poor type of ore, the sole exception being the Kiirunavaara 320 level (Table 35). In the Per Geijer ore bodies, magnetites and hematites are opposites as regards the distribution of vanadium in phosphorus-rich and phosphorus-poor ores (Table 36). In the combined test material, the magnetites show a vanadium deficiency only in the phosphorus-rich type of ore (Table 37).

When all the vanadium values are considered, the phosphorus-rich ore shows a vanadium enrichment in accordance with Table 38.

CHROMIUM

It was stated above that chromium was found in only four samples from the Kiirunavaara magnetites and in one hematite sample from the same ore. The four magnetite samples belong to the phosphorus-poor ore type. The hematite sample represents the phosphorus-rich type. Twelve samples from Luossavaara (magnetites) containing chromium and the two sample from Lussojärvi ore magnetites represent the phosphorus-poor type of ore.

Of the 74 samples from Per Geijer ores, 36 contain chromium. Most of the chromium values lie between 10—30 ppm. However, in two cases high chromium values (60 and 210 ppm) were detected in phosphorus-rich magnetites. Eighteen out of 22 magnetites and 11 out of 14 hematites belong to the phosphorus-rich type of ore.

MOLYBDENUM

Of the samples examined, none contained molybdenum.

MANGANESE

With the exception of the samples from the Kiirunavaara 800 m level, the deposits each show a manganese enrichment in phosphorus-poor ore. The phosphorus-rich ore in the Kiirunavaara ore body shows an increase in manganese with increasing depth. If the hematite samples (5 in all) from the Kiirunavaara 320 m level are disregarded, manganese enrichment is observed in the phosphorus-rich type of magnetite ore for the entire deposit.

Table 37 clearly shows that manganese is always enriched in magnetite ore.

When all the analyses are combined (Table 38), significant manganese enrichment is apparent in the phosphorus-rich ore.

COBALT

Table 35 shows an almost contrary relationship between phosphorus-rich and phosphorus-poor ores from the 320 m and the 800 m levels at Kiirunavaara. Phosphorus-poor ore from Tuolluvaara shows an obvious cobalt enrichment. Tables 36 and 37 show that it is always the magnetite ore which is enriched in cobalt in both the phosphorus-rich and phosphorus-poor ores.

When all the analyses are combined, cobalt enrichment is observed in the phosphorus-rich ore.

NICKEL

Nickel enrichment occurs only in the upper sampling level in Kiirunavaara ore body and in the Per Geijer ores, where it is associated with phosphorus-rich ore. In this respect, nickel differs from cobalt as regards its distribution in the phosphorus-rich and phosphorus-poor types from the Per Geijer ore bodies.

A decrease in nickel with increasing depth in the Kiirunavaara phosphorus-rich ore and indications of an increase for the phosphorus-poor type can be noted from Table 35.

Tables 36 and 37 show that the greater part of the nickel content is always associated with the magnetite in both the phosphorus-rich and phosphorus-poor ore types.

Only insignificant nickel enrichment in the phosphorus-rich ore is indicated in Table 38, which includes all 173 ore samples.

ALUMINIUM

According to Table 35, a decrease in aluminium with increasing depth can be detected at Kiirunavaara in both ore types. The decrease in aluminium is particularly apparent in the phosphorus-poor type. There is no difference between phosphorus-rich and phosphorus-poor ore at Tuolluvaara, although the phosphorus-rich ore at Luossajärvi shows a higher aluminium content.

The Per Geijer ores always show higher aluminium values in the phosphorus-poor ore, as shown by the analyses in Tables 35 and 36. In addition, Tables 36 and 37 show that aluminium is always enriched in hematite in both the phosphorus-rich and phosphorus-poor types.

When all the analyses are combined, aluminium is enriched in the phosphorus-poor type (Table 38).

MAGNESIUM

Although magnesium is enriched in the phosphorus-rich type of ore at Kiirunavaara, the opposite applies to the other ores. Both the Luossajärvi and Tuolluvaara ores are characterized by remarkable magnesium enrichment in the phosphorus-poor ore. With the exception of the phosphorus-poor magnetites from the Per Geijer ore bodies, the magnesium content is found to be 100 ppm in both the magnetite and the hematite in this ore.

When the samples are combined as in Table 37, it is found that the magnesium content is always higher in the magnetites. This is confirmed in Table 38.

The tables further show that ferrides in the phosphorus-rich type of ore total 2 685 ppm (and 3 555 ppm for all 12 trace elements). The corresponding total for phosphorus-poor ore is 2 230 ppm (and 2 790 ppm for all 12 trace elements).

DISTRIBUTION OF TRACE ELEMENTS IN CO-EXISTING MAGNETITES AND HEMATITES

Ore deposits of both co-existing and non-co-existing (referred to as "monotype" below) magnetite and hematite ores are represented in the Kiruna field. Examination of the co-existing iron oxides and their relationship to monotype iron oxides in the Kiruna field was therefore one of the objectives of the present paper.

"The ore mineral is magnetite. Hematite occurs as a primary mineral in very small amounts, as crystalline lumps enclosed in magnetite and as thin veinlets. Secondary (martitic) hematite is important within a portion in the southern part", states Geijer (1960) from Kiirunavaara. In recent years hematite ore has been found on a large scale in boreholes several hundred metres beneath the surface of the ore body. It occurs in the magnetite ore. Its width varies and can be as large as 25 m. Exploratory boreholes indicate that this hematite ore is very extensive in the Kiirunavaara magnetite ore body.

The results of drilling show that both magnetite and hematite ore occurs at Luossajärvi. The hematite ore forms a central part in the magnetite ore. Transitions between the two types of ore are continuous.

In this respect, the test material from the Tuolluvaara deposit is also of interest. Until very recently this deposit was known as essentially a monotype

(magnetite) deposit. Geijer wrote as follows (1920) on the Tuolluvara hematites: "Hematite only occurs in very minor amounts. It forms coarse crystalline lumps with rounded contours, seldom of more than a few centimetres in cross-section. In the Chulalongkorn ore body, hematite occurs along the transverse fissures in the ore, following them on both sides. The mode of occurrence thus clearly shows that the mineral is a secondary formation, at least in this instance" (translated from Swedish). However deep-lying hematite ore has also been found here.

In this paper, hematites from the Kiirunavaara, Luossajärvi and Toulluvaara deposits are represented by five samples each. Of these, eight were taken in such a way that both magnetite and hematite from the same hand specimen were subjected to trace element analysis.

The Per Geijer ores are the most represented test material in this section (22 samples). The Lower Hauki rocks (20 samples) and Vakko rocks (7 samples) are also represented. Samples included in the last two groups are mostly of the "impregnation" type. A hematite pebble containing some magnetite (57 % Fe, 0.16 % P), prepared from greywacke, was also included.

In all, 60 samples represent co-existing magnetites and hematites from the Kiruna field. An additional 44 ore samples (some of the Per Geijer ores, from diamond boreholes in the section between Rektorn and Lappmalmen (Fig. 37) were concentrated and analysed in the LKAB laboratory at Malmberget. (However, the latter samples were not studied jointly with the other 60 samples, but were used only as material for comparison. The intention was to find out whether the trace element distribution trend is the same even when the test matrial has been treated differently from sampling to analysis.)

The trace element content of co-existing magnetites and hematites is shown in Table 39. Table 40 shows the trace element distribution in the highly concentrated ore according to Fig. 37.

To permit comparison between the co-existing iron oxide type and the monotype iron oxide, analysis material from the latter type in the same deposit is presented in Table 41.

In Table 42, the total trace element content is presented together with the trace element content of the ferrides in magnetites and hematites from both monotype and co-existing samples from the Kiruna field.

In order to give a less rigid picture of the relationships between co-existing and monotype magnetites and hematites, Table 43 is supplemented with calculations of the percentage of ferrides in the total trace element content.

COPPER

The copper content in the magnetite shows no great difference in comparison with the same content in the hematite from co-existing test material. The copper

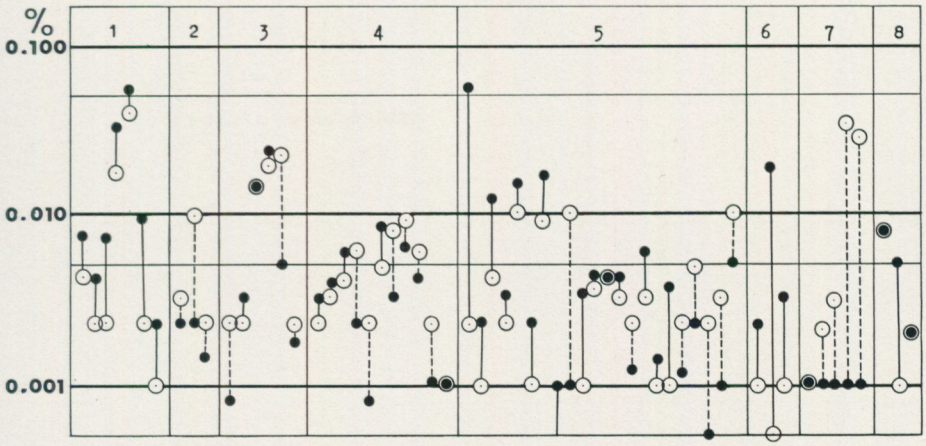

Fig. 41. The content of Cu in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

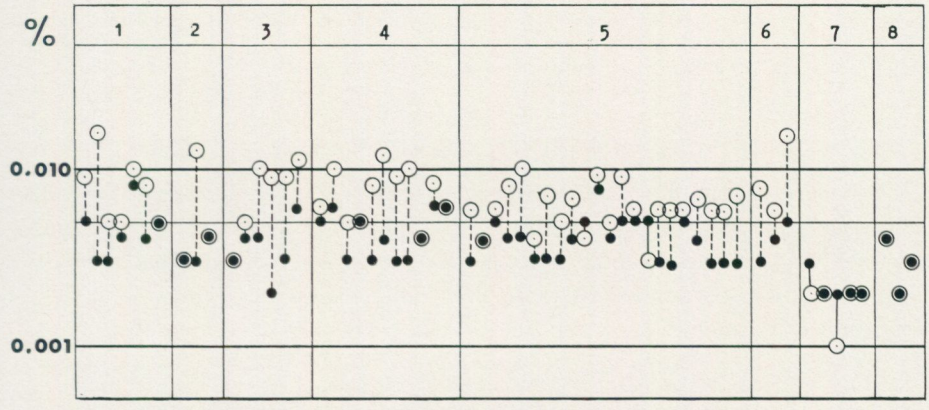

Fig. 42. The content of Zn in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

content varies between 10—70 ppm in the magnetites and 10—85 ppm in the hematites (Fig. 41).

ZINC

Zinc is usually enriched in the hematite, especially in the monotype. There is no great difference between magnetite of the monotype and the co-existing type, with the exception of magnetite from the Vakko rocks (Fig. 42).

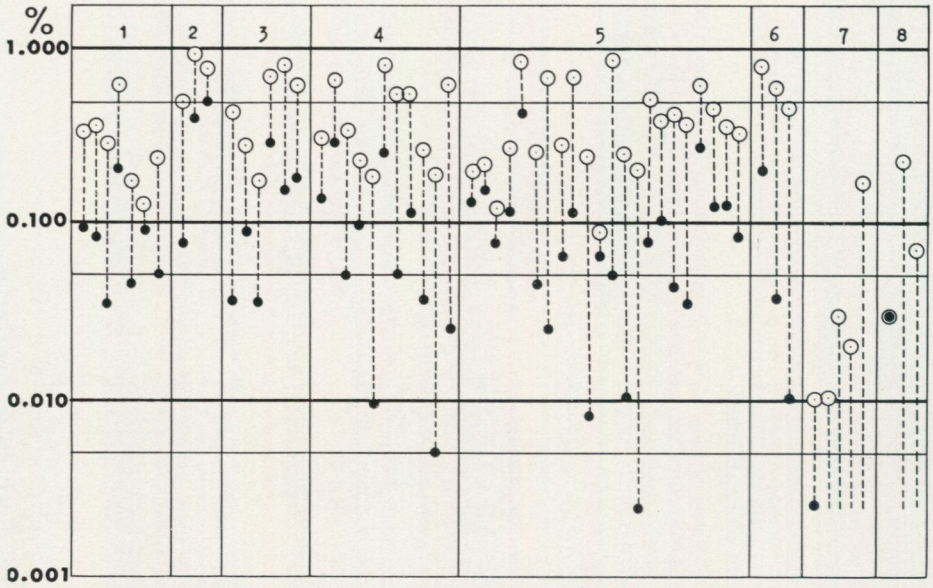

Fig. 43. The content of Ti in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

TITANIUM

The hematite generally has a higher titanium content than the magnetite. Moreover, the hematites co-existing with magnetites have a higher titanium content than other hematites from monotype deposits. Magnetites co-existing with hematites contain less titanium than other magnetites. The sole exception is provided by samples from the Vakko rocks (Fig. 43).

ZIRCONIUM

Analyses for zirconium were carried out on all the samples but zirconium was detected in oly one hematite co-existing with magnetite (110 ppm).

VANADIUM

According to the findings of the new investigation, vanadium is always enriched in the hematite phase of the co-existing test material. The Kiirunavaara samples constitute an exception in this respect (Table 41). Comparisons between co-existing and monotype analyses show that vanadium is enriched in monotype magnetite — the exception being test material from the Vakko rocks and from quartz-bearing porphyry — whereas the type of hematite co-existing with magnetite is vanadium-enriched (Fig. 44).

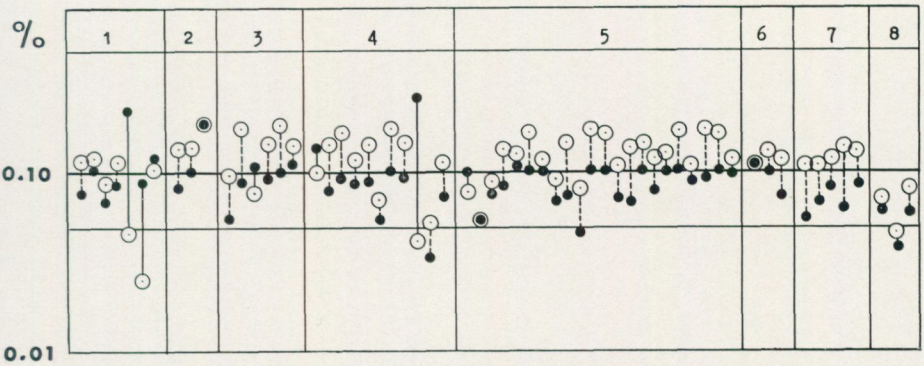

Fig. 44. The content of V in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

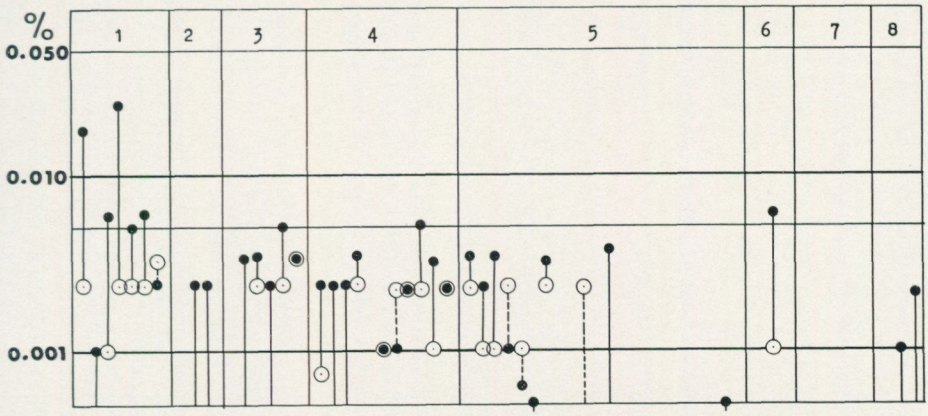

Fig. 45. The content of Cr in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

CHROMIUM

The highest chromium content was found in the magnetites co-existing with hematites from the Vakko rocks. In the other co-existing samples too, chromium is always enriched to a greater extent in the magnetite phase than in the hematite phase. With regard to hematite, it is remarkable that the co-existing type always has a lower content than the monotype. It is also worth noting that monotype hematite from detritus of porphyry and Per Geijer ores has a higher chromium content than monotype magnetites from the same groups of samples. The monotype iron oxides from Per Geijer ores and from quartz-bearing porphyry always contain chromium. This is not the case for the co-existing iron oxides (Fig. 45).

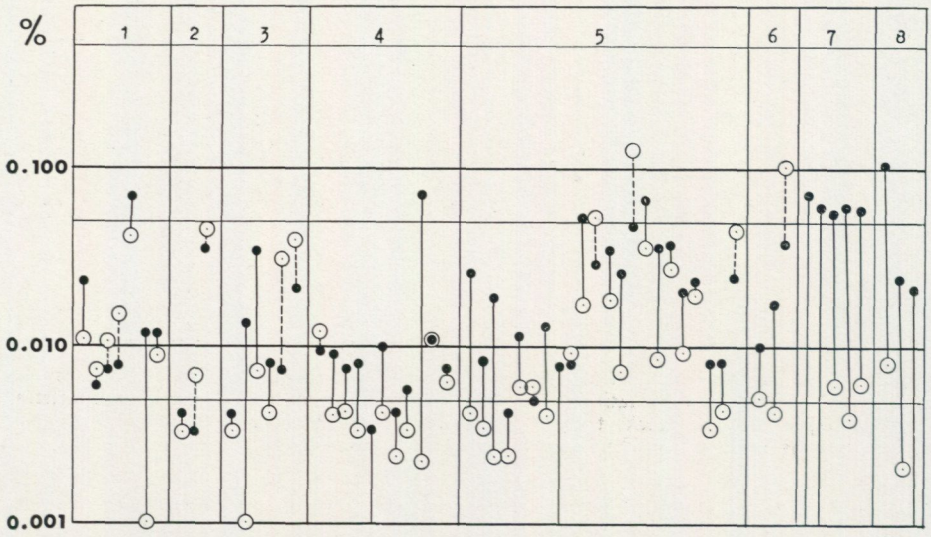

Fig. 46. The content of Mn in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

MOLYBDENUM

Analyses for molybdenum were carried out on all the co-existing iron oxide samples; but no molybdenum was found (limit of sensitivity of the instrument 25 ppm).

MANGANESE

In most cases, the median manganese content is lower than 220 ppm, both in co-existing and monotype magnetites and hematites. The sole exceptions are monotype iron oxides from Kiirunavaara (320 m level) and magnetites (co-existing type) from Luossavaara. Magnetite co-existing with hematite from the Per Geijer ores and their wall-rocks has a slightly lower manganese content than the corresponding monotype magnetite (Fig. 46).

As regards the hematite phase, the manganese content is always higher in the hematite co-existing with magnetite.

COBALT

Apart from hematite co-existing with magnetite in sericite quartzite and Hauki type syenite-porphyry, the magnetite samples have a higher cobalt content than the hematites. Of monotype and co-existing magnetites, the former are always richer in cobalt. However, the samples from quartz-bearing porphyry constitute an exception. With regard to hematite, on the other hand, the cobalt content is apparently higher in the sample co-existing with magnetites (Fig. 47).

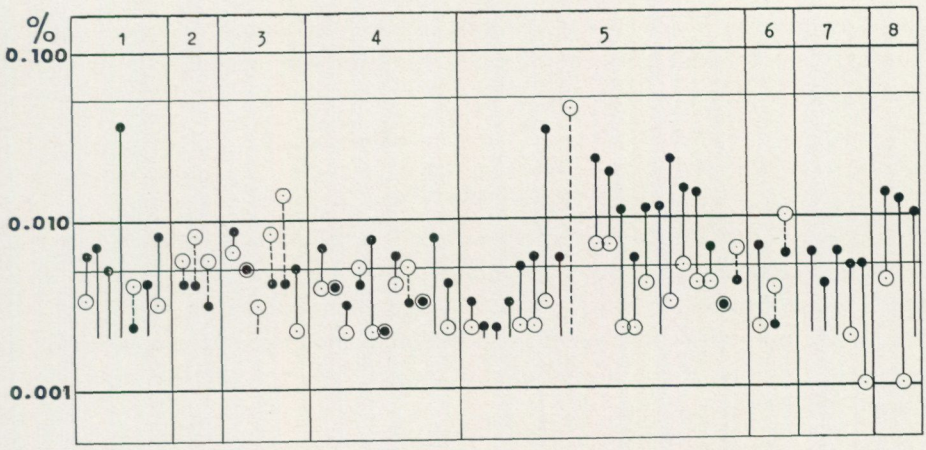

Fig. 47. The content of Co in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

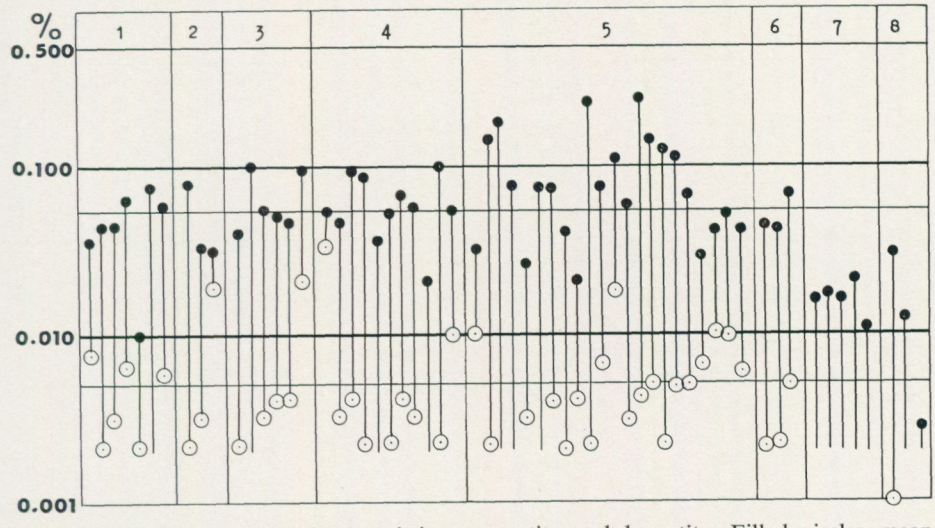

Fig. 48. The content of Ni in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

NICKEL

The nickel content of the magnetite phase is without exception markedly higher than the nickel content of the hematite phase. The difference is roughly one decimal power. The nickel content of co-existing magnetite is higher than that of monotype magnetite. Tuolluvaara magnetites are an exception. Apart from

the samples taken from Hauki type syenite-porphyry and from quartz-bearing porphyry, the hematite phase in the type co-existing with magnetite has a higher nickel content than the monotype (Fig. 48).

ALUMINIUM

In most cases the aluminium content is higher in the hematite phase. Generally speaking, the monotype magnetites and hematites are richer in aluminium than the co-existing types. In other words, the aluminium content in magnetites co-existing with hematite is lower than in the other monotype magnetites. This is also true of the co-existing hematite samples, apart from the detritus of porphyry test material (Fig. 49).

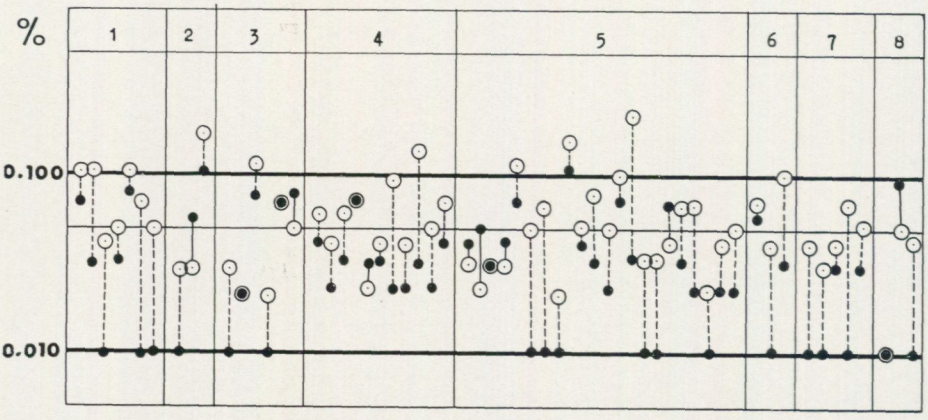

Fig. 49. The content of Al in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

MAGNESIUM

The median magnesium content in the co-existing types of iron oxide samples is at most 100—200 ppm. The Tuolluvaara samples constitute an exception. As a rule, the magnetites of monotype samples have higher magnesium contents than magnetites of the co-existing type. In the Per Geijer ores, hematite shows the same values regardless of whether it is co-existing or monotype. On the other hand, analyses show that the wall-rock of the ore bodies shows a higher magnesium content in the monotype samples. The hematite in the monotype sample groups (Table 41) shows a lower magnesium content than the magnetites. The detritus of porphyry samples constitute an exception in this instance (Fig. 50).

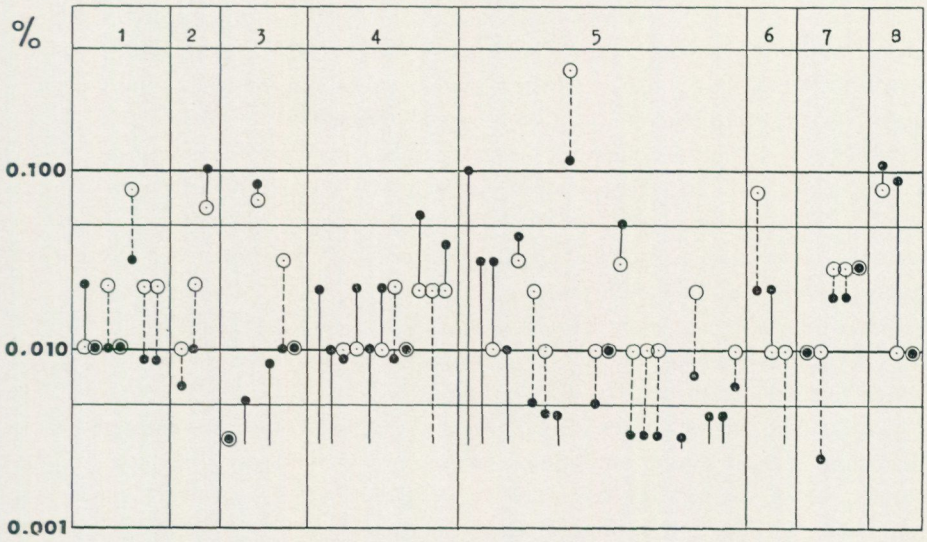

Fig. 50. The content of Mg in co-existing magnetite and hematite. Filled circles mean magnetite, open circles hematite. 1=Vakko sedimentary rocks, 2=Sericite quartzite, 3=Syenite-porphyry of Hauki type, 4= Detritus of porphyry, 5=Per Geijer ores, 6= Quartz-bearing porphyry, 7=Luossajärvi ore, 8=Tuolluvaara ore.

EVALUATION OF PREVIOUS AND NEWLY OBTAINED TEST FINDINGS

INTRODUCTION

In the first part of this paper a brief description of the rock types and ores which form the Kiruna field was given. New field observations were presented as well as new chemical analyses and microscopic investigations carried out since the previous publications.

The new observations and data give a new aspect on the evaluation of the Kiruna field. Owing to this even the question of the ore's genesis has to be reconsidered.

EARLIER GENETICAL INTERPRETATIONS

The earliest document concerning the origin of the Kiruna ores dates back to 1875. Kiirunavaara and Luossavaara were examined at that time by a State Commission which found the ores to be a sedimentary layer in sedimentary wall-rocks (hälleflints).

Up to 1910 a number of hypotheses on the genesis of the ores had been put forward by geologists who had examined the ore field at Kiruna. Geijer (1910) gives an excellent summary of this discussion in his monograph on the ores and rock types of the Kiruna field. In the same work he sides with those who advocated a magmatic origin for ores. Geijer's report came to play a

predominant role in Swedish geological research on ores. Other authors such as Daly (1915), Vogt (1927), Asklund (1949), Ridge (1956), Saksela (1970) and Frietsch (1970) have also published papers in which they have supported a magmatic origin for the apatite-iron ores of Kiruna field.

On the basis of geochemical investigations, however, Landergren (1948, 1949, 1958, 1961) and Hegemann & Albrecht (1954) have regarded the cross in Kiruna field as primarily sedimentary or submarine exhalative formations. Oelsner (1961) states that the apatite iron ores of N Sweden are submarine-hydrothermal-sedimentary formations.

According to Geijer, the apatite iron ores of the Kiruna field were formed by differentiation of a parent magma which also gave rise to the porphyries which form the wall-rocks of the ore bodies.

While the wall-rock types (porphyries) crystallized, the ore separated from them and passed into a subsequent phase in which the volatile constituents, chiefly water, played an important part. Geijer (1931, p. 166) states that indications of the differentiation process can be seen in the way magnetite appears in the porphyries. The magnetite-syenite-porphyries and the magnetite amygdule-bearing porphyries are quoted as examples of this. The final stage in this process gave rise to the hydrothermal Hauki hematite. The structural features, which are described as comparable to magmatic solidification structures, were assumed to indicate that the ores are magmatic intrusive.

Later, Geijer (1960, p. 46) still supported this course of events: "The ore bodies are intrusive, as shown by their contact relations, including the "ore breccias". Since the latter are offshoots from the main ore bodies, they cannot represent any later "mobilization" of material".

On the basis of new field observations and geochemical analyses, however, the author concludes that the Kiruna iron ores — and also those other Lapland iron ores which are equivalent to the Kiruna iron ores — are supracrustal formations which were deposited by chemical sedimentation. Evidence supporting this hypothesis will be presented in the following sections.

RECENT DEVELOPMENTS

GEOLOGICAL OBSERVATIONS

KIIRUNAVAARA—LUOSSAVAARA

Contact relations between the main ore bodies and the foot-wall rocks

The conglomerate-like formation in the foot-wall contact of Kiirunavaara, (Figs. 4 and 5), where the rock consists of pebbles in a magnetite matrix, can scarcely be considered a contact phenomenon produced during or after ore intrusion.

As seen in Fig. 2, the foot-wall syenite-porphyry is interbedded with amygdaloidal rock. These two types each have characteristic textures and are therefore readily distinguishable from each other. In the pebble accumulation shown in Figs. 4 and 5, these two varieties are irregularly intermixed. Only sorting by fragment size is discernible. The unaltered edges of the pebbles show that there has been no chemical weathering.

The rounded, occasionally spherical pebbles indicate that the material in question has been transported and subjected to abrasive wear. Deposition on an erosion surface has therefore been involved. An intrusive ore magma — along the contact between two rock types — could scarcely have rounded off those rock fragments which had become loose in this way. Nor is it likely that the loosened material would only have been found in the foot-wall contact within this limited area.

Evidence for surface erosion was found west of the Henry ore body. Here the top part of the syenite-porphyry (amygdaloidal) is broken up near the contact, forming a breccia. The matrix consists of low-grade ore (approx. 18—20 % Fe), and angular or slightly rounded rock fragments. The fragments are up to a few decimetres in size. Most of the fragments are composed of syenite-porphyry and magnetite-syenite-porphyry. Amydaloidal porphyry is also represented. In the interstitial material, it is possible to distinguish fragments with an iron content which is slightly higher than in the rest of the matrix.

North of Luossavaara, at the place where the agglomerate occurs (Geijer, 1910, appended map), it is difficult to define a rock boundary with the syenite-porphyry because the section of syenite-porphyry near the contact is brecciated and contains many different rock fragments.

The formation at the upper contact of the syenite-porphyry to the west of the Henry ore body and the conglomerate-like formation at the foot-wall contact of the Kiirunavaara ore body indicates that the main ore bodies were deposited on an eroded surface.

Contact relations between the main ore bodies and the hanging wall rocks

The reason that the extrusive theory (Geijer 1910) was abandoned was that the hanging wall contact in the southern section of the Kiirunavaara ore body was uncovered when mining commenced. Geijer (1919, p. 8) states that "In four places, contact phenomena were found that exactly correspond to those long known from the foot-wall contact".

Close examination of the condition of the hanging wall at Kiirunavaara and Luossavaara shows that there is no evidence of ore intrusion. The contact zones of up to 3 m width, referred to by Geijer, are now known to be very limited. The hanging wall contact relationships are similar to those found at the foot-

wall contact in so far as "ore breccias" are controlled by the Kiirunavaara fault system. This clearly apparent on maps which follow mining of the ore from level to level.

Kaolinization, which occurs in places along the hanging wall contact, can be the result of a reaction between a sub-aquatic ore and an extrusive hot porphyric lava. Changes of this type can of course also be taken as evidence in support of a theory which assumes intrusive ore magma with a high water content.

The contact relations between the "main ore" and "hanging wall porphyry" as shown by recent (and also previous) field data display many features which make it very difficult to interpret the porphyry as older than the ore. This statement is valid for the ore xenoliths in the porphyry as well as the conglomerate formations at the base of the porphyry.

The quartz-bearing porphyry, which occurs as the hanging wall nearest the main ore body in Luossavaara, has the highest number of ore fragments noted to date. Geijer (1968, p. 14) states that: "The fragments are so numerous in places that they have even been found to cover more than half of a surface measuring 0.5×0.5 m. A slight preferred orientation parallel to the general bedding is discernible. The fragments are mostly angular" (translated from Swedish). Geijer further states that no resorption seems to have taken place and that xenoliths from the hanging wall seem to be absent. He emphasizes that the ore xenoliths represent the same variations as those found in the Kiirunavaara and Luossavaara ores and that both apatite-rich and apatite-poor types occur. This last observation has been verified by new investigations including chemical analyses from 10 different ore xenoliths in the quartz-bearing porphyry, the results of which cover very well the variations in the main ores.

In his later consideration on these phenomena, Geijer (1968) admits that an extrusive interpretation of the Luossavaara ores with the occurrence of ore xenoliths in the hanging wall porphyry would provide a more reasonable explanation to the field data, but rules out this possibility on the grounds "that the Luossavaara ore body is formed in the same way as the Kiruna ore, which is of course definitely intrusive". The consequence must be, according to Geijer, that the ore xenoliths emanate from some older, at present completely eroded, ore deposit which contained all of the ore types now present in the Kiruna and Luossavaara ores.

Against these ideas the present author wants to present the interpretation that the quartz-bearing hanging wall porphyry is younger than the main ores and that the ore xenoliths emanate from the main ores. This alternative interpretation is supported by the new finds of erosional phenomena at the lower part of the porphyry.

Thus one part of the Kiirunavaara ore body (Fig. 51) shows a contact surface pattern which would be characteristic of an erosion of the ore body.

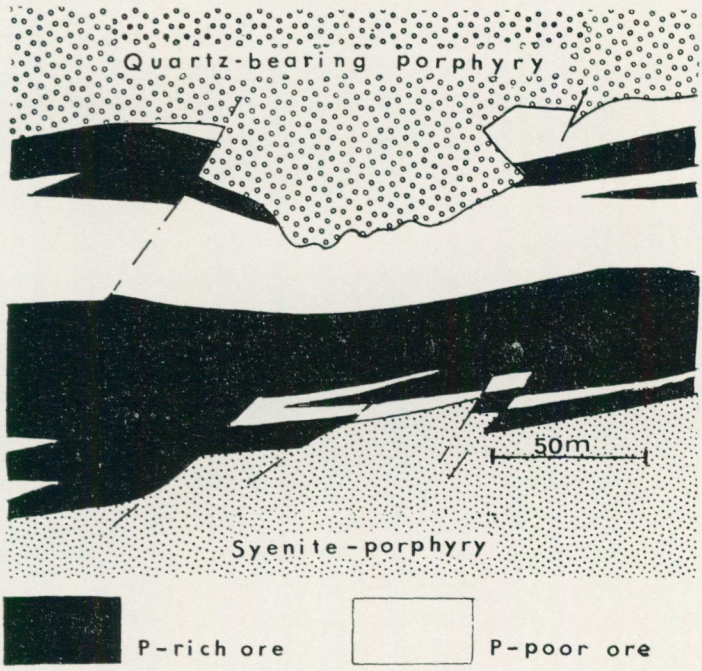

Fig. 51. Part of the contacts of the Kiirunavaara ore (320 m level). After P. Forsell.

Figure 51 shows rapid changes in ore body thickness. These changes are determined by the faults. In fact, the ore contact shows that the banding, which consists of apatite-rich and apatite-poor ores, is cut-off to a varying extent. The actual contact between the ore body and the hanging wall porphyry is sharp at this point and shows no alteration or brecciation whatever.

An alternative explanation for this phenomenon at Kiirunavaara would be that the ore body was more or less "cut-off" when it moved up from its original horizontal position. However, the absence of slickensides and slips at this point does not support this explanation.

Apart from porphyries bearing fragments of ore and hanging and foot-wall porphyry, conglomerate is also found in the hanging wall of the Luossavaara ore body. This polymictic formation, which mostly contains completely rounded pebbles, was encountered in an adit near the ore contact zone. Magnetite ore pebbles, which can be several decimetres in size, are found among the pebbles of the rock. These pebbles of ore clearly consist of ore types which are identical with those of the main ore body.

The rock fragments and agglomerate beds which occur in the quartz-bearing porphyry likewise play an important part in this respect. The fragment material chiefly consists of variants from the foot-wall porphyries. However, some

inclusions correspond to rock types found in the hanging wall. The most interesting fragments nevertheless consist of slightly altered, sericitized or silicified rocks, which in the Kiruna field belong to the Lower Hauki rocks.

No information is available on "offshoots" upwards from the ore bodies. This is remarkable, since the hypothesis of extensive ore magma intrusion (in Kiirunavaara the ore body is approximately 90 m thick) must of necessity involve raising of the hanging wall rock. "Offshoots", breccia formation, rock alteration and enrichments in halogens along the hanging wall contact would be expected in the main ore bodies after ore magma intrusion. Instead, a contact zone generally freed from such phenomena is found.

An ore intrusion would have influenced the hanging wall rock to a large extent, assuming that the hypothetical ore magma had a high content of water, fluorine, etc.

In this respect it should be pointed out that ore fragments also occur in the wall-rock of Malmberget. (Malmberget — the Gällivare ore field — is the next largest apatite iron ore body in Lapland.) Geijer (1930) states that ore fragments and ore-impregnated grey leptite are found in the Kapten-type leptite (hanging wall rock). From this he draws the conclusion that the Kapten-type leptite at this point is younger than the ores and the ore-impregnated rocks from the same area.

TUOLLUVAARA

The Tuolluvaara ore bodies occur in the quartz-bearing porphyry. In this respect they are similar to the Päronmalmen and Neptunus ores and Ekströmsberg ore (30 km west of Kiruna). The ore bodies at Tuolluvaara probably were continuous at one time, but have been subjected to faulting (Geijer, 1920), which split them into several pieces.

The Tuolluvaara field has not been surveyed by the author, but it has been reported that a deep-lying P-rich hematite ore body has been found here (p. 40 Vietnam ore).

THE PER GEIJER ORE BODIES

Contact relations between the main ore bodies and the foot-wall rocks

The foot-wall of the Rektorn ore body consists of quartz-bearing porphyry. The apatite-banded ore lies partly directly on this rock type (Fig. 52) and partly on a weathering breccia which in places is conglomeratic and in places brecciated (Fig. 53). The contact with the quartz-bearing porphyry is sharp. However, the boundary line between the apatite-banded ore and the weathering breccia presents certain difficulties. The matrix-material of the weathering breccia is usually hematite and/or magnetite-impregnated. It is rich in apatite. Fine banding is seen in the matrix. Even graded bedding was discovered in the

Fig. 52. The apatite-banded ore resting directly on the quartz-bearing porphyry. Rektorn.

southernmost section of the Rektorn mine (Fig. 14). The fragments show a preferred orientation parallel to the general direction of strike. The material consists mainly of quartz-bearing porphyry, although fragments of phenocryst-free rocks, quartz and magnetite and hematite ore are common. From this weathering breccia, it is possible in places to follow the banding upwards and into the apatite-banded ore without interruption.

The contact between the apatite-rich ore and the quartz-bearing porphyry at Nukutusvaara is sharp. In the Henry ore body and to the south of it the contact relationship is more complex. In the foot-wall contact of the Henry ore body, apatite accumulations of up to several square metres can be observed. These apatite sections contain large and small fragments of hematite ore (Fig. 54). Lumps of ore, both with and without bands of apatite, can be observed among the fragments. All observations made to date of such phenomena relate to tectonically disturbed places.

Fig. 53. The apatite-banded ore resting on a weathering breccia. Rektorn.

To the south of the Henry ore body, the quartz-bearing porphyry is broken up and the fissures are filled with a white apatite. This "apatite-impregnated" porphyry area is extensive. Numerous outcrops provide good possibilities of observation. The contact between the apatite and the porphyry is always sharp. Most of the exposed area resembles "ore breccia" (type 3, see p. 50), similar to that known from other parts of the Kiruna field, with the difference that in this instance the intersititial matter consists of apatite instead of magnetite. Large inclusions of banded hematite ore, up to more than one metre in size, can be observed here and there in the "apatite-mass" (Fig. 21). However, most of the ore inclusions which are enclosed in turn by porphyry are considerably smaller. Judging from the apatite-particle size, it is a matter of mobilization and recrystallization in this case.

Contact relations between the main ore bodies and the hanging wall rocks

Geijer (1919a) interpreted the contact relations between the ore bodies and the hanging wall rocks (according to Geijer; "Rektor porphyry") as an intrusive contact. New observations, however, show two instances of the hanging wall contacts of the Per Geijer ore bodies which suggest a new view of the age

Fig. 54. Fragments of hematite ore in apatite. Henry.

relations between the ore and the hanging wall. In one instance, a surface of erosion is exposed in the Rektor open cast mine. The other case is concerned with the contact relationship between the apatite-rich ore and the quartz-banded ore.

The Rektorn ore body invariably has an eroded top surface, i.e. a surface which was exposed and was eroded after deposition of the ore. This is most clearly apparent in the Rektorn open cast mine where, as a result of mining, the ore has been cut off roughly in the middle so that the contact relationships in a vertical section of some 60 m can be studied on both the foot-wall and the hanging wall (Fig. 55). As mentioned above, the most common rock type in the Rektorn hanging wall is an ore-impregnated detritus of porphyry with cross-bedding or syenite-porphyry of Hauki type.

The former rock type is partly sedimentary in origin, while the latter is probably volcanic. Figure 55 shows how the detritus of porphyry overlies the apatite-banded ore. The rock contains a large number of ore pebbles and frag-

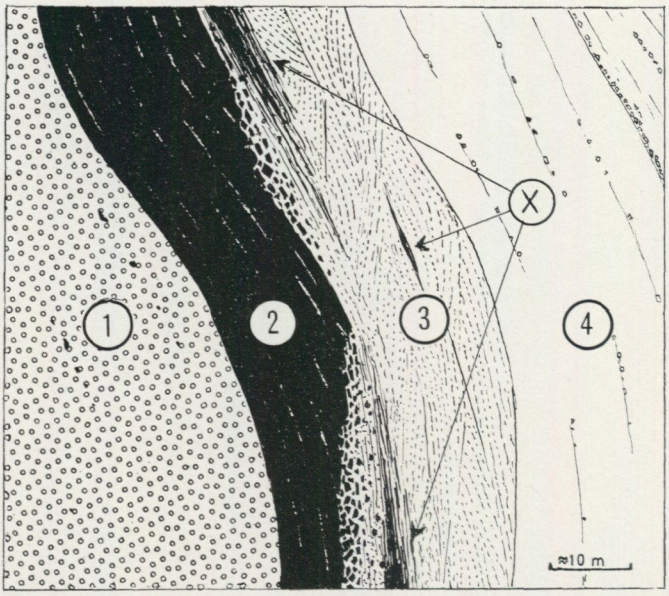

Fig. 55. Drawing showing the foot-wall and hanging wall contacts from the central part of the Rektorn ore body. Observe the eroded surface of the ore to the detritus of porphyry. 1=Quartz-bearing porphyry, 2=Apatite-banded ore, 3=Detritus of porphyry, 4=Syenite-porphyry of Hauki type, X=thin layers of hematite.

ments of the underlying ore. These ore fragments are most abundant where the ore contacts are eroded. The picture resembles the hanging wall of the Luossavaara ore body where ore fragments in the form of inclusions occur most abundantly very near the ore contact. However, there is a difference between the phenomenon at Rektorn and at Luossavaara. Whereas the ore fragments at Rektorn are enclosed in a rock type which shows well-preserved cross-bedding, the ore fragments at Luossavaara are enclosed in lava rock types (and conglomerate).

The other observation concerns the apatite-banded and the quartz-banded ores. The Per Geijer ore bodies consist of apatite-banded ore types. However, the apatite content often decreases in the topmost section of the ore body. Where the Hauki hematite or the quartz-banded ore lies directly on the main apatite-rich ore body, the boundary line is easy to discern in most cases. However, exceptions have been encountered in several boreholes (e.g. Dh 1284, 370 and 1368). At these points a continuous transition can be observed between the apatite-rich ore and the quartz-banded ore type.

The quartz bands, in fact, begin to appear even in the apatite-rich magnetite ore. This banded intermediate type then continues upwards with increasing quartz until the ore can be classified as a typical apatite-poor, quartz-banded,

magnetite-hematite ore. Small isolated quartz lenses occur here and there in the main ore bodies. These relationships have never before been reported from the Kiruna field.

"ORE BRECCIA"

The appearance of the "ore breccia" has been very important for those who argue that the main ore bodies are intrusive (Geijer, 1920, 1931b, 1960). The present author does not, however, regard the main ore bodies as being of the same origin as the ore breccias. For this reason, the origin of the latter will be discussed from another point of view. As has already been pointed out (p. 50), the so-called "ore breccias" are represented by different types of mineralization in the Kiruna field. In the following the author will call attention to the relationship between some different types of "ore breccias". These relationships may be of great importance in interpreting the genesis of the ore breccias.

One of these ore breccias occurs as fine-grained magnetite impregnations (type 2, p. 50), magnetite bands, or magnetite-filled nodules in the country rocks. This type of ore mineralization could be considered as primary. Geijer (1920, p. 14) describes similar "primary magnetite bands" in the porphyry from Toulluvaara. According to the same author (1920, p. 34), the magnetite-filled nodules which occur in syenite-porphyry at Mertainen correspond to these primary magnetite bands at Tuolluvaara.

Another type of ore breccia (type 3, p. 50) consists of splintered wall-rock fragments in the ore. An example of this type is found at Tuolluvaara (Geijer, 1920).

Geijer (1920) believed that this type of ore breccia was formed in the following way: the porphyry was subjected to tension and cracked. Into these fissures the ore mass was forced. Geijer (1967, p. 4) states that "It is important to note that commonly the field evidence unequivocally indicates forceful injection, not a filling of pre-existing open fissures". He also states that various kinds of replacement indicate a gaseous transport of material.

In the present description, it has already been mentioned that the "ore breccias" in the Kiruna field are not always connected with the main ore bodies (see p. 52). That is the case W of Henry and to a great extent W of Syväjärvi. Within these areas both types of "ore breccias" occur. They also occur in other large iron ore deposits outside the Kiruna area, such as Leveäniemi, Mertainen and Malmberget.

According to Parák (1965), the following types of ore breccias occur at Leveäniemi: 1. Well-developed vein networks of magnetite ore, which are irregular and enclose angular wall-rock fragments, 2. breccias characterized by ore-streaks in the wall-rocks, the streaks following the schistosity, 3. fine-grained ore impregnations disseminated in the various wall-rocks.

Lundberg (1965) classified the ore breccias from Mertainen into three different types, i.e. real ore breccia where the magnetite ore surrounds the fragments of syenite-porphyry, impregnation breccia with magnetite-nodules disseminated in the syenite-porphyry, and diffuse impregnation breccia with fine-grained magnetite disseminated in the syenite-porphyry. Furthermore, Lundberg states that transitions and combinations of these types of structures are the most usual.

An interesting phenomenon in this respect is the breccia formation at Malmberget (Gällivare). Geijer (1930) has in fact described how the ore banding in the wall-rock grades into ore breccia (type 3).

Most of the ore breccias (type 3) are, in fact, found in connection with "primary" iron ore impregnations (type 2) in the country rocks. It is therefore possible that there exists some relationship between en earlier ore mineralization of the ore breccias. What is meant here is not a "massive injection of ore material in fissures", but rather a mobilization of the ore material in solutions from an ore impregnation to a vein.

Although some of the ore breccias, at least in the foot-wall of the Kiirunavaara ore body, may have originated through precipitation of iron-oxides on a fissure-rich weathered rock surface, others were most likely formed in the same way as the manganese breccias of the Ultevis deposit as proposed by Ödman (1947).

With regard to formation and age relationships between ore banding and breccia formation, there is great similarity between Ödman's description of the Ultevis district and the rocks described here from the Kiruna district. In the Ultevis field, volcanic rock types occur which are regarded as being equivalent to the Kiruna—Arvidsjaur vulcanites. Sedimentary formations are also found together with porphyries (the quartz-bearing type), tuffs and tuffites. Greenstone lava is also found. The sediment includes thin layers of hematite ores and/or manganese ores. Ferruginous quartz (jaspilite) was also found in places. Breccia ores — manganese to a greater extent and hematite to a lesser extent — occur in the area and are said to be epigenetic. Ödman (1947, p. 56) points out that ". . . it is an interesting coincidence that they occur in the comparatively limited area in which there are found sedimentary manganese and iron precipitations of a rather specialized type". Ödman therefore assumes that "The mineralization as here outlined is the result of a mobilization process in which primary sedimentary material was brought into solution by means of deep-seated hydrothermal emanations. In other words, the process may be described as a lateral secretion at an elevated temperature."

Ödman (1947, p. 42) states the following about Tjatitsaure: "The ore boundaries are irregular and the ore sends "offshoots" into the walls". Eight pages later in the same papper he writes, "The observations tend to show that the epigenetic mineralization was contemporaneous with and was partly follow-

ed by a recrystallization and metamorphism, which, however, ended up before the epigenetic mineralization was completed".

Ödman's description is illustrated (Ödman 1947, Figs. 28 and 29). The pictures, together with the description, are in full agreement with what is known of the Kiruna deposit ore breccias (cf. Geijer 1920, Figs. 5 and 6). The difference lies in the fact that the interstitial material in the ore breccias in the Kiruna deposit consists of iron oxides, whereas the interstitial material in the Ultevis deposit consists of manganese oxides. Hematite ore breccia also occurs to a lesser extent at Ultevis.

Ödman's descriptions of manganese and hematite ore mineralization are particularly interesting with respect to the "ore breccias" which occur to the west of the Henry ore body and to the west of Syväjärvi (type 2). No high-grade ore is associated with these ores, which means that these formations cannot be explained by an "offshoot" brecciation. The rocks at these localities consist of different types of syenite-porphyry. The magnetite mineralization in these porphyries consists of magnetite bands or veins running in the general direction of strike of the rocks and of magnetite impregnations. The impregnation ore contains up to 30 % iron. The distribution of this ore is highly variable. In addition, the porphyries often contain magnetite in the form of fillings in the amygdules, a "primary" magnetite ore mineralization.

The secondary origin of the ore breccias (type 3) by mobilization of the primary ore material, as described by Ödman, is therefore also acceptable with respect of the Kiruna depost. Nevertheless, it should be remembered that the interstitial material in the Ultevis ore breccia consists of manganese. No magmatic intrusive origin of manganese ores — similar to the magmatic intrusive theory for iron ores — is known.

GEOCHEMICAL DATA AND CONSIDERATIONS

INTRODUCTION

The magmatic differentiation theory implies the following genetic series for the Kiruna field: syenite-porphyry (magnetite-syenite-porphyry), quartz-bearing porphyry, Lower Hauki rock types (at least in part), the apatite iron ores such as Kiirunavaara—Luossavaara—Luossajärvi (in one "horizon"), Tuolluvaara (in the next "horizon"), the Per Geijer ores (in a third "horizon") and Hauki hematite. In accordance with the theory of magmatic genesis, Geijer (1920, 1967) further assumed that several ore intrusions had taken place, with an apatite-poor ore proceeding the apatite-rich ore.

In view of the known distribution of elements in various rocks and ores (see pp. 53—88), one might assume that the differentiation which is supposed

to have taken place in the Kiruna deposit could be elucidated by certain trends in variation of the trace elements. The trace elements which are contained in the ore mineral lattices should be good indicators in this respect. If the main ore bodies and the ore breccia have originated from the same "ore injection", a relatively similar trace element distribution might be expected.

RATIO OF SOME ELEMENT PAIRS

Wager and Mitchell (1951), Ringwood (1955, 1955b), Sen et al. (1959) and Taylor (1965) state that chromium, cobalt, nickel, magnesium and vanadium decrease while copper and molybdenum increase during the magmatic differentiation process.

A summary of the trace elements present in magnetite and hematite (hematite in parentheses) from the Kiruna deposit rock types and ores is given in Table 44. There are no magnetite determinations for Hauki hematite. The values given for it in the table therefore relate to hematite. The grouping in Table 44 follows Geijer's magmatic differentiation theory for the Kiruna field.

As can be seen in Table 44, the cobalt, nickel, magnesium and vanadium values show irregularity with respect to their distribution in the various "partial magmas". This fact scarcely provides support for the hypothesis of ore formation by magmatic differentiation terminated by the formation of a separate ore magma. The chromium content also shows subsequent enrichment, which is of course remarkable if normal differentiation were involved.

According to Hegemann and Albrecht (1954), the Ti/V value should serve to indicate the manner of formation of the iron ores. They therefore compared the Ti/V ratio (2.9) for magmatic rock types with the same ratio for iron ores which were formed in a different way. This comparison showed that the intramagmatic and contact-pneumatolic ores have a higher Ti/V value, while ores formed in a different way show a lower Ti/V value.

The new investigation provides the following Ti/V ratios for the Kiruna field:

	Magnetite	Magnetite+Hematite
Kiirunavaara 320 m level	0.7	0.7
Kiirunavaara 800 m level	0.5	0.5
Luossavaara	0.8	0.8
Luossajärvi	0.4	0.4
Tuolluvaara	0.4	1.0
Per Geijer ores	1.0	1.9
Hauki hematite	—	27.5

The V/Zn ratio: The lower electronegativity etc. of vanadium means that this element has priority over zinc in differentiation. The V/Zn ratio should therefore increase in such a process.

The V/Zn ratios for the Kiruna field are as follows:

	Magnetite	Magnetite+Hematite
1. Syenite-porphyry	30.7	30.7
2. Magnetite-syenite-porphyry	31.0	31.0
3. Quartz-bearing porphyry	21.5	19.3
4. Detritus of porphyry	27.3	20.0
5. Syenite-porphyry of Hauki type	27.6	23.2
6. The ore bodies:		
Kiirunavaara 320 m level	24.6	28.0
Kiirunavaara 800 m level	28.9	28.9
Luossavaara	20.7	20.7
Luossajärvi	34.9	43.2
Tuolluvaara	26.7	27.4
Per Geijer ores	27.3	23.8
Hauki hematite	—	3.1

A great deal of attention is paid to the Co/Ni ratio in geochemical literature. According to Sahama (1945b), the following Co/Ni ratios are found in various rock types from Finnish Southern Lapland: ultra-basic rocks = ∼0.30, gabbro and dolorites = 0.51, granites = max. 4.0, syenites = 1.0. Landergren (1948) states that "Since nickel is enriched in the early crystal fractions rich in magnesium, the ratio cobalt: nickel consequently increases as the crystallization proceeds."

Landergren found a Co/Ni ratio of 1 for the apatite iron ores (central Sweden, northern Sweden). In a study of the Co/Ni ratios in magmatic rock types, Davidson (1962) found the following values:

SiO_2 %	Co (ppm)	Ni (ppm)	Co/Ni
72.5—80	3	3	1.0
67.5—72.5	7	11	0.64
62.5—67.5	10	15	0.66
57.5—62.5	19	23	0.83
52.5—57.5	22	39	0.56
47.5—52.5	33	140	0.24
40.0—47.5	52	282	0.18
40.0	160	1600	0.10

For primary ores, Davidson (1962) reports the following Co/Ni values:

Type	Example	Co/Ni
Cobalt Fahlbands	Skutterud	30:1
Mispickel-Pyrrhotine skarns	Nickel plate	30:1
Copper sulphide bodies	Outokumpu	15:1
Magnetite skarns	Vysokogorsk	15:1
As—Co—Ni veins	Erzgebirge	1:1
Co—Ni sulphides in basic rocks	Sudbury, Norilsk	1:30

The new investigation of the Kiruna deposits gives the following Co/Ni ratios:[1]

	Magnetite	Magnetite+Hematite
1. Syenite-porphyry	0.6	0.6
2. Magnetite-syenite-porphyry	0.3	0.3
3. Quartz-bearing porphyry	0.4	0.8
4. Detritus of porphyry	0.2	0.7
5. Syenite-porphyry of Hauki type	0.2	1.2
6. The ore bodies:		
Kiirunavaara 320 m level	0.4	0.6
Kiirunavaara 800 m level	0.4	0.4
Luossavaara	0.6	0.6
Luossajärvi	0.4	0.7
Tuolluvaara	0.4	0.6
Per Geijer ores	0.3	0.7
Hauki hematite	—	0.5

The results given in Table 44 and the ratios between the different pairs of elements indicate that the Kiruna ores were not formed by magmatic differentiation. If the Kiruna deposit were formed intrusively, the intruding magma would have formed sheets and dikes and at places brecciated wall-rock. The main ore bodies and the ore breccias would then have the same parent magma. A similar distribution of elements would be expected in them. However, investigation of the trace element distribution in the magnetites (Tables 24—34) shows much higher titanium, chromium and aluminium values and higher manganese (nickel) values in the magnetites which occur in the ore breccia (wall-rock) than in those found in the main ore body.

Before leaving the discussion of the magmatic ore genesis theory, it should be mentioned that Geijer (1960, p. 47) refers to laboratory investigations carried out by Fischer (1950) in support of this theory. According to these investigations, two melts are produced in the fusion of Na-silicate, magnetite and apatite with fluorite, with the magnetite and apatite together in one of them. However, these experiments were carried out at temperatures of approx. 1 300°C—1 400°C, and therefore are of greater interest from the metallurgical viewpoint than from that of ore genesis. Conditions such as composition, temperature, pressure, gravity, etc. are considerably different in a laboratory experiment from those found in nature.

In his argumentation for a magmatic origin of iron ores of the Kiruna type, Geijer (1967) has referred to comparisons with the "iron ore-flow" from El Laco, Chile, described by Park Jr. (1961). Park states that the ore is composed of magnetite and hematite, the only impurities being tiny needles of apatite and a few small blebs or patches of silica. The texture of the flow resembles that

[1] The content of some trace elements (Co, Ni) is below the limit of detection (10 ppm). They have been assigned a value of 5 ppm when calculating the Co/Ni ratios.

of basalt flows. The wall-rocks are described as light coloured tuffs, probably nearly dacitic in composition. Park finishes by saying that "A more precise statement of the nature and origin of the Laco deposits must await detailed studies and possibly exploration at depth".

Two hematite ore samples from El Laco have been chemically analysed at the LKAB laboratory in Kiruna. (These hand specimens were kindly supplied by Prof. C. F. Park Jr.) Both ore specimens had a porous slaggy appearance. No textural equivalent of the El Laco ores in known in the Kiruna region. The chemical analyses also show features which differ from those of the Kiruna deposit ores. The determinations produced the following results (%):

	Fe	P	SiO_2	Al_2O_3	CaO	MgO	MnO
Sample I	66.41	0.070	0.93	0.33	0.10	0.15	<0.01
Sample II	66.99	0.79	0.30	0.18	0.03	0.15	<0.01

	Ni	Cr	Co	Cu	Mo	Zn	V	Ti
Sample I	0.13	0.040	0.03	0.005	—	0.003	0.095	0.078
Sample II	0.08	0.40	0.04	0.006	—	0.003	0.090	0.11

The analyses show that phosphorus is not bound to apatite in the El Laco hematite ore, as is the case in the Kiruna deposit ores. Attention should also be drawn to the low SiO_2, MnO values and the high Ni, Cr and Co values in the El Laco hematite samples, compared with the Kiruna ores.

Because important data on El Laco are not available and the available information shows substantial differences in comparison with the data characteristic of the Kiruna deposit ores, the author feels that El Laco cannot be used for definite comparative purposes. However, the extrusive nature of the ores at El Laco is conspicuous.

CLASSIFICATION OF IRON ORES BY HEGEMANN AND ALBRECHT

Hegemann and Albrecht's investigation (1954) of genetically different iron ore types is of interest. The results of their analysis (1954, Fig. 5) of 10 different magnetite types have been published in table form. This table is presented in Fig. 56, together with the new analyses of magnetites from the Kiruna deposit.

The trace element distribution in the main ore bodies of the Kiruna deposit presents a picture which differs completely from that suggested for ore types described as "intramagmatic" (Taberg type), "metamorphic" or "alpine cracks". The most important difference between those ore types and the Kiruna deposit ores lies in the chromium content, which genetically is so characteristic. Only the magnetite in the magnetite-rich inclusions from Kiruna greenstone shows a roughly equivalent chromium value (1 400 ppm). The magnetite from the

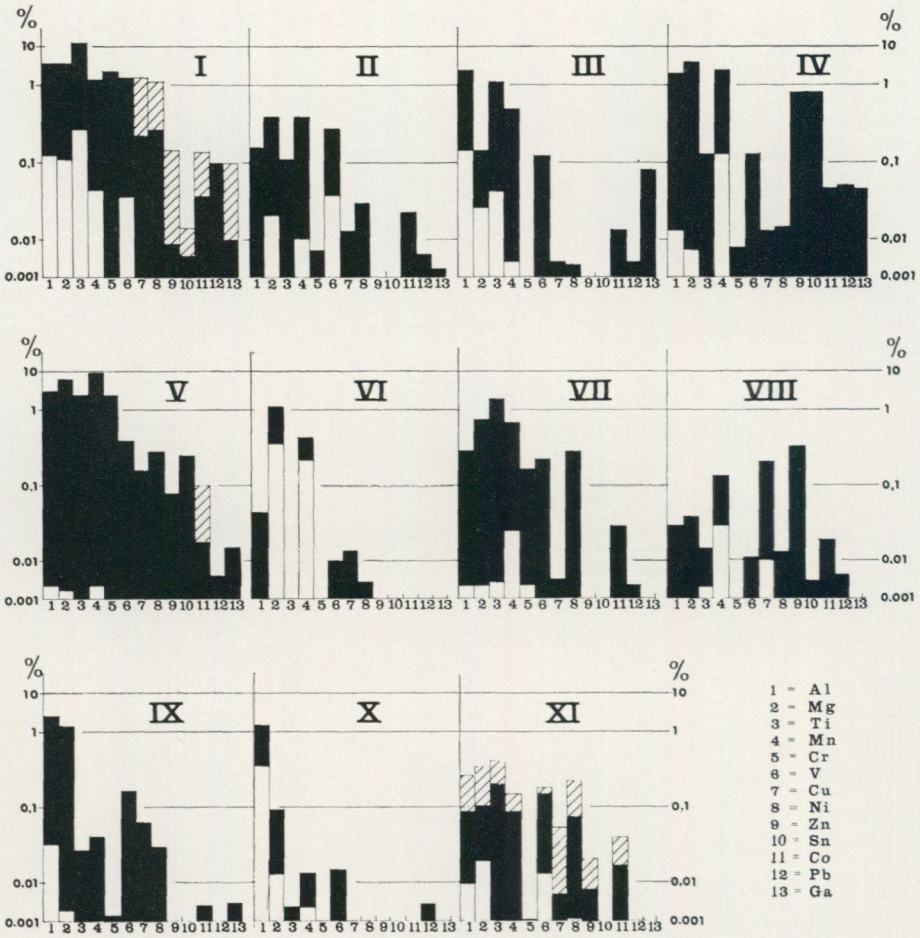

Fig. 56. Contents of trace elements in magnetite from iron ores of different origin. I = intramagmatic, II = intrusive magmatic, III = pegmatitic, IV = contact-pneumatolytic, V = metamorphic, VI = hydrothermal, VII = Alpine cracks, VIII = exhalative, IX = extrusive-submarine, X = sedimentary ('magnetite type' according to Hegemann and Albrecht 1954), XI = magnetite ore from Kiruna area (according to Parák).
Black columns mean range of contents (for XI 90 %), columns with inclined lines highest occasional contents.

Kurravaara conglomerate contains 550 to 345 ppm Cr. The magnetites in the actual main ore bodies contain virtually no chromium (Kiirunavaara 0 ppm and the Per Geijer ore bodies 3 ppm). The formation of the Kiruna deposit ores must therefore be different from that of these ore types, viz. "intramagmatic", "metamorphic" and "alpine cracks".

The "contact-pneumatolytic" type shows considerably higher manganese, zinc, tin and lead values than the Kiruna deposit ores. Only the highly enriched

test material (44 samples), which was taken from boreholes in the Rektorn—Lappmalmen section, was analysed for tin and lead, as indicated in Fig. 37. In the magnetite phase, tin was found in 6 samples (50—150 ppm) and lead in 11 samples (20—140 ppm). In the hematite phase, tin was found in 18 samples, (20—160 ppm) and lead in 6 samples (20—30 ppm). In the gangue, tin was found in 6 samples (30—260 ppm) and lead in 7 samples (20—340 ppm).

The above values thus preclude the Kiruna field ores from having an origin similar to that of the "contact-pneumatolytic" type.

The Co/Ni ratios, the nickel and zinc contents of the "pegmatitic" type, the titanium, vanadium, nickel, zinc and cobalt contents of the "hydrothermal" type and the titanium, manganese, vanadium, copper, nickel, zinc and cobalt contents of the "sedimentary" type suggest a different mode of formation than that of the Kiruna ore bodies.

According to Hegemann and Albrecht (1954), the "exhalative" and "extrusive-submarine" ore types each show certain differences in comparison with the Kiruna deposit ores. However, a combination of these two ore types comes very close to the picture presented by the Kiruna deposit ores. The similarity is of course greatest between the "intrusive-magmatic" type and the Kiruna field ores according to Fig. 56, since Hegemann and Albrecht (1954) used analyses of apatite iron ores from Lapland and central Sweden. The authors therefore called this group "Kiruna type" ore.

Hegemann and Albrecht (op.cit.) conclude that the "Kiruna type" of ore mineralization was probably connected with extrusive-submarine activity. Subsequent metamorphism of various kinds could have given the ore formations their present appearance. However, they admit that their conclusions were drawn merely on geochemical grounds and must be supplemented by thorough geological and tectonical investigations.

DISCUSSION OF THE ORIGIN AND DISTRIBUTION OF APATITE IN THE KIRUNA FIELD ORES

ORIGIN OF THE APATITE

The apatite in the Kiruna field ore bodies was assumed by Geijer to be of magmatic origin. The same was considered to be true for the apatite in other Precambrian apatite iron ores. In the paper in which Geijer discusses the significant minor occurrence of apatite in the Precambrian sedimentary formations, he states (Geijer, p. 166) that sedimentary concentrations of phosphorus are virtually absent in the Precambrian. (Only two exceptions are mentioned, viz. "concretions" from the Grythyttan slate, belonging to the leptite formation in central Sweden and "nodules" from the Visingsö formation in southern Sweden.)

Somewhat later, however, Davidson (1963) presented new data, which show that phosphorus may be enriched in old Precambrian. For example, the "Pretoria Series in South Africa", which, according to determination of the "radiometric age" must be at least 2 000 million years old. Geijer (1962, p. 169) reports more than 0.5 % P for the sediments from this series. According to Davidson, "the important bedded iron ores in the Fig Tree Series of Swaziland, occurring amid the oldest known sediments recently dated at more than 3 440 ± 300 m.y., range in 14 analyses from 0.05 % to 0.71 % (average 0.18 %) P_2O_5, values which although relatively low are quite within the range found in some fossiliferous ironstones".

Information on Precambrian sedimentary formations which are rich in phosphorus has recently been supplemented with examples from Sweden. Sedimentary phosphorites were found by the Geological Survey of Sweden at Påläng in southeastern Norrbotten on drilling a radioactivity anomaly. The bedrock at this point consists of schistose, fine-grained stratified sediment which alternates with dolomitic limestone. Very low-grade iron ore mineralizations are found in different layers. In this series, phosphorite-rich interbeds 1 m thick are found, containing up to 10 % P_2O_5. According to Welin (1970), these rocks are dated at more than 1 880 million years, which is higher than the Kiruna volcanics.

It has frequently been discussed whether or not organic activity has been important in old phosphorus concentrations. As mentioned previously, a 14 m thick graphite schist, together with other sediments, was found in the Kiruna greenstone at Valkeasiipivaara. Since these greenstones lie under the Kurravaara conglomerate, living organisms must have been active before the formation of the apatite iron ores. Thus the participation of micro-organisms in the deposition of phosphate cannot be excluded.

In view of the above, there is reason to regard the sedimentary process as a probable alternative in further discussion of the origin of the apatite. The reason for this can be further stressed as follows.

Landergren (1936, 1948) has discussed the formation of the apatite iron ores. In his geochemical work, he has, among other things, analysed the apatite ores and compared them with other iron ores of varying origin. In Landergren's test material from northern Sweden, the Kiruna deposit was represented by three apatite-rich and four apatite-poor ore samples. Landergren (1948, p. 172) commented as follows on the investigation results: "All the geochemical features indicate that the author's conception regarding the formation of the apatite iron ores of central Sweden (Grängesberg) can be applied also to the origin of the apatite iron ores of northern Sweden" and (p. 171): "... the origin of the Kiruna ores cannot be regarded as the result of a primary magmatic differentiation..."

DISTRIBUTION OF THE APATITE

Geological observations

Many publications deal with the relationship between apatite and ore minerals in the Kiruna ore. One example is Geijer's (1924) paper in which it is stated that the proportion of phosphorus-poor ore increases with increasing depth at Kiirunavaara. Several of the publications include a description of the different structural elements which are the result of a mechanism which distributed the apatite and ore minerals in these ore bodies.

In recent years there have been increasing demands for mining operations to be carried out more selectively with regard to the phosphorus content of the ore. Consequently, mapping of the phosphorus distribution in the ores has improved. The method is based on systematic detailed drilling of the ore, after which analyses of the core material are entered on "phosphorus" or "quality" maps. In part, these investigations have provided a new picture of the phosphorus distribution in the apatite iron ores of the Kiruna field. In addition, core samples of previously unknown or univestigated phosphorus ores in the Kiruna field (Nukutusvaara, Henry, Haukivaara, Lappmalmen, Luossajärvi) have been taken.

The structural elements which directly affect apatite and magnetite distribution in the ores have been described by Geijer (1967). A detailed description of these phenomena will therefore not be given here. Instead, reference should be made to the relevant works by Geijer (see Part 2 and the appended references).

The apatite and the ore minerals (both magnetite and hematite) show a rapidly changing composition (lamellation) which Geijer (1910) termed "stratified ore". However, this term was changed by Geijer (1967, p. 6) for the following reasons: "Stratified" implies a genetic interpretation which is clearly not applicable; besides there are transitions to a more streaky distribution of the two components, magnetite and apatite". This lamellation of apatite and magnetite generally conforms to the strike and dip of the ore bodies (Fig. 57). The thickness of the individual lamellae varies and is usually more than 1 mm. Here and there, apatite occurs in the form of layers several decimetres thick in the ore body. Here again they conform to the strike and dip of the ore bodies (Fig. 58).

In his discussions of the apatite ore lamination, Geijer admits that this pattern could be taken to suggest a sedimentary origin for the ores. On behalf of his arguments for a magmatic-intrusive origin, however, he rejects this possibility. One alternative explanation would according to Geijer be some kind of rhythmic crystallization. The most probable interpretation is, however, according to Geijer, that lamination originated through flow movements in the still plastic mass, which would more easily be comprehended if apatite crystallized prior to the ore minerals. On the other hand, Geijer (1931 b, p. 7) states

Fig. 57. Stratified hematite ore. Henry. Photo B. Rönnberg.

that in general the apatite has crystallized later than magnetite. Therefore there must have been two different phases of apatite formation.

Nevertheless, in the new exposures of the "stratified" ore type, examples have been found where the apatite-magnetite (hematite) distribution in the ore bodies closely resembles graded bedding (Figs. 59 and 60). Apatite bands with this texture are most common in the Per Geijer ore bodies but are also found in other ore bodies. Discordant bedding has also been observed in places within the "stratified" ore bodies.

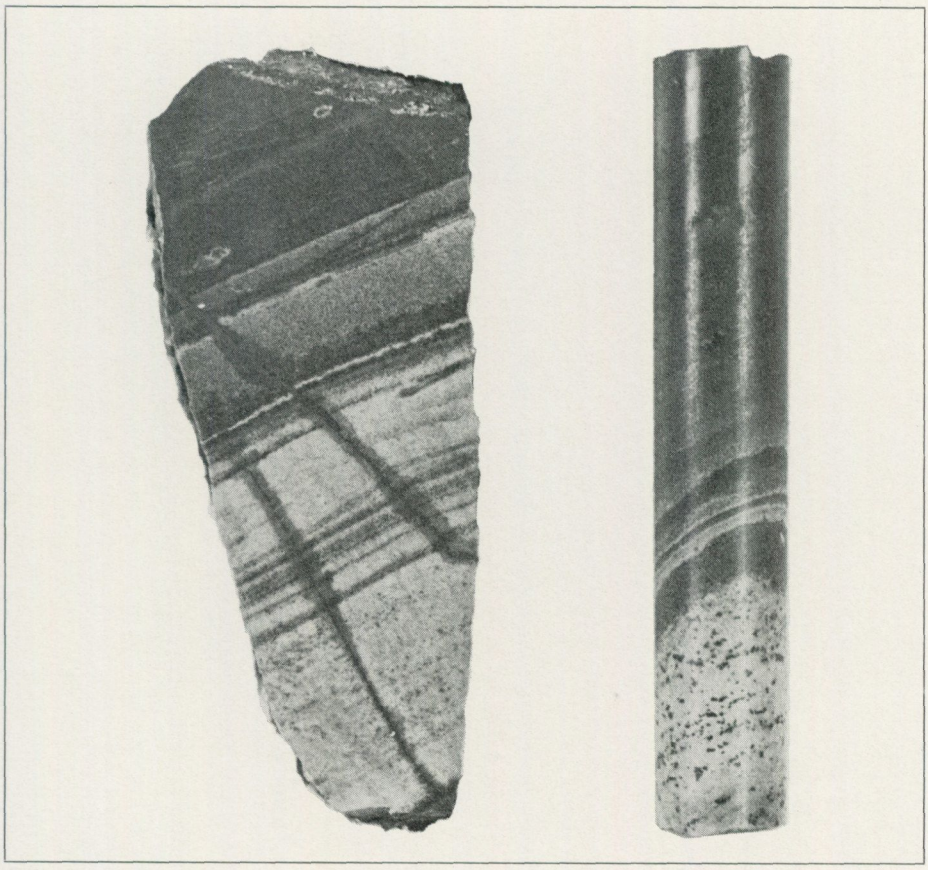

Fig. 58. Banding of apatite in hematite ore and in magnetite ore (left from Henry, right from Lappmalmen).

In the author's opinion *it is impossible for structures such as lamellation, the graded bedding-like texture and the cross-bedding to originate from an "apatite ore-magma", in which the apatite crystallized before the magnetite.* It must be remembered here that the ore containing no apatite also shows stratification in places.

It has been pointed out above that the boundary between the apatite-rich and apatite-poor ores is usually sharp. Continuous transitions from a very apatite-rich ore to an ore with a moderate apatite content nevertheless do occur. These changes can often be observed in apatite-banded ores in which the transition from a high apatite content to a low apatite content takes place gradually in each band (Figs. 59 and 60).

Another ore type composed of apatite and magnetite, which Geijer referred to as "skeleton ore", is found here and there in the apatite-rich ore. Still

Fig. 59. Photo showing the distribution of apatite and hematite in a banded apatite-ore. Nukutusvaara.

another ore type which is spotted with apatite and has an appearance similar to amygdaloidal porphyry is also found locally (Fig. 61). The composition of these ores is identical to that of the apatite-banded ore. Only the textural properties

Fig. 60. Photo showing the distribution of apatite and hematite in the bands of the apatite-banded ore. Henry.

argue against an identical genetic mechanism. Since the "skeleton ore" and the "spotted ore" are often found included in the apatite-banded ores, it is remarkable that these ore types were able to avoid "rolling out in layers" (Geijer, 1910, 1967). According to the intrusive magmatic theory, their appearance in the apatite-rich ore would in fact have taken place at the same temperatures and pressures as those prevailing during intrusion of the other ores.

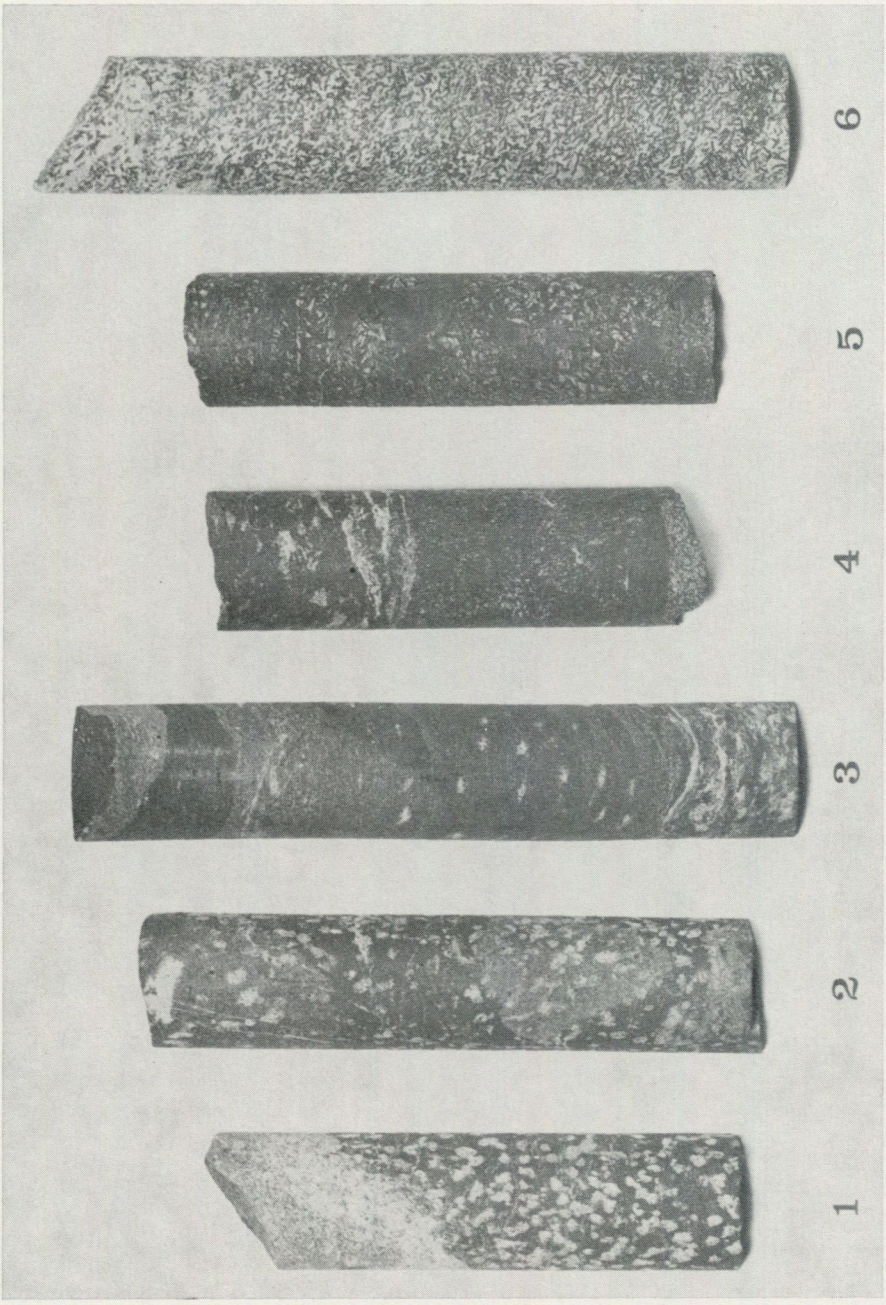

Fig. 61. Apatite-spotted ore (1—3) and skeleton ore (4—6) from the Per Geijer ores. 1 = drill hole 408, 2 = drill hole 482, 3 = drill hole 409, 4 = drill hole 258, 5 = drill hole 333, 6 = drill hole 1117.

Formation of the textures of the "skeleton ore" and the "spotted ore" can possibly be explained as a result of mineralization in a colloidal state. The circumstances prevailing during supracrustal (exhalative-sedimentary) ore formation provide excellent conditions for the formation of such textures since rapid changes can take place in the conditions under which the ore substancs are distributed and deposited. The transition from a solution (suspension-colloidal) to a solid phase is controlled by several factors. This subject will be dealt with in greater detail in the section headed "Sedimentation related to volcanic activity".

Geijer states that apatite crystallized during two distinct phases, one before and the other after the crystallization of the magnetite. Geijer (1931b, p. 7), like Lundbohm and Stutzer before him, states that "In general, the apatite has crystallized later than the magnetite. Thus there are often seen irregular streaks and veins of pure apatite, or of apatite mixed with some magnetite, which brecciate the richer magnetite ore. A very striking texture is represented by arborescent skeleton crystal growths of magnetite in a mass of apatite". In the same paper and on the same page, he further states that, "A most peculiar variety is the *stratified ore* (16), in which the apatite has crystallized before the bulk of the magnetite" (16) (see Geijer 1910).

Field observations show that the "skeleton ore" generally occurs in the apatite-banded (lamellated) ore. The chemistry of these ore types is identical. They differ only in their structural appearance. The idea described above of two apatite crystallization phases would thus imply that the apatite both began and terminated the ore formation process. This is a remarkable conclusion. In view of the temperature and pressure conditions of the ore magma, with its high water content, one would expect fusion, structural change or at least dissolving of the edges close to the newly injected ore magma. Such phenomena have not been observed.

Another phenomenon is the occurrence of the apatite crystals in a way described by Geijer (1931 b, p. 7) as a fluidal arangement of the apatite grains. This texture appears only when the apatite forms small, thin prisms, which can be arranged in typical "trachytoidal whirls". From the lamellated ore, Geijer (1967, p. 7) states that ". . . a single lamella, or a few in succession, are moderately plicated, without this deformation having visibly affected those above and below. In one case I have observed that a band of apatite sent out one thin vein upwards and one downwards at the same point."

Such phenomena are known from several localities and occur in connection with tectonical movements, and mobilization associated with these. Thus they are younger than the ore formation. Figures 62, 63 and 64 show how these movements can deform an apatite band. Here and there along movement-planes, "apophyses" can also be observed (Fig. 65). "Fluidal-like structures" also occur in places in connection with deformation.

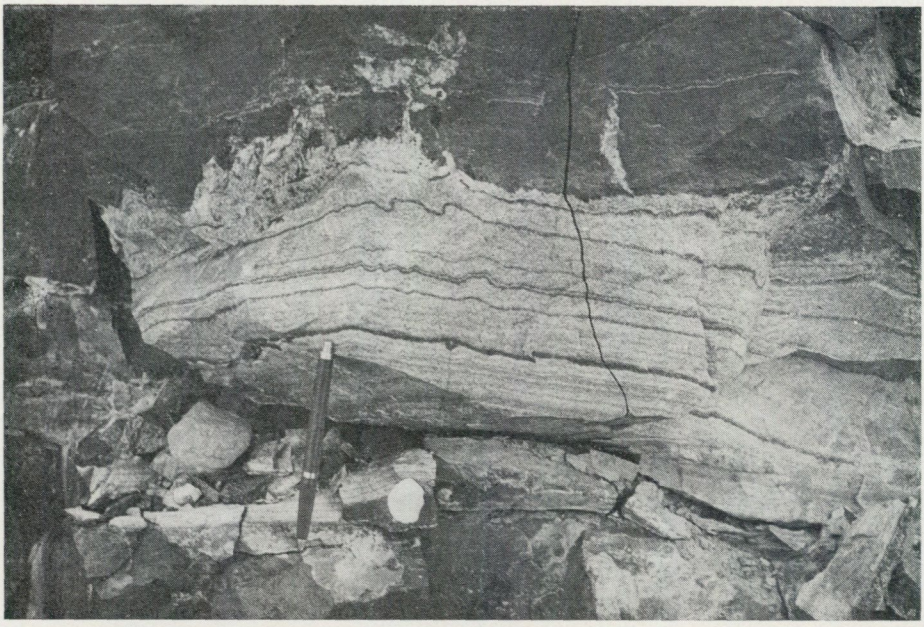

Fig. 62. Minor folding in an apatite band. Nukutusvaara.

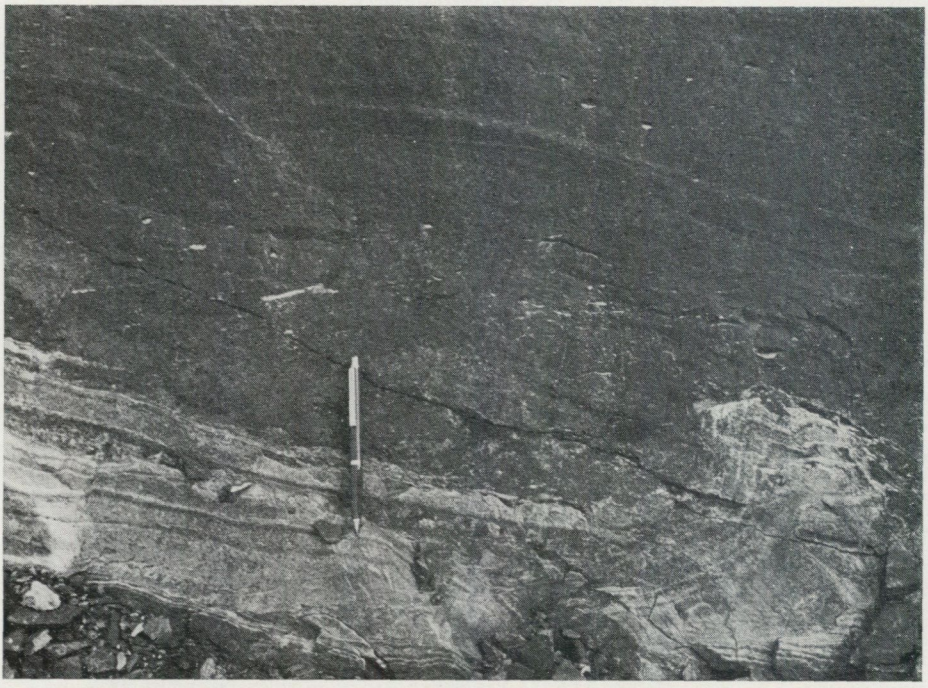

Fig. 63. Photo showing the deformation effect of a small fault on an apatite band in the magnetite ore. Nukutusvaara.

Fig. 64. Folded apatite band in magnetite ore. Nukutusvaara.

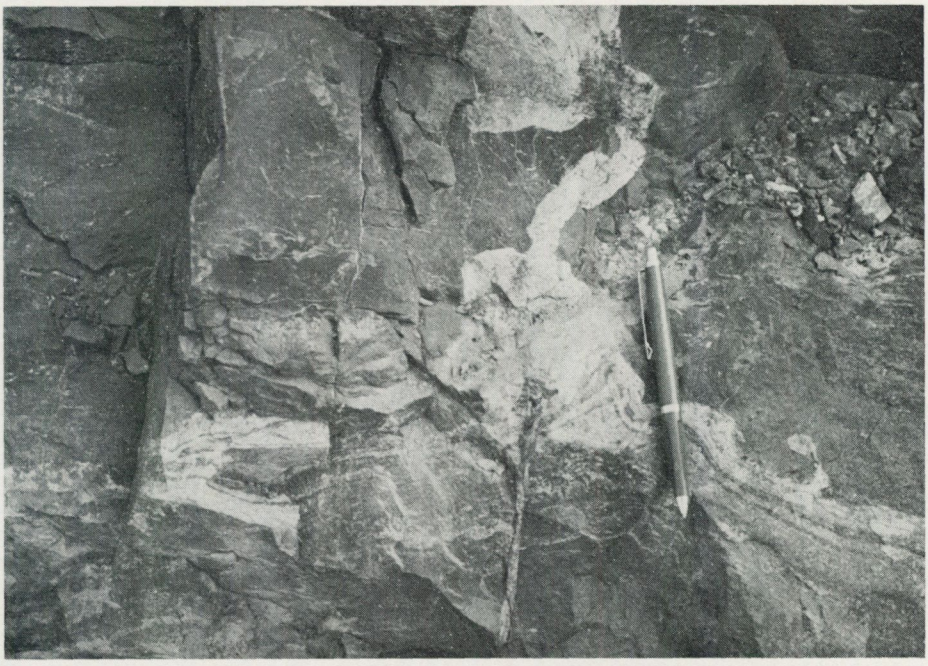

Fig. 65. "Apophyse" from an apatite band. Nukutusvaara.

Fig. 66. "Offshoot" from an apatite band brecciating the ore. Nukutusvaara.

In the opinion of the author, the apatite was thus mobilized in connection with tectonic deformation. In some cases the mobilization could be so far-reaching that only fragments of magnetite (hematite) remained in the apatite material (Fig. 66). The apatite in such localities is mostly red or green and is coarser grained than the "normal" light grey apatite. It is possible that such mobilizations account for at least some of the two apatite generations in Geijer's interpretations.

Apatite which occurs in a similar way described by Geijer from Malmberget (1930, p. 37) and from Ekströmsberg (Geijer 1912).

Geochemical data and considerations

Analyses were carried out on 103 samples of phosphorus-rich ore and 70 samples of phosphorus-poor ore. Tre results are given in Tables 35—38, which

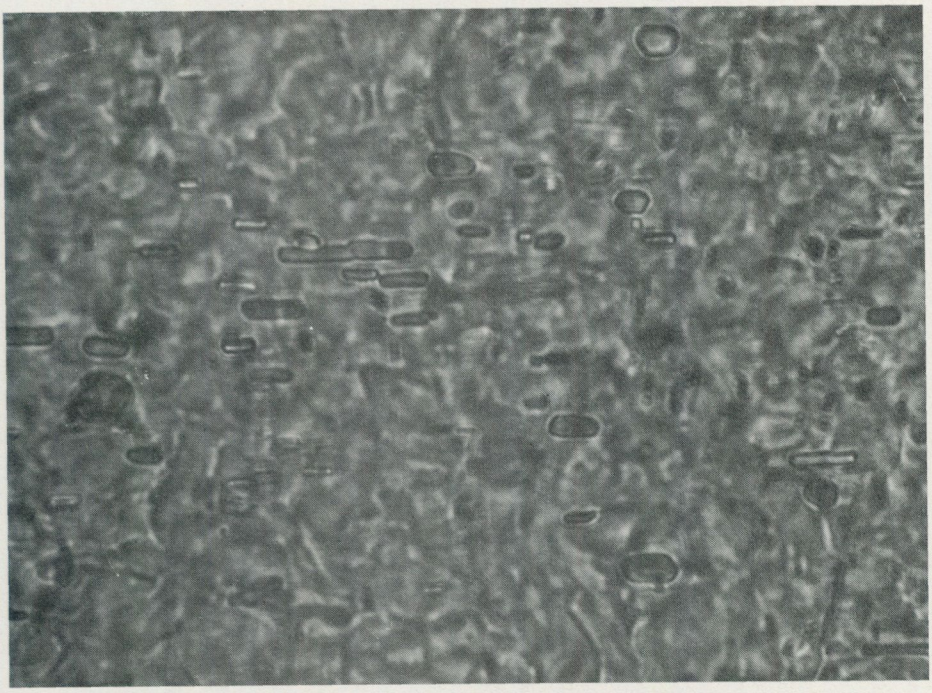

Fig. 67. Inclusions of monazite in apatite. Kiirunavaara. 672 x.

indicate the distribution of trace elements in the two ore types. A detailed account of the distribution of various elements in the Kiruna field ores is given on pp. 60—75. Only a summary comparison of the different ore types will be made below.

The trace element investigation revealed a geochemical difference between the phosphorus-rich and the phosphorus-poor ore types. Table 38 shows that ferrides in the phosphorus-rich ore type total 2 685 ppm (and 3 555 ppm for all 12 trace elements) while the corresponding total for the phosphorus-poor ore types is 2 230 ppm (and 2 790 ppm for all 12 trace elements). The reason for this difference is that zinc, titanium, vanadium, manganese, cobalt (also nickel with a slight excess when all the magnetite and hematite samples are combined) and magnesium are enriched in the apatite-rich ore type (Tables 35—38). The aluminium content alone was found to be higher in the apatite-poor ore while the copper content was the same in both ore types.

In connection with the investigation of the content of rare earth metals in apatite (Parák, 1973), small needles of monazite were observed in the apatite grains (according to Dr. T. Ekström, Uppsala). The monazite needles are orientated parallel to the C-axis of the apatite (Fig. 67). The C-axes of the individual apatite crystals on the other hand apparently lie in varying directions

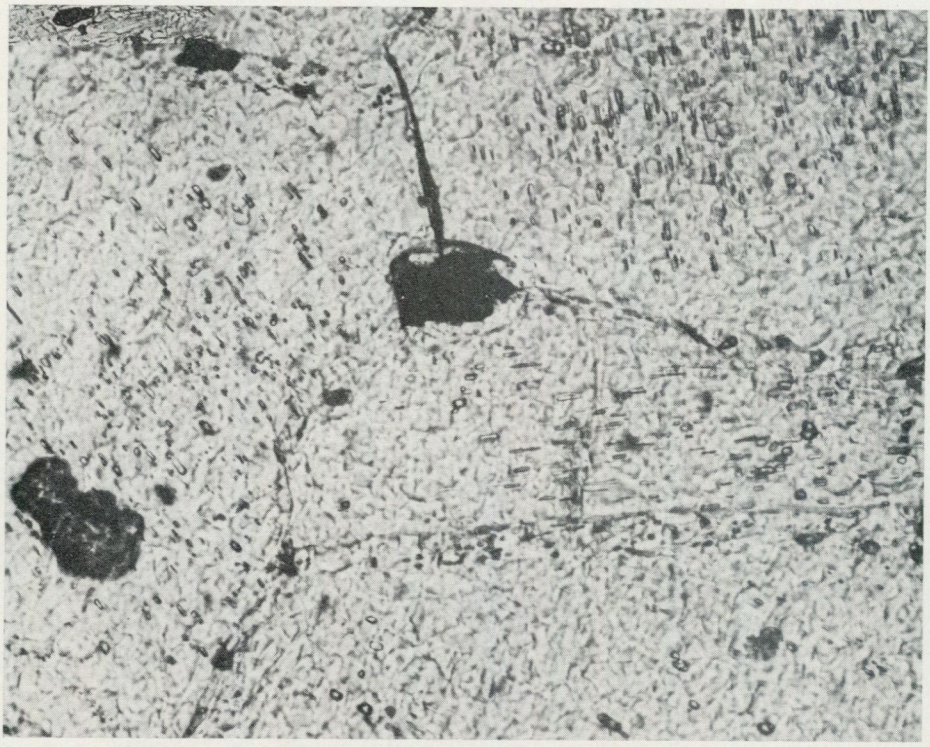

Fig. 68. Inclusions of monazite oriented in different directions in the apatite grains. Kiirunavaara. 280 x.

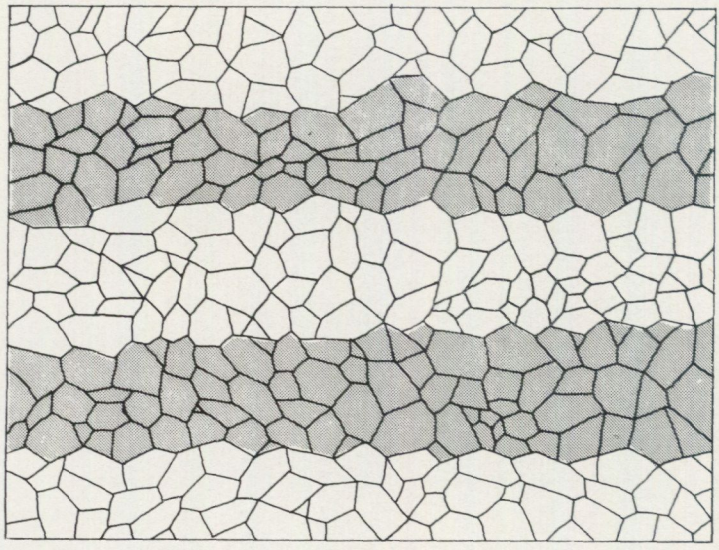

Fig. 69. Banding of apatite with monazite inclusions in the monazite-free (or manazite-poor) apatite. Kiirunavaara.

(Fig. 68). However, the apatite crystals which contain these inclusions occur in bands parallel to the apatite layer (Fig. 69).

The apatites of the Kiruna deposits contain slightly more than 0.5 % rare earth metals. Determinations were carried out on apatites or apatite concentrate for all the rare earth metals (and yttrium) in 19 cases and for yttrium, lanthanum and cerium in 44 cases. The analyses values were then compared with available information on rock types of varying origin (from magmatic to sedimentary). The results of these comparative studies indicate that the Kiruna apatites are closer related to sedimentary than to magmatic phosphates.

Geochemical analyses of the Kiruna field ores do not support the hypothesis of a magmatic differentiation process with different intrusions in which an apatite-rich ore was preceeded by an apatite-poor ore.

RELATIONS BETWEEN MAGNETITE AND HEMATITE

GEOLOGICAL OBSERVATIONS

Drilling in recent years has revealed a significant amount of hematite in the Kiirunavaara ore body. A section of hematite was also found in the Luossajärvi magnetite ore and a presumably isolated hematite ore has been located at Tuolluvaara. Hematite ore thus constitutes an important part of the ores in the Kiruna field.

On the basis of the relations shown between magnetite and hematite ores in the Kiruna deposit, these two ore types can be divided into the following groups:

1. *Hematite ore enclosed by magnetite ore.* This relationship is found in the Luossajärvi ore where the central part of the ore body consists of hematite. Approximately 36 m of hematite ore is enclosed by about 20 m of magnetite ore on each side. At Kiirunavaara, up to 25 m of hematite ore in magnetite ore is found in places. At Tuolluvaara, hematite occurs in the form of lumps to a few decimetres in size or as fissure fillings in the magnetite ore.

2. *Hematite ore side by side with magnetite ore.* In this case it is always the hematite ore which occurs in that section of the main ore body which is adjacent to the hanging wall. This group includes Rektorn and Lappmalmen. Nukutusvaara should probably also be included. However, the picture presented by this deposit is not very clear, since the ore has been affected by subsequent displacements. Magnetite is also found in the Henry ore body in the western part of the deposit.

The quartz-banded ores consist of both hematite and magnetite in varying proportions. However, the overall proportion of hematite increases towards the hanging wall. In addition, both hematite and magnetite occur in the form of

lenses, bands or unevenly distributed grains in the iron oxide impregnations in the Lower Hauki rocks.

3. *Hematite ore as independent ore bodies.* The Haukivaara deposit can be included in this group. In this ore body, however, hematite occurs with a small admixture of magnetite, which increases with increasing depth. The hematite ore (Vietnam ore) found in the vicinity of Tuolluvaara should, like Hauki hematite, be included in this group.

DISCUSSION AND THE GEOCHEMICAL DATA

Primary and secondary hematite ores have been mentioned earlier in the literature (Geijer 1910, 1950, 1960; Frietsch 1967, 1970; Ekström 1967). Martitization on a small scale is also known in these ores. In the descriptions, the ores are suggested to have originated through magmatic processes, or as in the case of the Hauki hematites, hydrothermal processes. A secondary phase is assumed to have arisen by metasomatic alteration and martitization of the primary magnetite.

Frietsch (1967) considered hematite — at least in some deposits (among others Haukivaara, Henry, Nukutusvaara, Rektorn) — to be formed from magnetite, and suggested that the transformations were due to oxidizing solutions which also could bring about metasomatic transformations of the wall-rocks. There should be no additional exchange of elements between the iron minerals. They ought to be expected to have the same trace element composition.

In the present investigation of the Kiruna district, it was not possible to establish any relationship in space between alteration of the wall-rock and alteration of the magnetite to hematite. This applies both to the main ore bodies and the impregnations of the wall-rock. It may be stated that magnetite ore lies on an altered quartz-bearing porphyry (Rektorn) whereas hematite ore lies on an unaltered quartz-bearing porphyry (Henry).

Hematite impregnations in the sericite quartzite or in the other Lower Hauki rock types cannot be related to a later alteration of the wall-rock. In fact magnetite impregnations, often together with hematite impregnations, occur in the same rock types and even in the same rock sections.

Microscopical investigations show substantial agreement between the apatite-rich hematite ores in the Kiirunavaara, Luossajärvi and Tuolluvaara magnetite ores on the one hand and the apatite-rich hematite ores in the magnetite of the Per Geijer ore bodies on the other. Well-defined hematite grains can sometimes be observed in a magnetite ore (Fig. 70). In other cases, recrystallization of the ore can be noted. In such cases, the grain boundaries are completely obliterated and the crystal form can then only be discerned in the "magnetite islands" formed by recrystallization. (Figs. 71 and 72). The apatite is usually driven to

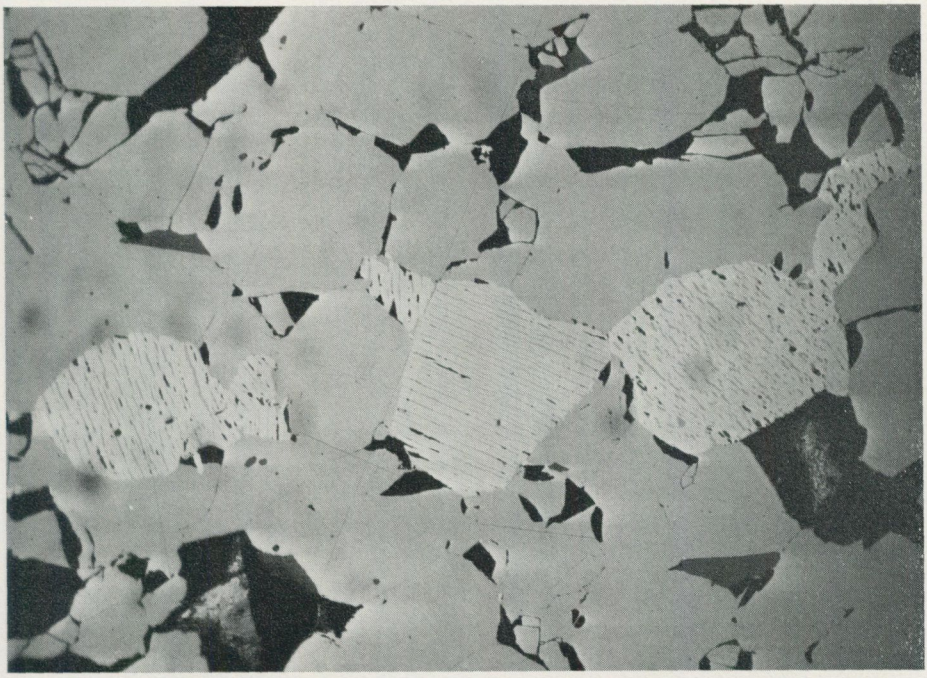

Fig. 70. Grains of hematite with lamellæ of magnetite in magnetite ore. Tuolluvaara, drill hole 249. 100 x.

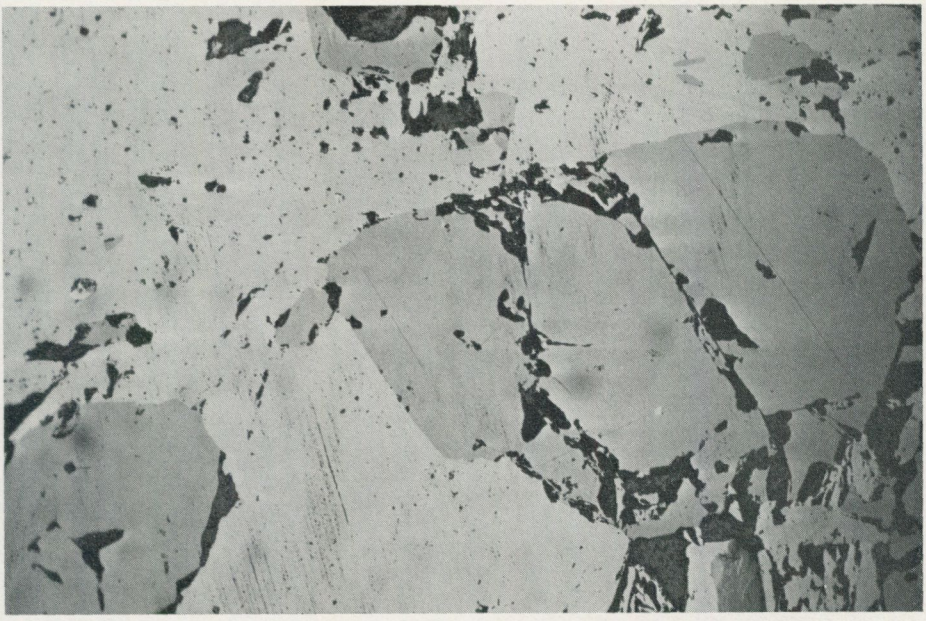

Fig. 71. Aggregate of magnetite-apatite in hematite ore. Lappmalmen, drill hole 333. 100 x.

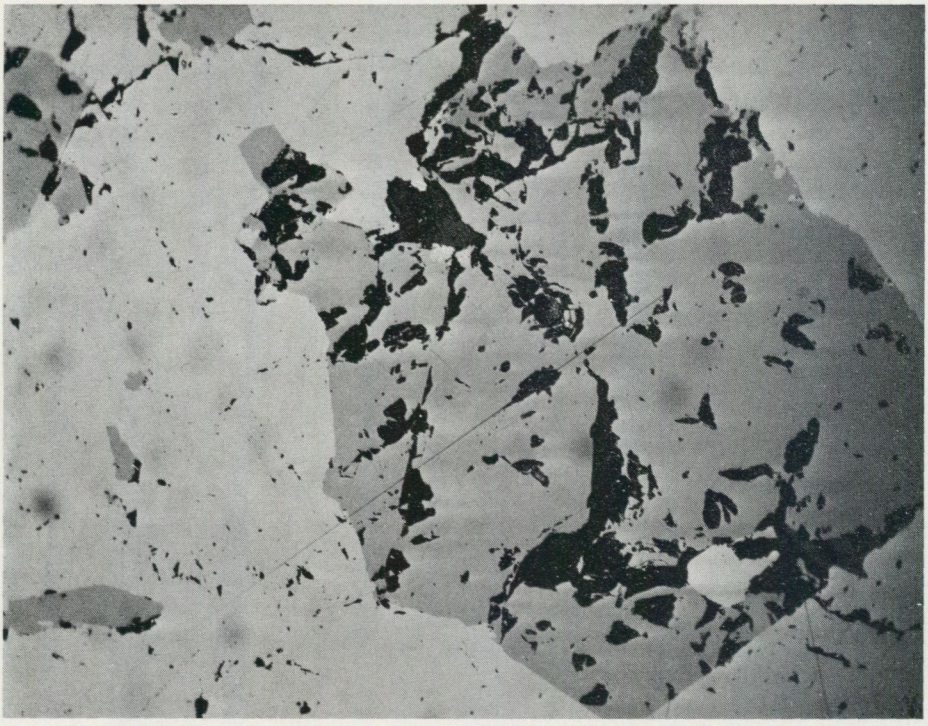

Fig. 72. Aggregate of magnetite-apatite in hematite ore. Tuolluvaara, drill hole 249. 100 x.

the magnetite. There is a big difference between the amount of apatite in the altered ore and that found in these "magnetite islands". This phenomenon was found in the hematite ore, regardless of the ore bodies from which the samples were taken.

As part of the geochemical investigation of trace elements in the magnetites and hematites from the Kiruna field, 60 samples with co-existing iron oxides were analysed. The samples were compared with monotype magnetites (128 samples) and hematites (45 samples). Thirty of the co-existing samples were taken from the main ore bodies. The most comprehensive material comes from the Per Geijer ore bodies (22 samples).

The result of these analyses are presented in Tables 39—43. Of the monotype sample results (Table 41), only those sample groups which are also represented by co-existing specimens, have been included.

The difference in the trace element content between magnetite and hematite is great. The median value for the ferrides is 2 235 ppm in magnetite and 3 400 ppm in hematite. If magnetite constituted the primary phase, there is no reason why that part of it which was oxidized to hematite should have a higher trace element content than the unaltered part.

The following median values (in ppm) were obtained for the trace elements in magnetites and hematites from the main ore bodies (Luossavaara is not included):

	Cu	Zn	Ti	V	Cr	Mn	Co	Ni	Al	Mg
Magnetite	20	40	550	1000	0	320	95	270	200	600
Hematite	30	60	2100	1200	0	60	20	20	500	100

The table below shows the approximate degree of enrichment of all the elements found in the various sample groups:

	Cu	Zn	Ti	V	Mn	Co	Ni	Al	Mg
Monotype magnetite	1	2	2	3	4	4	3	3(2)	4
"Co-existing" magnetite	3	1	1	2	3	3	4	1	2
"Co-existing" hematite	2	3	4	4	1	2	1	2(3)	1
Monotype hematite	4	4	3	1	2	1	2	4	3

1 means lowest and 4 highest degree of enrichment.

The table shows that the degree of enrichment of the elements, with the exception of zinc and, to a certain extent, aluminium, differ from that of titanium, and vanadium. Manganese, cobalt, nickel and magnesium are predominant in the magnetite. The table nevertheless indicates a possible migration of cobalt. Monotype hematite shows the highest copper, zinc and aluminium values.

Titanium and vanadium are far more enriched in the hematite co-existing with magnetite than in the other hematites and magnetites. This is true for ore minerals from both the main ore bodies and from the wall-rock. It also applies to titanium in the highly enriched test material (Table 40).

The analyses show that titanium in the magnetite co-existing with hematite is "deficient" in comparison with the monotype magnetite. The results do not in themselves preclude titanium migration from the magnetite to the hematite. The highest and lowest titanium values were in fact obtained for hematite and magnetite of the co-existing type, respectively.

The trace element distribution in ores from different ore bodies in the Kiruna field thus shows a common feature, which is in full agreement with the microscopical investigation. This also indicates similar conditions of formation. Only the Tuolluvaara test material constitutes an exception when all 12 elements are combined (Table 42). This is due to two samples which represent the monotype hematites.

Discussing the trace element contents of the Missouri iron ores, Kisvarsányi and Proctor (1967, p. 460) state that "Theoretically, a primary hematite crystallizing from the same melt as magnetite should contain smaller amounts of trace elements than the magnetite. This is predictable from the crystal structure, because hematite has fewer positions with varied properties available for substitution than magnetite. However, if hematite is secondary and formed by the transformation of lattice, it should accommodate ions inherited from the original magnetite".

If these considerations are applied to the ores of the Kiruna field, the hematites in the apatite-rich ore type could not be primary, at least not of a magmatically primary origin. The high trace element content in the hematite should reveal that in this instance a magnetite of primary origin is involved.

It is the author's opinion that the hematite ores in the Kiruna field — excluding martite — are of primary origin. Their origin cannot — as in the case of martitization — be associated with tectonic movements, in which a mechanical process made it possible for solutions with a high oxygen content to oxidize the magnetite ore.

The hematites in the Kiirunavaara ore body and in the Per Geijer ores have the same mineralogical-geochemical characteristics. If an intrusive theory is accepted, their stratigraphic position in the Kiruna iron ores, compared with that of the magnetic ores, would involve a complicated and far-fetched reconstruction of their origin.

The present investigation has clearly shown that the origin of the iron ores at Kiruna must be interpreted as supracrustal.

SEDIMENTATION RELATED TO VOLCANIC ACTIVITY; A COMPARATIVE STUDY

INTRODUCTION

The deposition of the ore minerals, or more specifically iron oxides and apatite, might occur in different ways, which may also include magmatic-extrusive processes.

In his monograph, Geijer (1910, p. 269) states that, "The *mise en place* of the Kiirunavaara—Luossavaara ores is believed by the writer to have been as follows. After the solidification of the syenite out-flow, during the period of eruption of the syenite-porphyry dikes, there have taken place eruptions of magnetite, spreading out as somewhat irregular lava beds. These eruptions were followed by a comparatively slight fumarolic action. That only little water emanated is shown by the fact that the foot-wall rocks are but little metamorphosed. The much complicated outlines of the feldspars in some rocks in

the very wall may perhaps depend on metamorphism. It is impossible to determine whether the ore beds are made up each of one or several eruptions, though the last-mentioned origin seems quite probable at least as regards Kiirunavaara."

This theory was, however, criticized by many geologists and Geijer (1919, 1967) himself admits that this interpretation has several weaknesses. At the same time, however, he poins out that the discovery of the surface flows of magnetite at El Laco support the magmatic theory.

The author agrees with Geijer (1910) in regarding the Kiruna ores as supracrustal formations. The Kiruna field ores can, however, scarcely have arisen from an extrusion of ore-lava. The structural-textural composition of the ores is inconsistent with this. The ore bodies must therefore be regarded as chemically deposited formations with minor mechanical sedimentation.

Interpretation of the Kiruna ores in this way suggests of course that the same genetic theory should be applied to the other apatite iron ores in Lapland which are similar in formation to the Kiruna deposit ores.

COMPARISON WITH OTHER AREAS FROM NORTHERN SWEDEN

The bedrock around the apatite-rich iron ores — and the Hauki type iron ores — is chiefly made up of soda-dominant, or to a lesser degree potassic, porphyries. Because transitional types are present, these rock types cannot always be distinguished. The distribution of these rock types varies from ore deposit to ore deposit. In some areas only one type is found.

The primary features of these rock types are obliterated to varying degrees by metamorphism, which is the reason why preservation of primary structures varies from place to place. For example, it can be mentioned that the volcanites are best preserved around Ekströmsberg (WSW of Kiruna), whereas the original texture is almost completely obliterated in the eastern part of the Kiruna field (the Tuolluvaara area).

The Ekströmsberg ore deposit, which resembles some of the ores of the Kiruna district, could well be worth comparative examination because of the well-preserved original features in the rocks.

At Ekströmsberg, the ores occur as parallel beds which alternate with porphyry. The porphyry resembles the quartz-bearing porphyries of the Kiruna field. According to Geijer (1912), the porphyries at Ekströmsberg are certainly extrusive. Even syenite-porphyry, partly rich in magnetite, occurs to a lesser extent. Geijer (op.cit.) also states that a fluidal structure of primary origin and in some place bands of a greyish or bluish-white quartz up to 1 m in width appear. "Offshoots" have never been reported from this deposit.

Reference is also made (p. 737) to "an originally coarsely crystalline apatite band showing the effects of mechanical granulation in an uncommonly perfect

development". Geijer (op.cit., pp. 742 and 743) states that veins of hematite and apatite stripes consisting of a fine-grained mixture of apatite and quartz occur in magnetite ore at Ekströmsberg. The quartz is said to be of secondary origin. With regard to the origin of the hematite, it is stated (Geijer, 1912) that the hematite ores are as closely associated with the porphyry as the magnetite beds. "There are many factors at a surface eruption (perhaps even submarine!) that may cause the iron compounds to crystallize now as magnetite, now as hematite."

The Kuosatvare deposit, which is situated approximately 20 km SSE of Ekströmsberg, provides further evidence of ore sedimentation in the porphyry epoch. Geijer (1931, pp. 139 and 140) gives such a detailed description of this ore that its origin cannot be doubted.

The exposed part of the ore-bearing zone is approximately 1 500 m long (Frietsch 1966, p. 255). The zone is included in a dark grey basic syenite-porphyry, or albitophyre. No faults are visible in the numerous exposures. The zone consists of two chief constituents, namely a stratified, light blue-grey rock and ore. The former consists of albitic feldspar and iron glance together with apatite, muscovite, rutile and a few thin layers of microline. The ore has a conglomeratic character, with pebbles of hematite up to a few decimetres in diameter. With regard to the origin of the deposit, Geijer (1931) states that the material in the ore zone clearly originates from a deposit most closely resembling Haukivaara.

Geijer (1931, p. 136) also mentions a smaller hematite deposit at Skuokimjokk (8 km SE of Ekströmsberg) which is equivalent to Ekströmsberg.

In his description of Norrbotten County, Ödman (1957) has provided valuable information on the volcanites and sediments which form the bedrock in this area. In addition to lava-breccias, tuffs and conglomerates, Ödman mentions limestones which occur in the volcanites of the Kiruna—Arvidsjaur complex.

"Limestone also occurs in association with volcanic sediments, e.g. to the east and northeast of Aktsek. The limestones, which form a fairly constant horizon in the Ultevis area, are in close association with acid and basic lavas and tuffite sediments, ..." (translated from Swedish).

Ödman (1957) gives only a brief summary of the ores. The hematite ores which occur next to the apatite iron ores at Ekströmsberg and Skuokimjokk are placed in the apatite iron ore group by Geijer, whereas Ödman includes these hematite ores in the sedimentary iron ore group.

In his description of the Kiruna region, Offerberg (1967) gives a more detailed picture of the volcanites and of the mechanical and chemical sedimentary formations occurring in them. Offerberg (1967, p. 85) states that the sedimentary intercalations in the porphyries (Kiruna porphyries and their equivalents) are numerous, but they form no key-horizons.

Offerberg (1967) reports, among other things, that small pebbles of hematite ore are found in places to the southeast of Kamastjärro. The Eustillako sediments — the thickness of which is said to be at least 150 m in places — are intercalated by several acid and intermediate volcanites. The pebble material is said to include magnetite-syenite-porphyry and skarn. The sediments, which are rich in quartz, also include felspar, hornblende, magnetite, titanite and less frequently epidote, apatite, mica and a little tourmaline, chlorite and zircon. The sediments are composed of everything from coarse conglomerate to mudstone-type rocks, limestone and quartzite ("probably chemical sediment"). Cross-bedding and graded bedding are also mentioned to occur frequently in the sediments.

COMPARISON WITH AREAS OUTSIDE SWEDEN

Sedimentary iron ores as intercalations in volcanites are known from both Precambrian and younger rock. One of the most famous examples is quartz-banded ores occurring in the region of Lake Superior. Although a number of different theories have been formulated concerning the origin of these ores, all geologists agree that they are sedimentary in origin. The theories include some which assume a mechanical sedimentation process, but most assume chemical precipitation. Varying importance is attached to the contribution made by bacteria. Theories favouring ore genesis by leaching of volcanic rocks also exist. A number of geologists assume the presence of a colloidal state prior to precipitation.

In this respect, the author would like to draw attention to the Michipicoten district in the Lake Superior area. The volcanic environment of the ores of this deposit shows great similarity to the conditions in the Kiruna field.

The following quotation from a paper by Goodwin (1962, p. 561) gives a summary of the geological structure of the Michipicoten district. "The Michipicoten group, of Precambrian age, comprises flows and pyroclastic rocks of the andesite-rhyolite association together with conformable zones of clastic sediments and banded iron formations", and further "Clastic sediments are interpreted as products of contemporaneous erosion of expanding volcanic piles. Development of the Michipicoten, group is viewed as a continuous process which, once initiated, proceeded through explosive, erosional, and chemical phases to produce a complex volcanic-sedimentary family group in which the members, although each possessing unique characteristics, are related by common volcanic heritage".

Discussing the genesis of the ores (known as Algoma type), Goodwin wrote in the same abstract, "Banded iron formations are ascribed genetically to largescale hot-spring and fumarolic activity. Iron carbonate and sulphur components appear to be of subvolcanic, presumably magmatic derivation,

whereas silica was largely derived by chemical leaching of the volcanic rocks. The clastic sediments are like true volcanic sediments in that rock and mineral components have their counterparts in subjacent volcanic rocks in either extrusive or intrusive from and appear to have been derived from them by rapid, contemporaneous erosion."

Goodwin (op.cit., p. 579) states further that the relatively high porosity of the iron formations suggests rapid chemical deposition during a period of extrusive quiescence.

In his paper Goodwin (1962, Figs. 1—4 volcanic and sedimentary formations) reproduces photographs of rock textures which are very similar to those known from the Kiruna field (The Lower Hauki rocks).

However, there is one major difference between these two ore fields. In the Kiruna area, apatite is the most important mineral after the iron minerals in the "stratified ore". In the Algoma ore type (Michipicoten, Ontario), this important part is played by quartz. This difference is significant and will be discussed later.

The iron ores of the well-known Lahn and Dill district provide another example of iron ore associated with volcanites. They occur in keratophyre, basalt tuff and lava (greenstone) of Devonian. The iron ore formation is associated with the basic volcanism (Schneiderhöhn, 1941). The chief constituents of the banded ore are hematite and quartz, although calcite occurs in places instead of quartz. In addition, chlorite, siderite, dolomite and pyrite are also present. The pyrite shows some enrichment in the magnetite ore.

Both the hematite and the magnetite are considered to be primary. There are several theories on the mechanism of the ore formation. The most widely accepted is that the ores originated from emanations from eruptive rocks.

It would be possible to extend this comparison. Many iron ore deposits seem to have an almost similar mode of formation. The origin of these ores in interpreted in different ways. Some of the theories of ore genesis include processes which may have planed an essential part in the formation of the ores of the Kiruna field.

Oftedahl (1958) has presented an interesting hypothesis for ore genesis in volcanic environments. According to him, the orogenic pyrite and magnetite ores in Norway, certain iron ores in Central Sweden and ores in the "Rio Tinto" type could have emanated in a gas phase from granite plutons. The emanations were then precipitated in water basins.

This hypothesis was suggested by observations from the Oslo district. Oftedahl found that the final acid stage of the magma series has a higher content of metals than the basic stages. He assumes that gas emanations which reach the surface of the earth on a continent disappear without a trace. Emanations which occur in the sea, on the other hand, would, he believes, be precipitated, at least in part.

As concerns the behaviour of metals during volcanic activity, valuable infor-

mation is given by Naboko (1959). Her studies relate to different volcanoes from Kamchatka (USSR). Naboko's publication contains the following comments on the eruption of the Klynchevsky volcano (op.cit., p. 123), "... when basaltic and andesite-basaltic lavas flowed out at temperatures of 1 000—800°C and down to 500°C, alkaline metals (Na and K) volatilized out of these lavas in compounds with chlorine. This happened in the same proportion in which they have occurred in the original lava (Na: K:3:1). In visible quantities, iron chloride flew out of basalt, becoming part of sublimates formed (erythrosiderite and kremersite)". Naboko states that copper, for instance, was enriched 6 000 times in sublimates of basalt in comparison with normal content in the rock type. She also found that Si and Fe escaped very intensely from basalts and andesite-basalt of Klynchevsky volcano in compounds with fluorine.

Transport of metal in gaseous form in connection with fumarole activity was established. Rock decomposition is also caused by the volcanic activity in the Kamchatka volcanoes. According to Naboko, the decomposed rock, in comparison with rock which is not affected in this way, shows a deficiency in the oxides of aluminium, iron, calcium, magnesium and sodium.

Naboko's paper (1959) describes present-day volcanic activity. Processes which are related to this activity, such as the leaching, transport and deposition of metals, have been established. The fumarole minerals include, among others, magnetite, hematite, pyrite, tenorite, opal, chlorite, calcite, fluorite, anhydrite, gypsum. These minerals also belong to the environment of Precambrian volcanics in which iron ores were deposited on a large scale. Alterations of rock types similar to those from the Kamchatka volcanoes described by Naboko are also known among Precambrian volcanics.

Although the metal concentrations mentioned by Naboko (op.cit.) are lacking in economic importance, her study of the behaviour of metals during present-day volcanic activity is of general interest. It may make it possible to reconstruct the formation and distribution of metals in Precambrian volcanics.

The deposition of metals from the Ebeko volcano in the Okhotsk Sea (USSR) is another example. Zelenov (1958, 1960) was able to establish considerable redistribution of elements in the region of the active volcanism. The areas discussed by Zelenov are situated in the volcanic mountain chain of the Kamchatka—Kurril Island (USSR). In this region, virtually all the processes of volcanism are in progress, i.e. lava, ash and volcanic breccia are being produced. Large quantities of gases and solutions emerge. The fumarolic and solfataric springs thus produce material and play an important part in breaking down the lava and pyroclastic formations. The elements released from the volcanic active areas are then carried via streams and rivers out into the Pacific Ocean and the Okhotsk Sea. The interaction between acidic thermal water and different rock types is illustrated by examples from the Ebeko volcano, which is in the solfatare stage and is situated in the northern part of

the island of Paramyshis. This volcano (1 138 m above sea level) is built up of lavas and tuffs, with an andesitic-basaltic composition. A large number of hot springs run out in the craters and on their slopes and in the ravines of the slopes. Both the temperature and the composition vary in these springs.

In Ebeko's central crater system there are three small adjoining craters, with lakes which are 200—300 m in diameter. The most important of these acidic hot crater lakes is situated furthest to the south. Large quantities of gases bubble through this lake. A large number of springs emerge from the shores of the crater lake. The water from the Ebeko craters is collected in three streams (Fig. 73). The eastern stream runs out into the Pacific Ocean while the two other thermal streams flow into the Okhotsk Sea.

The water in these streams was analyzed. By relating the dissolved metals in the water to the different rock types, it was possible to establish a close association between the hot acidic water and the rock types through which it had passed. Hydrothermal alteration of lavas from Ebeko is illustrated in Table 45 (Zelenov, 1960, Table 2, analysis by Sisova).

The table shows that Al, Fe, Mn, Ca, Mg, Na, K and P are dissolved and removed in large quantities and that SiO_2 and Ti largely remain. Below, a direct translation is given of part of Zelenov's paper (1960, pp. 62—65) which is of current interest as regards formation of the iron ores.

"When water-bearing levels are opened up by erosion, a series of rich thermal springs appears. When this water enters a stream of ordinary water, it is mixed with other meteoric water. The acidic iron then alters to oxidized iron and the concentration of hydrogen ions is reduced. Reduction of the hydrogen ion concentration is the decisive factor, which determines the precipitation of elements from the solution. As is known, independent compounds, such as hydrates and oxides, are precipitated out of solution at strictly determined pH values. Thus, $Fe(OH)_3$ begins to precipitate out of the solution at approx. pH 2; $Al(OH)_3$ at pH = 4.1; $Cu(OH)_2$ at pH = 5.4; $Fe(OH)_2$ at pH = 5.5; $Pb(OH)_2$ at pH = 6.0; $Ni(OH)_2$ at pH = 6.7; $Co(OH)_2$ at pH = 6.8; $Mn(OH)_2$ at pH = 8.5—8.8; $Mg(OH)_2$ at pH = 10.5 etc."

"Emergence of the thermal waters through the surface at pH >2 is followed by intensive precipitation of iron which is altered from the acidic to the oxidized form. Since oxidation of the iron begins immediately after the emergence of the thermal waters to the surface, the precipitation of iron hydroxide is observed in all springs of pH >2. This is particularly apparent in the spring of the *Bogdan Chmelnitskii* volcano (Iturup island). This spring forms a large funnel with a diameter of more than 1.5 km and a depth of 500 m and is situated within the decomposed rock types between the peaks of Tjirip and *Bogdan Chmelnitskii*. In former times the spring was filled by a large crater lake. Its western wall is now pierced by the flows from the deep canyon in Northern Tjirip and only the bottom sediments remain of the crater lake.

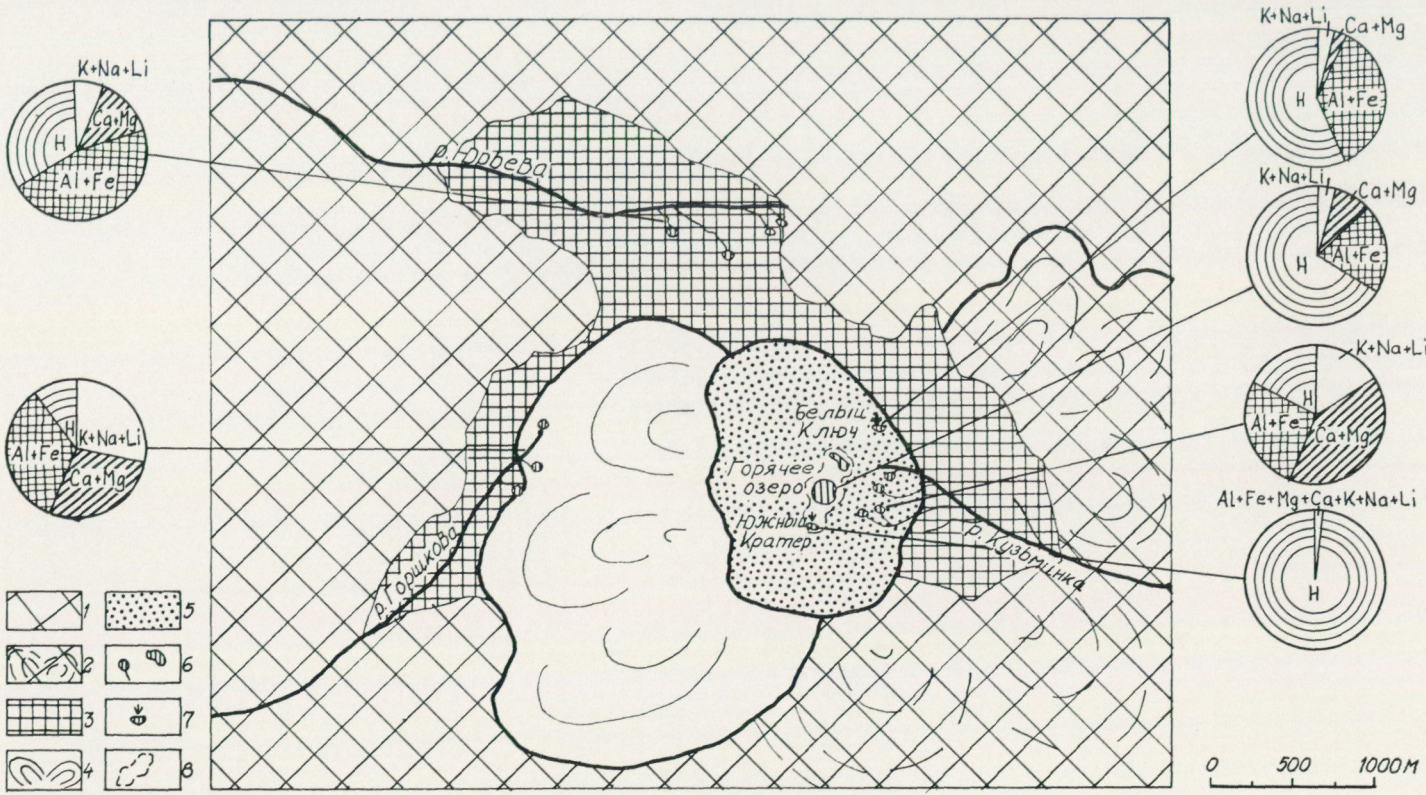

Fig. 73. Distribution of cations in the hot waters of Ebeko volcano. 1=unaltered lavas and tuffs, 2=early andesite lavas with rugged surface, 3=zone of decoloured rocks, 4=young andesite lavas with rugged surface, 5= pyroclastics from 1935, 6=acid springs and lakes, 7=solfataras, 8=crates of Ebeko volcano. After Zelenov, 1960.

In the northern part of the spring, there are a few shallow basins, the largest of which — Lake Tyhoe ('Still Lake') — has a diameter of approximately 300 m and a depth of 8 m. In these basins, which stretch out to form a chain and are connected by a flow which opens out into Northern Tjirip River,

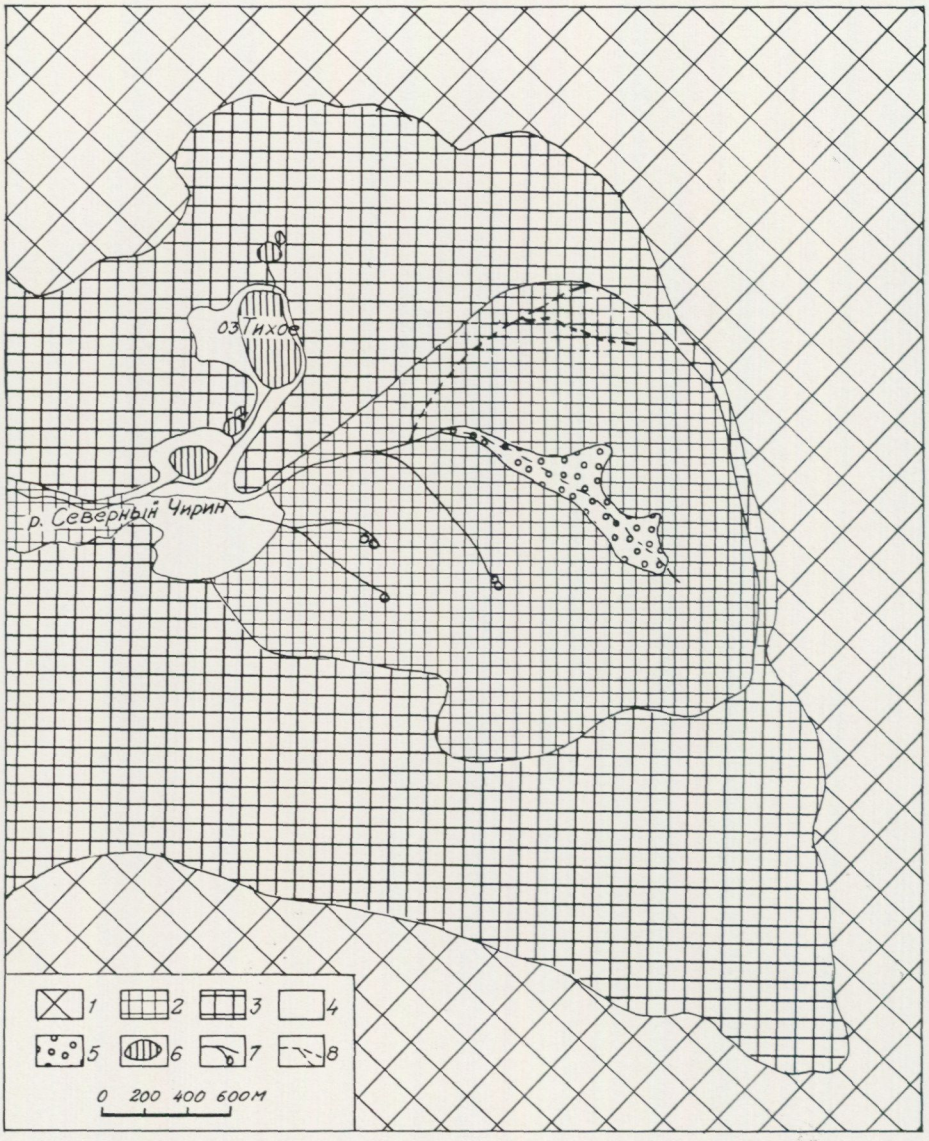

Fig. 74. Scheme of the iron ore deposits of "limonite cascades" island Iturup. 1 = unaltered primary lavas and tuffs, 2 = zone of altered (kaolinized opalized) lavas and tuffs, 3 = dissolved lavas and tuffs, 4 = recent accumulation of limonite, 5 = rock fragments (from the altered zone) with limonite as matrix, 6 = acidic lakes with depositions of limonite, 7 = springs and streams with acidic water, 8 = streams with fresh water. After Zelenov, 1960.

intensive settling of limonite is at present in progress (Fig. 74). Iron and aluminium are entering the 'Still Lake' chiefly from a cold acidic spring which is situated in the northeastern part of the lake. The spring has a pH of 3 and a flow rate of approx. 60 l/sec. One litre of spring water contains 75 mg aluminium and 188 mg iron oxide. The latter, which is oxidized after the spring water comes to the surface, precipitates on the bottom of the lakes and their connecting channels, forming a strange limonite deposit over a surface of approximately 0.5 km^2. To date, the limonite deposited attains a thickness of 10—12 m in isolated parts of the *Limonite Cascade*. "The intensive precipitation of limonite forces the channel to move, with the result that the surface covered by the limonite is gradually being increased. In a number of places strange *limonite wells* and *limonite streams* are observed; at the top there is a small lake, which forms a weak spring. From the water flows through these regions, limonite is precipitated, the result of which is that the *wells* and *limonite-hillocks* become increasingly raised, separate from the channel and sometimes reach a considerable height."

"Out of every litre of water, Northern Tjirip is supplied with approximately 3 mg of oxidized iron. In this way 185 x 60 x 864 000 mg of iron, which is slightly less than one ton, is precipitated every day into suspension in the lakes of the Limonite Cascade. A certain amount of this accumulation is doubtless carried out mechanically into the Okhotsk Sea."

"It is essential to note the extreme purity of limonite which is produced in the limonite lakes (Table 46). Spectographic analyses reveal in a majority of samples insignificant content of manganese, vanadium and nickel. Most of the aluminium remains in solution and is not precipated in the bottom sediment before it reaches the Okhotsk Sea. At the mouth of the Northern Tjirip River it forms, together with mechanically transported suspension limonite, a viscous yellow loop of turbid water. Limonite precipitation from thermal springs or from water mixed with them can be observed in varying amounts on all islands where thermal springs are found. On Kunashir Island, for instance, limonite alluvium with an Fe_2O_3 content of approximately 70 % is deposited, mostly in the river channel of the Lesnaya River, which collects acidic thermal water from Mendeleev volcano."

"Here again, as in other places, the limonite provides very pure precipitates which are very nearly completely free from impurities. Aluminium, the content of which in the water leaving the springs is usually twice as high as the iron content, remains in solution. Raising of the pH value proceeds extremely slowly in the streams in which the heat quantities released to the surface are mixed with meteoric water."

Zelenov (1958) gives a detailed description of the analyses results from a 3 km long stretch of the Zureva River. A rapid change of Fe^{2+} to Fe^{3+} is noted. After all the thermal waters have merged together, pH 1.3, $Fe^{2+} = 150$ mg/l

and $Fe^{3+} = 120$ mg/l are found. Some 700—800 m downstream and after a small inflow from a brook, the pH is 1.4, $Fe^{2+} = 20$ mg/l and $Fe^{3+} = 200$ mg/l. After one more kilometre, the pH value is found to be 1.6, $Fe^{2+} = 5$ mg/l and $Fe^{3+} = 320$ mg/l. At the outlet where the flow rate of water is 1.8 m^3/second, this river produces remarkable amounts of iron in solution, amounting to 400—580 g/sec or 35—50 tons/day.

Zelenov's descriptions (1958, 1960) of the reaction of the thermal water with sea water can be summarized as follows. When acidic thermal water is mixed with alkaline sea water, a yellow turbid solution with blueish-green edges is produced. The inner zone spreads out to a radius of 50—80 m from the outlet. This zone consists of clear greenish water. In the next zone, which extends up to 1 500 m, intensive precipitation of iron oxide (flocculation) takes place. The iron content drops first to 7 and then to 1 mg/l in the filtered water at the same time as the pH rises from 1.7 at the outlet to 7.6 in this zone. Fe^{2+} is not present in the precipitation zone. To raise the pH of the river from 1.5 to 7.6 at a flow rate of 1.8 m^3/sec, 1 800 000 m^3 of sea water per second are required.

Zelenov (1960) states that there has been a redistribution of iron and aluminium at the mouth of the Northern Tjirip River. Just at the mouth, Al_2O_3 constitutes 14 % of the alluvium. In the yellow zone the aluminium content is increased to 43 % and in the blue-coloured peripheral zone it reaches 65 %. The iron content is correspondingly reduced from 80 % at the shore to 35 % in the blue-coloured zone. The SiO_2 content, which is obviously of erosional origin, was only noticed at the actual mouth, where it amounted to 6.5 %. These analyses verify the previous observation that iron and aluminium are not mixed but are in fact separated in connection with an exhalative sedimentation. The iron which is transported out into the sea coagulates and forms suspensions which are distributed according to the hydrodynamics of the recipient medium (Zelenov 1958).

Zelenov's work (1960) was primarily concerned with the formation of geosynclinal bauxites. Iron constitutes the next most abundant exhalative material in the Kurril Islands. If it is assumed that the proportional relation found in Ebeko between aluminium and iron applies to all of the Kurril Islands, the iron too must reach vast proportions. The explanation for this is given by Zelenov (1960): "Geographical material bears witness to the fact that rivers, which in the sea form something resembling alluvium, flow from solfataras in the "Matyecha" and "Kudrya" volcanoes on the island of Iturup and from the Ivao volcano on the island of Urup. There are also springs on the islands of Sheashkotan, Ketoi, Broutono, Makanrushi and in many other places. The total amount of dissolved aluminium transported from the islands in the Kurril mountain chain can be estimated at thousands of tons per day."

If the extent of iron deposition in the Kiruna field is assumed to correspond

to the output of the Ebeko volcano, a rough calculation shows that the ores in the Kiruna deposit could have been formed over a period of approximately 100 000 years. During this time, 1 800 million tons of iron would have been deposited. This period could of course have been reduced by the presence of several "springs".

It may be mentioned as a curious fact that if a layer thickness of almost 1 mm is assumed, approximately 100 000 layers are obtained in the entire ore body. This does not allow for the fact banding of the Kiruna ores might be related to the seasons, as has been assumed for quartz-hematite (magnetite) "stratification" in Precambrian iron ores (Sakamoto, 1950).

Sakamoto assumes the following: "Supposing that the annual rainfall was great and divided into periodically wet and dry seasons. Shallow ground above the water table became neutral or even alkaline in a dry season and the phreatic zone near the water table became nutral or temporarily even acidic in a wet season . . . In wet seasons, iron migrated in the acidic surface water while in dry seasons, silica migrated in the alkaline ground water."

The origin of the apatite-banded ores cannot be discussed solely on the basis of their iron component. This would be as absurd as discussing the formation of quartz-banded ores without considering the quartz. Unfortunately, however, detailed discussions on the origin of the apatite bands as an important component in an exhalative-sedimentary iron ore are not available. The relatively high P-values from the limonite formations described by Zelenov (1960) are therefore worth consideration (see Table 46).

The occurrence of phosphorus in the Precambrian rock basement has already been discussed in a previous section. Sedimentary deposition with a high phosphorus content during this period has also been mentioned. A discussion on the behaviour of phosphorus in connection with volcanic activity is appropriate here. Below, reference is made to apatite bearing formations which occur in a volcanic environment similar to that of the Kiruna field.

Remarkable amounts of phosphorus occur in direct relation to volcanics (Kutai phosphorite) in western Georgia (USSR). This entire formation formed during the late Cretaceous. It is composed of pyroclastic rocks, lavas and limestones. The pyroclastic rocks consist of sintered or cemented slaggy tuffs, which occur in layers of varying thickness and particle size. The volcanic glass is now devitrified. The lavas constitute separate lava flows and dikes which vary in thickness between 0.8 and 1.2 m. The dikes consist of olivine basalt, trachybasalt, olivine-analcime basalt and phonolite. In places, these rocks have become colourless and have changed to clay. In the volcanic rocks narrow bands of limestone occur. In connection with this, it has been suggested that they correspond to times of quiescent volcanic activity (Il'inskaya, 1964). Silicate concretions are associated with the limestone. In the pyroclastic formations, 5—7 m large blocks of organic limestone also occur.

Phosphorite occurs irregularly. High P-values are found in the pyroclastic rock types, while lower values are found in lava rocks. Il'inskaya (1964, p. 172) states that in olivine-analcime basalt 5 km from Kutaisi, ". . . a hard porcelain-type white phosphorite makes up nodules 12 to 14 cm across and veins 3 to 4 cm wide of various lengths. Sections show that the phosphate has needle structure. Acicular crystals of apatite form veinlets and random aggregates, which sometimes penetrate the colourless altered (clayey) basalt, which is metasmoatically replaced. The P_2O_5 content of such rocks is 31.46 %. The harder and less altered basalt in adjacent areas does not have these veins of needle phosphate; instead, aggregates of acicular crystals form pseudomorphs after olivine." In the tuff series two phosphorite beds occur. It is stated that ". . . phosphate cements the ash particles and slag fragments in tuffs, which in places form lenses 20 to 25 cm long and 5—7 cm thick. The phosphate forms a cement of basal type or of pore-filling type and has a cryptocrystalline collomorphic texture, or occasionally a needle structure. It is quite clear that in places the phosphate not only fills the gaps between slag fragments but also metasomatically replaces them, leaving only small relics of the primary rock." Il'inskaya (1964, p. 172) further states that, "The following four features of the phosphorite distribution are notable:

1. The phosphorites are closely related to volcanic rocks; accumulations occur in tuffs or lavas but are not present in the limestones.
2. The phosphorus content falls as the carbonate content rises.
3. Phosphatization takes the form of localized deposition with the character of metasomatic replacement in basalts and tuffs.
4. The phosphatization occurs in altered clayey or decolorized zones in volcanic rocks; these zones are the result of postmagmatic process."

With regard to the origin of the apatite in volcanics and lavas, Il'inskaya (op.cit., p. 172) states that, first gas saturated slag and ash masses were formed; and thereafter different types of basalts and phonolites. The phosphorus is assumed to have been deposited as a gel under subaqueous conditions and dispersed in the sea water. Il'inskaya states that "This provides an example of mineralization associated with the volcanic-sedimentary type of lithogenesis (Strakhov, 1960)."

Il'inskaya presents additional theories for the genesis of these apatites. One theory assumes that the apatite was leached from basalt and tuffs by water. Another envisages a true sedimentary origin.

The publications presented by Goodwin (1962), Hegemann and Albrecht (1954), Oftedahl (1958), Naboko (1959), Zelenov (1958, 1960) and Il'inskaya (1964) are undoubtedly of great help in interpreting the genesis of the Kiruna ores.

The reconstruction of a course of events can be verified by means of a comparison. The possibility of carrying out such an analyses has increased recently. A large number of descriptions of deposits, detailed descriptions and interpretations of different ore types which occur in areas of "continental size", have recently been translated from Russian, Chinese and Japanese.

When the textural relations between ore minerals and apatite were discussed (p. 113), the so-called "skeleton ore" and "apatite spotted ore" were briefly considered. It was stated that they frequently occur in connection with apatite-banded ore and that there exist transitions between the different types and also to types where apatite is evently distributed. It was tentatively postulated that colloidal precipitation might be responsible for the two first-mentioned types.

If the ore formation took place in an exhalative-sedimentary environment, a colloidal solution consisting mainly of phosphate and iron hydroxides (iron oxides) is perhaps a prerequisite for the formation of these textures. A colloidal state, which precedes the solid state, is known in many such contexts. Hubbard (1922, p. 95) pointed this out. "Many substances which occur in crystalline form can be prepared in the colloidal state without any compositional difference." He then continues, "In the case of some substances there seems to be no line fixed between the crystalline and colloidal state. In the same way, there seems to be no line which can be definitely drawn between a true solution and a colloidal solution." According to Hubbard, colloidal state also means "solid gel", suspension and emulsion. Hubbard mentions several instances of such formations. They include limonite, bauxite, manganese oxides and silicates to a large extent.

LABORATORY EXPERIMENTS

An interesting laboratory experiment by Martin and Piwinskii (1969) supports the hypothesis put forward by Oftedahl (1958) concerning the source of the iron. However, they do not presume the presence of a granitic magma. It was found from the experiment that "Hypersolidus and subsolidus hydrothermal quenching experiments on calc-alkaline plutonic rocks between $1^1/_4$ and 10 kb water pressure indicate that iron fractionates into the vapour phase". In the experiment, various granites and basic rock types were used. The test material was placed in capsules of varying size. It was then subjected to different temperatures for varying periods. The liquid used was distilled water. Martin and Piwinskii (1969) noted that in the experiment with granite very pure monohedral hematite crystals were formed on the inner wall of the capsule at a temperature of between 650°C and 850°C and pressures of from $1^1/_4$ to 10 kb. The experiment was also carried out on granodiorite and tonalite under different temperature and pressure conditions. As in the previous test, rhombohedral hematite was again formed on the inner wall of the capsule. Diabase

and andesite were heated to 700°C and 2 kb pressure for two weeks. The result of this experiment was as follows: "Iron was dissolved at the high temperature end of the sealed gold capsule and was fixed as hematite in cooler regions of the capsule. Hematite crystals, commonly attached delicately by an edge or by a corner, nucleated and grew in a relatively restrincted band corresponding to temperatures between 470°C and 515°C." A little later in the same paper: "In an experiment, lasting 60 days, an entire zone of hematite crystals was produced between 455°C and 510°C".

The hematite which has been quenched out of a rock can be quantified by chemical analyses. According to Suhr and Ingamells (reference in Martin and Piwinskii, 1969), approx. 6 % by weight of the total iron in W-1-diabase is driven out over 14 days at 10 kb pressure.

Martin and Piwinskii's experiment shows that iron can easily be mobilized and enriched.

Kinoshita's conclusions are based on both field observations and laboratory experiments (Kinoshita 1924, 1930). In the laboratory experiments conditions of formation were simulated by means of material from the various ore deposits. Series of potash solutions and sodium solutions and mixtures of these and different rock material produced different reactions. The material was placed in distilled water. Whilst dispersion was in progress, H_2S gas was bubbled through the container. When pieces of tuff, clay slate, liparite and andesite were dipped into the colloidal (disperging) solution, an interesting phenomenon occurred. The experiment showed that clay slate has the strongest coagulation effect after tuff, liparite, and andesite, respectively. "Siliceous ore (Keikô)" had the weakest coagulation effect (Kinoshita 1924, p. 28).

Kinoshita's conclusion (1924, p. 26), drawn from these experiments, was that "... the coagulation power of the country rocks may greatly affect the genesis of the ore deposits".

Certain textural features in the ores of the Kiruna field were probably caused by colloidal solutions. The often rapid changes between potassium and sodium, together with other factors such as the pH, Eh and trace element content (mineralizers) etc., may have produced those factors which govern a transition from a colloidal to a solid state.

Kinoshita indicated that such a transition can in some places take place very rapidly. The ores of the Kiruna district and at least some of the other iron ores in Lapland show potassium dominance despite the fact that most of the wall-rock is sodium-dominant. A rapid change from sodium-dominant to potassium-dominant conditions may have been one of the important factors which governed the textural composition of the ores.

Kinoshita's experiments led the present author to conduct a similar experiment with material from the Kiruna deposit. Powdered apatite and hematite, distilled water, H_2S gas, a heater and sodium chloride and/or potassium chloride

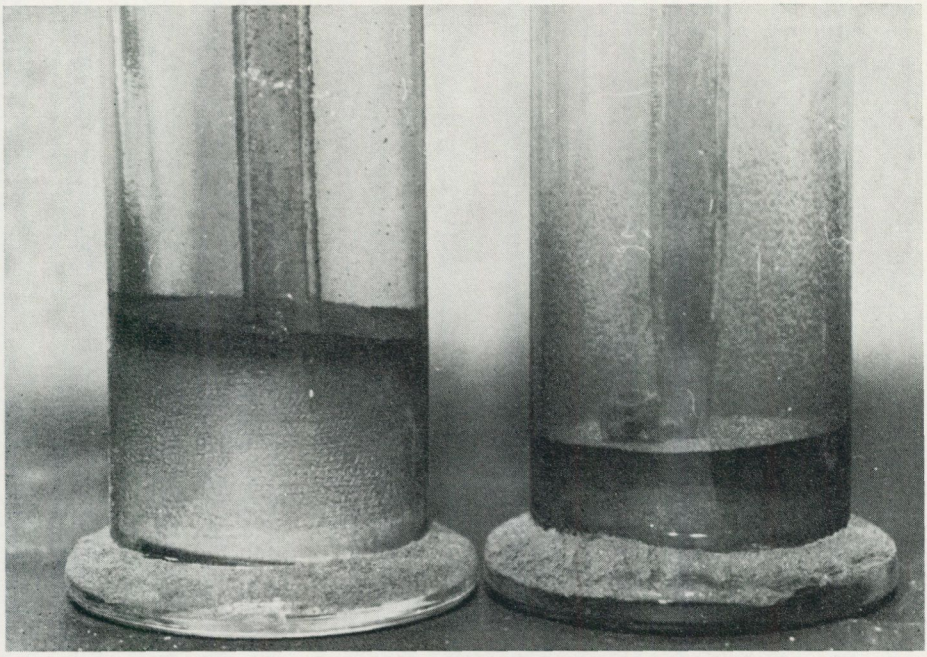

Fig. 75. Leyering of an experiment in the sedimentation of hematite and apatite. Note that the hematite is deposited over the apatite.

were used for the experiment. The sodium chloride and/or potassium chloride were placed in a container containing distilled water. The water was then heated to approx. 80°C. When the specified temperature was reached, the apatite and hematite powder was mixed into the water by vigorous shaking. The H_2S flow was conducted into the test material through a tube which entered the container just above its base. The upward flow of bubbles kept the muddy solution in constant movement. After one to two minutes a light grey sludge (sometimes also coloured red) was deposited on the bottom of the container. After a further few minutes a black sludge began to be deposited on the light grey sludge. Once the supply of H_2S gas was decreased and the heat was reduced, the turbid water settled completely and a semi-transparent green liquid covered the black band.

The above experiment was repeated eight times. The same phenomenon occurred each time, i.e. the light grey bottom sludge was covered by the black sludge, forming a sharp contrast (Fig. 75). In experiments without H_2S and/or heat supply, the apatite and hematite were deposited without the occurrence of banding. The experiment thus produced apatite-hematite banding similar to that found in the Kiruna deposit ores. However, it is not possible here to give any explanation for the mechanism of deposition.

The experiment was also carried out on apatite and hematite material, each of which was ground and sifted separately to under 0.4 (corresponding to the size of "colloidal dispersions" according to H. B. Weiser (1949). The apatite-hematite banding described above was again obtained in this experiment.

GEOLOGICAL HISTORY OF THE KIRUNA FIELD

Important papers concerning the geological history of the Kiruna field have been published by Lundbohm (1910), Geijer (1910, 1912, 1919a, 1920, 1924, 1927, 1931, 1931b, 1950, 1958, 1959), Sundius (1912, 1915, 1919, 1956), Ödman (1957), Offerberg (1967) and Welin (1970).

Sundius and Geijer regarded the formation of the Kiruna field as a simple monoclinal structure with an almost N—S strike and dipping steeply to the east. Ödman assumed that the Kiruna porphyries were older than the greenstones. The present conditions would thus have been determined tectonically. Ödman's point of wiev was based partly on the fact that the rock type association in the Kiruna greenstones shows a striking similarity to certain other greenstones in the county. Ödman also thought that part of the pebble material in the Kurravaara conglomerate, in particular apatite ore and magnetite-syenite-porphyry pebbles, corresponds to the ores and rock types which occur in the Kiruna porphyries.

Ödman's account of the pebble material in the Kurravaara conglomerate was questioned by Geijer on the grounds that there is greater affinity between the pebble material of the conglomerate and greenstones than between the pebbles and the porphyries.

Offerberg found no proof for Ödman's hypothesis concerning the age of the Kiruna greenstones. He considers them and associated sediments to be older than the Kiruna porphyries. In Offerberg's stratigraphic scheme, Kurravaara conglomerate is placed in the same position as in Geijer's, since "the conglomerate rests conformably on Kiruna greenstone and at one point (Valkeasiipivaara) can be said to alternate with the greenstone" (translated from Swedish) (Offerberg 1967, p. 35).

Welin has published the results of radiometric age determinations. His investigation material also includes samples which relate directly or indirectly to the stratigraphic history of the Kiruna deposit. Welin says of some of the rocks of the deposit (1970, p. 45) that "In the Kiruna district the Vakko formation was deposited on the porphyries and is thus at most 1605 million years old" and "The Kurravaara conglomerate, on the other hand, is older than 1605 million years."

The results of the new investigations confirm Geijer's idea as regards the origin of the pebble material in the Kurravaara conglomerate. At the same time,

they contradict the magmatic intrusive ore genesis theory and indicate that the quartz-bearing porphyry was produced after the main ore bodies at Kiirunavaara—Luossavaara and Luossajärvi.

Offerberg and Welin placed the Kiruna greenstone under the Kiruna porphyries, which is in agreement with the new investigation results. However, it should be pointed out that these geologists have not discussed the origin of the ores.

Before indicating the course of events which formed the bedrock of the Kiruna district, a brief summary is given of the new data (including data taken from Offerberg's map survey 1967), which have been used for the re-interpretation of the geological history and ore genesis of the deposit.

1. *Kiruna greenstone*

a. A 14 m thick bed of dolomite was found in the Kiruna greenstones near the Kurravaara road (p. 9).

b. In the schistose greenstone type, oblong magnetite-rich pebbles were found together with pebbles of a light red quartzitic sandstone (p. 9).

c. The magnetite in the pebbles is quite different from the other magnetites in the field as regards the trace element content (1 400 ppm Cr were found in the magnetite from a pebble in the greenstone) (p. 67).

2. *Contact between the Kiruna greenstone and the Kurravaara conglomerate*

a. The Kurravaara conglomerate shows discordance with the Kiruna greenstone south of the map area (p. 10).

3. *Kurravaara conglomerate*

a. The magnetite in the pebbles shows a difference in comparison with the magnetite of the main ore bodies and ore breccias (also impregnation type) as regards the zinc, chromium, (manganese) and aluminium contents (p. 170, 172—174).

b. The trace element content of the magnetite in the interstitial material differs from the distribution in the magnetite in the pebbles (p. 170—175).

c. While he magnetites in the pebble material show major differences in comparison with some other magnetites in the field, a closer relationship can be established between the interstitial matter and the greenstone (p. 170—175).

4. *Syenite* occupies a central position in the syenite-porphyry (p. 16).

5. *Syenite-porphyry*

a. The trace element distribution shows major differences between the magnetites of the ore breccia (p. 170—175) and the magnetite-syenite-porphyry. The copper, titanium, (vanadium), chromium, cobalt and magnesium contents are substantially lower in the magnetites of the magnetite-syenite-porphyry than in the magnetites of the ore breccia (p. 170—175).

b. The "ore breccias" are not "offshoots" formations, but in most cases occur separated from the main ore bodies, yet always together with magnetite impregnations (p. 50).

c. Chloritic inclusions occur in two of the thicker "ore veins" in the Luossavaara ore veins (p. 51).

d. Thin magnetite dikes, which run across the ore veins, were found at Luossavaara (p. 51).

e. Major differences are found between the trace element distribution in magnetites from the foot-wall "ore breccia" and that in magnetite from the main ore bodies (p. 170—175).

6. *The contact-zone between syenite-porphyry and the main ore bodies*

a. The boundary between the main ore body at Luossavaara and the "ore breccia" is marked by a 5—50 cm thick chlorite skarn zone (p. 52).

b. Prior to the deposition of the ore at Kiirunavaara and agglomerate and quartz-porphyry lava to the west of Henry, the syenite-porphyry was exposed to erosion. The conglomerate-like formations at Kiirunavaara and the weathering breccia to the west of Henry bear witness to this (p. 91).

c. Discordance between the syenite-porphyry (tuffaceous intercalations) and the ore contact (directions of strike and dip of the ore body) has been found in the Kiirunavaara open pit (p. 13).

7. *The Kiirunavaara—Luossavaara main ore bodies*

a. Monazite-rich, millimetre thick lenses, concordant with the general direction of strike and dip, have been found at Kiirunavaara (p. 38).

b. White to light-red albite-quartz rock, as veins and lenses concordant with the ore contact, have been found at Kiirunavaara (p. 19).

c. Narrow chloritic inclusions, concordant with the ore, have been observed in the Luossavaara ore body (p. 39).

d. Hematite ore was found in boreholes in Kiirunavaara and Luossajärvi magnetite ore. The boreholes show that this ore is orientated according to the regional conditions of strike and dip (p. 38).

e. The distribution of trace elements in the magnetites and hematites of these ores does not support a magmatic formation theory (p. 170—175).

8. *The contact-zone between the main ore bodies and the quartz-bearing porphyry*

a. Phenomena which may indicate erosion of the ore body have been observed in the hanging wall contact (p. 93).

b. A skarn banded rock, probably originally tuffs, was found at Kiirunavaara close to the hanging wall contact (p. 18 and 19).

9. *Quartz-bearing porphyry*

a. Ore-lenses and layers of erosion material with fragments (sometimes well rounded) of ore and porphyries indicate that the quartz-bearing porphyry has been extruded as separate beds (p. 17).

b. A conglomerate was found in the hanging wall of the Luossavaara ore body (p. 20).

c. Inclusions of quartz-rich and apatite-banded hematite ore are found in the upper section of the quartz-bearing porphyry (p. 28).

d. At Rektorn, the top surface of the quartz-bearing porphyry has probably been exposed to erosion. The porphyry surface is broken up in places and the transition to Rektorn ore takes place via a weathering breccia with intermixed polymic material and chemically and mechanically deposited sediments (graded bedding) (p. 21).

e. One drill core showed 5 m of diffuseli banded anhydrite E of Luossajärvi (p. 29).

10. *The Per Geijer ore bodies (Haukivaara, Rektorn, Henry, Nukutusvaara and Lappmalmen)*

a. Drilling has shown that the surface ore bodies (Haukivaara, Rektorn, Henry and Nukutusvaara) extend to great depths where they form a continuous ore body. (Lappmalmen) (p. 45).

b. Small fragments of a phosphorus-poor ore have been observed in an ore with a higher phosphorus content at the foot-wall contact (p. 41).

c. Phyllitic or chloritic inclusions, concordant with the ore bodies and with each other, were found in places (p. 45).

d. Cross-bedding occurs in apatite-banded ores (p. 42).

e. Stratification of the phosphorus-poor ore — on the basis of grain size — has been observed in places (p. 44).

f. Trace element analyses of magnetites and hematites suggest a primary formation of the hematite and magnetite ore (p. 126).

11. *Contact between the Per Geijer ore bodies and their hanging wall rocks*

a. The upper surface of the ore has been exposed to erosion in places (Rektorn) (p. 98).

b. Diamond boreholes revealed at places a continuous transition between apatite-banded and quartz-banded ore (Lappmalmen) (p. 47).

12. *Detritus of porphyry*

a. Sedimentary structures have been observed in a section which lies in the same position as the rocks which Geijer (1950) termed "Rektor porphyry" (p. 32).

13. *Quartz-banded ore*

a. Drilling has revealed a quartz-banded ore between Rektorn and Henry (p. 46).

14. *Syenite-porphyry of Hauki type*

a. The syenite-porphyry, which belongs to the Lower Hauki rocks, in the northern part of the field, lies directly on syenite-porphyry of the foot-wall type (Kiirunavaara, Luossavaara) (p. 31).

15. *The iron-poor Hauki hematite* has a high barium content, sometimes exceeding 6 %. Higher barium values were found in the northern part of the deposit (Syväjärvi) than in its southern section (Haukivaara) (p. 49).

16. *An inverse relationship* exists between uranium and thorium in the N—S direction in the Lower Hauki rock types (Parák 1973).

17. *The distribution of rare earth metals* in the apatites of the ore bodies indicates that the ore bodies in question were not formed magmatically (Parák 1973) (p. 121).

18. *The trace element analysis* shows a decreasing ferride content (except Fe) from the Kiirunavaara ore body to the Tuolluvaara ore body. The ferride content of the magnetite (monotype) in the Kiruna district shows the following distribution:

Kiirunavaara 320 m level	3 240 ppm
Kiirunavaara 800 m level	2 790 ppm
Per Geijer ore bodies	2 770 ppm
Luossavaara	2 640 ppm
Luossajärvi	2 160 ppm
Tuolluvaara	1 590 ppm

On the basis of the previous discussions and the new data mentioned above, the formation of the bedrock of the Kiruna field can briefly be described as follows. See Fig. 76 for a schematic presentation of the stratigraphy of the field.

Many of the spilitic Kiruna greenstones with interbedded sediments are subaquatic formations. However, basic to ultra-basic hypabyssal intrusives, which presumably originated from the same parent magma, are found among the effusive rocks.

The syenite-porphyry lies on a conglomerate, the "Kurravaara conglomerate", which in turn overlies Kiruna greenstone. The conglomerate includes pebbles from both Kiruna greenstone and Kiruna porphyries. It should be emphasized that the porphyry types in the pebbles are identical to the porphyries found to the west of the syenite. These acidic to intermediate lavas form a transition between the spilitic Kiruna greenstones and the normal keratophyre-type Kiruna porphyries.

Deposition of the Kurravaara conglomerate perhaps commenced at the same time as, or more probably, even before, extrusion of the syenitic magmation started. The pebbles of keratophyre-type indicate that deposition of this rock type then continued during the first stage of the keratophyre period. Thus, keratophyric volcanism began before the spilitic activity ceased. The lava flows of keratophyre may have followed each other in quick succession.

There are several possible explanations of the formation of syenite in the central part of the syenite-porphyry. One is that the rapidly formed thick syenite-porphyry mass permitted heat accumulations. This may have led to alteration (grain coarsening) of the central sections of the large mass. Another explanation may be that a subsequent metamorphism occurred in only that part of the deposit. (It is not impossible that there exist deep intrusions in association with the syenite.) The syenite still shows textures in which it is possible to recognize structures which may have been primary in the original lava beds. Furthermore, the contact between the syenite and the syenite-porphyry is continuous.

Towards the end of the volcanism which created the syenite-porphyries of the region, intercalations of pyroclastic material and of small chemical —

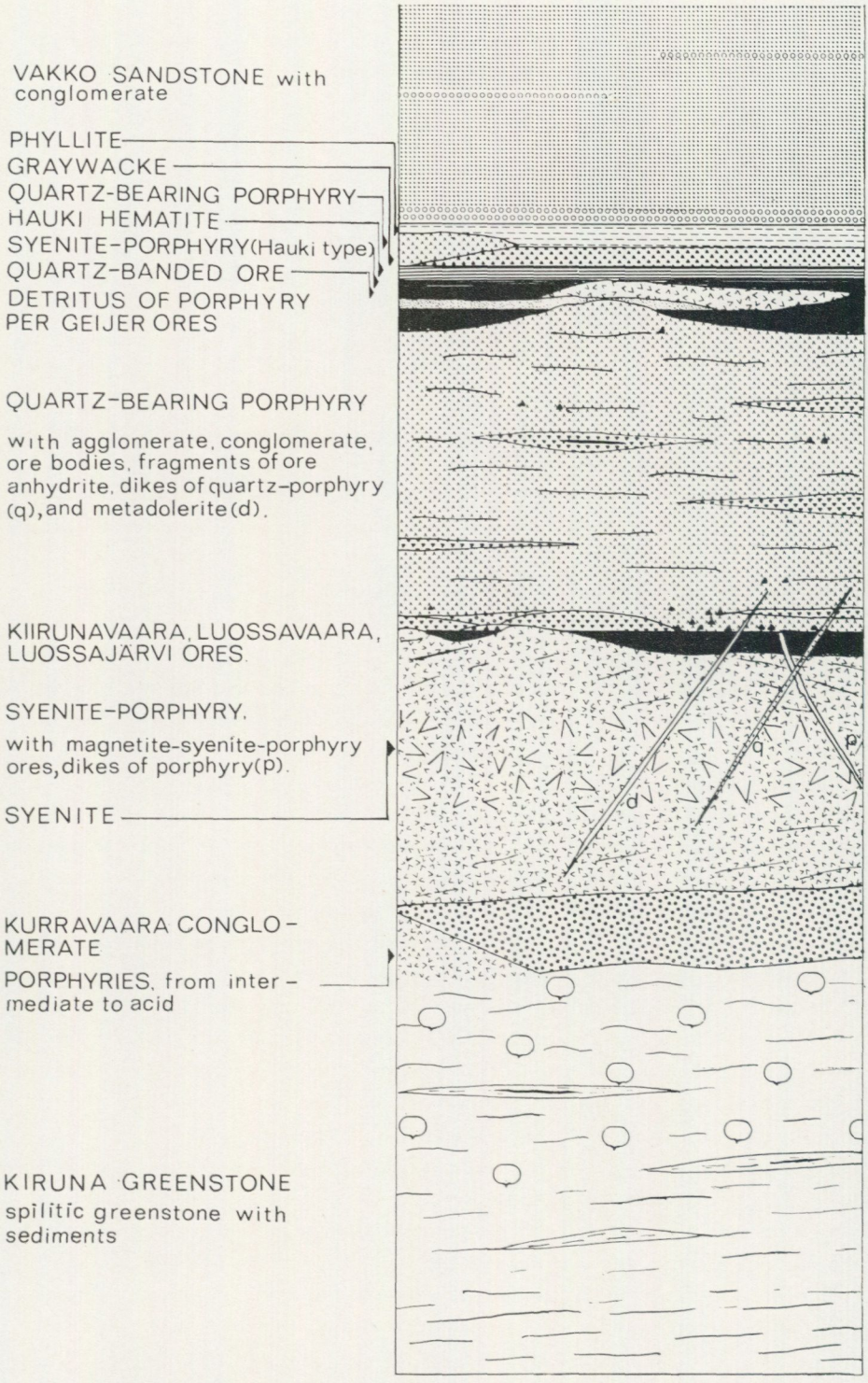

Fig. 76. Stratigraphic scheme of the Precambrian volcanic complex at Kiruna, Northern Sweden. Basement probably granite.

sedimentary iron ores increased. The end of this period in the region was marked by:

a. erosion of the syenite-porphyry,
b. deposition of iron ores,
c. erosion, and
d. the eruption of more acidic, quartz-bearing porphyry.

After the lava production of keratophyre type cassed, fumarole activity began. The new products were transported and deposited in water basins. The iron oxides and apatite were deposited simultaneously in topographically suitable basins. However, it is difficult to determine which factors caused the rhythmic formation of the ore. In a previous section, examples were given of how various researchers attribute different roles to the contributory factors. Known factors are temperature, composition of gases produced, solutions and rocks percolated by the solutions, the pH — and Eh-values and the amount of oxygen and electrolytes. As already mentioned, the rapid change between potassium and sodium dominance in the rocks may also have played an important part in the precipitation (see p. 140).

It is not impossible that hematite was formed first and was then almost completely altered to magnetite in a reducing sedimentary environment. The water-depth may have been significant in this respect.

After solidification of the deposited iron oxides and apatite, erosion of the ore and wall-rock occurred. The next stage was characterized by a quartz-keratophyric — rhyolitic volcanism.

The acidic lavas then covered the entire ore surface and the conglomerate and built up a huge mass. During this period, pyroclastic material was also produced. Periods of non-activity probably occurred for varying lengths of time between the lava flows. This is indicated by erosion products and the deposition of chemical sediments (iron ore and anhydrite).

Before these acidic lava extrusions ceased, a fumarole-solfatara activity commenced. For the map area, this meant that a basin with a somewhat eroded uneven lava basement began to accumulate the water flows from the hot springs. This basin may have had an external diameter of approximately 10 km. Deposition of the Per Geijer ores took place, at least initially, in more or less continuous basins.

In the first phase of sedimentation, phosphate precipitation constituted the next most important constituent after iron in the basin. In the later stages of sedimentation silica took over this role. This took place almost at the same time as a consolidated part of the ore was elevated and eroded. Sandy erosion material was deposited in part even on the ore (and also to a lesser extent on the surface of quartz-bearing porphyry lavas which were not covered by ore

sludge). The material consisted almost entirely of only quartz, feldspar and iron oxides. Probably volcanic ash in varying amounts was intermixed.

The mineral composition of these formations was probably also influenced by the fumarole-solfatara activity. The question could be asked to what extent the sediments were deposited from normal streams and which part was played by "volcanic waters". In fact, apatite occurs only in subordinate amounts in those rocks which overlie the arkosic sediments.

The sedimentation was followed by volcanism, which produced both lava and pyroclastic material (Hauki type syenite-porphyry), although of fairly limited extension.

After deposition of the rocks mentioned above, the area was exposed to erosion and later to deposition of greywacke. The detrital material in this rock consists almost solely of the Lower Hauki rock types. This indicates that the greywacke is a local formation, since the material apparently is free from intermixtures of porphyritic rock types.

After deposition of the greywacke, the transgression continued and reached its culmination in the deposition of phyllite, and quartzitic sandstone with conglomerate beds. Pebbles of quartz-bearing porphyry are predominant in the conglomerates. This fact may indicate that a quartz porphyry volcanism occurred after the deposition of the Lower Hauki rock types. In addition to quartz-bearing porphyry, pebbles of the Lower Hauki ores and rocks also occur. Quite often, fragments of phyllite are found in the lower parts of the quartzitic sandstone.

It is impossible to estimate the thickness of the quartzitic sandstone, since it is bounded to the east by a fault.

As mentioned previously, fragments of ores and rock types identical to those occurring in the Lower Hauki series have been found in the upper sections of the quartz-bearing porphyry. This indicates that deposition of the Lower Hauki series must be older than, or contemporaneous with, the extrusion of the quartz-bearing porphyries. This implies that, prior to the erosion period which produced the Vakko rocks, the Lower Hauki series was covered by quartz-bearing porphyry. There are no observations from the Kiruna field where the quartz-bearing porphyry occupies a position above the Lower Hauki rock types. On the other hand, it is known that formations equivalent to the Lower Hauki rock types occur in the quartz-bearing porphyry to the west of the Kiruna deposit (Ekströmsberg region).

The tectonic disturbances which affected the Kiruna deposit were dealt with in an earlier section (p. 52).

TABLES

TABLE 1. Chemical analyses of Kiruna greenstones (weight %)

	1 Dh 402 m 33	2 Dh 402 m 39	3 Dh 477 m 199	4 Dh 487 m 20	5 Dh 487 m 25	6 Dh 487 m 68
SiO_2	50.0	48.5	50.4	51.9	49.6	40.8
TiO_2	1.11	1.06	0.80	0.72	0.73	0.57
Al_2O_3	13.0	13.7	15.8	14.1	14.2	12.0
Fe_2O_3	12.80	12.81	11.71	5.71	11.80	1.31
Fe_3O_4	1.45	2.78	1.12	9.54	—	12.44
MnO	0.18	0.15	0.24	0.11	0.21	0.28
MgO	6.30	6.63	7.13	11.6	8.22	1.72
CaO	7.70	8.75	6.88	1.05	5.46	13.9
BaO	<0.01	0.02	0.06	<0.01	0.09	0.04
Na_2O	3.80	3.20	1.70	1.70	1.08	4.60
K_2O	0.94	0.60	2.50	0.66	2.98	0.28
P_2O_5	0.08	0.11	0.14	0.17	0.17	0.08
V_2O_5	0.12	0.21	0.15	0.04	0.07	0.07
F	0.04	0.01	0.11	0.09	0.02	0.01
Cl	0.08	0.04	0.06	0.04	0.01	0.02
CO_2	0.96	0.77	0.78	0.67	5.27	11.8
S	0.049	0.50	0.043	0.002	0.005	<0.001
CuO	0.03	0.04	0.02	<0.01	<0.01	0.01
Σ	98.63	99.43	99.64	98.10	99.01	99.92

1—3 = drill hole from the Kurravaara road
4—6 = greenstone with schistosity from west of Syväjärvi

TABLE 2. Chemical analyses of iron ore and magnetite-bearing pebbles from the Kiruna greenstones (weight %)

	Skarn ore	Magnetite-bearing pebbles from greenstone		
	1	2	3	4
Fe_3O_4	86.82	15.05	18.37	23.67
Fe_20_3	0.16	5.59	6.52	4.39
SiO_2	7.06	50.0	46.3	45.6
MnO	0.04	0.12	0.21	0.14
CaO	0.48	4.42	6.77	4.59
MgO	3.58	2.65	1.43	1.46
P_2O_5	0.01	0.08	0.09	0.07
Al_2O_3	0.43	11.7	8.69	10.0
TiO_2	0.07	0.78	0.74	0.68
V_2O_5	0.29	0.07	0.07	0.09
CuO	0.01	0.01	0.07	0.01
CO_2	0.20	3.86	6.06	3.86
Na_2O	0.13	5.18	4.45	5.18
K_2O	0.11	0.36	0.17	0.22
Fe	62.93	14.80	17.85	20.20
Fe^{2+}	20.94	3.63	4.43	5.71
P	0.002	0.035	0.039	0.032
S	0.021	0.005	0.066	0.006
F	0.05	0.02	0.01	0.01
Cl	0.05	0.04	0.04	0.02
Σ	99.51	99.93	100.05	99.99

1 = drill hole, Suolojåkk 69001, 2 = drill hole 487—68 m, 3 = drill hole 487—69 m, 4 = drill hole 487—70 m

TABLE 3. Chemical analyses of pebbles from the Kurravaara conglomerate (weight %)

	Kurravaara					Valkeasiipivaara					Pahtosvaara	
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	53.2	50.0	57.5	59.5	52.2	59.8	54.2	55.0	54.3	57.2	58.4	50.6
TiO_2	0.19	0.20	0.26	0.39	0.74	0.11	0.18	0.40	0.57	0.44	0.08	0.17
Al_2O_3	18.2	17.0	17.9	17.9	19.7	17.7	19.5	17.8	18.9	17.9	18.4	14.6
Fe_2O_3	1.77	2.09	1.03	1.07	2.43	2.26	8.55	1.90	2.02	1.39	3.53	1.72
Fe_3O_4	12.07	16.05	2.11	—	11.40	4.10	0.12	4.10	10.08	8.08	—	15.71
MnO	0.10	0.07	0.06	0.06	0.04	0.04	0.06	0.05	0.03	0.04	0.06	0.03
MgO	1.70	1.09	0.62	0.13	1.54	1.28	0.33	0.75	1.58	1.60	0.17	3.24
CaO	2.26	3.01	6.09	7.62	2.20	2.54	4.14	5.56	2.17	3.10	4.34	3.62
BaO	0.01	0.04	0.01	0.03	0.02	0.03	0.04	0.03	0.01	0.02	0.02	<0.01
Na_2O	8.26	7.99	7.83	7.71	6.98	9.64	8.40	7.47	7.71	7.21	9.30	7.85
K_2O	0.08	0.88	0.32	0.65	0.53	0.49	1.18	0.81	0.33	0.59	0.60	0.10
P_2O_5	0.32	0.32	0.16	0.23	0.37	0.25	0.46	0.21	0.27	0.25	0.19	0.34
F	0.03	0.03	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.02	0.03	0.08
CO_2	0.24	0.53	5.09	4.48	1.26	0.62	2.75	4.50	1.17	0.18	2.96	1.03
S	—	—	0.03	0.06	0.05	—	—	0.32	0.02	0.03	—	0.03
CuO	0.01	<0.01	<0.01	0.03	0.01	<0.01	0.01	0.08	0.01	0.01	0.01	0.03
Σ	98.44	99.30	99.03	99.86	99.49	98.88	99.96	99.00	99.19	98.06	98.09	99.15

1, 2, 6, 7, 11, 12 = pebbles of typical porphyry
5, 9, 10 = light grey nonporphyric pebbles
3, 4, 8 = skarn-bearing porous nonporphyric pebbles

TABLE 4. Chemical analyses of magnetite-syenite-porphyry pebbles from the Kurravaara conglomerate (weight %)

	1	2	3	4	5	6	7	8	9	10
SiO_2	45.5	51.0	46.2	44.0	29.8	41.2	41.1	44.1	56.8	44.4
TiO_2	1.20	0.72	0.84	0.80	0.44	0.64	0.60	0.40	0.68	0.92
Al_2O_3	11.7	13.4	13.6	10.4	2.76	8.58	14.6	7.28	8.26	10.5
Fe_2O_3	3.72	7.43	6.43	5.15	19.7	11.6	5.29	5.86	3.57	6.15
Fe_3O_4	21.1	15.3	19.9	24.5	31.1	24.5	21.1	31.9	18.7	26.9
MnO	0.12	0.09	0.08	0.12	0.22	0.15	0.18	0.10	0.16	—
MgO	2.07	2.62	2.62	2.12	1.01	2.77	2.16	1.29	2.62	0.99
CaO	5.45	2.60	2.95	4.84	7.33	4.09	4.22	3.10	2.98	2.85
BaO	0.07	0.13	0.13	0.06	0.09	0.09	0.16	0.10	0.03	0.11
Na_2O	4.50	3.10	3.10	3.90	0.60	2.20	2.80	2.40	2.80	4.50
K_2O	0.26	1.40	1.30	0.42	0.38	0.80	2.70	0.64	0.78	0.20
P_2O_5	0.11	0.14	0.27	0.23	1.63	0.09	0.34	0.11	0.06	0.34
V_2O_5	0.03	0.07	0.14	0.14	0.12	0.11	0.14	0.14	0.07	0.09
F	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cl	0.03	0.03	0.03	0.03	0.02	0.04	0.04	0.05	0.07	0.04
CO_2	3.71	0.89	1.07	3.32	4.61	2.74	3.14	2.23	2.42	1.50
S	0.071	0.002	0.009	—	0.022	0.010	0.004	0.002	0.008	0.010
CuO	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.07
Σ	99.65	98.93	98.67	100.04	99.88	99.62	98.58	99.81	100.01	99.57

1—10 = hand specimens from north of Kurravaara

TABLE 5. Chemical analyses of magnetite-syenite-porphyry (weight %)

	1 Dh 597 m 22	2 Dh 597 m 39	3 Dh 597 m 40	4 Dh 597 m 182	5 Dh 597 m 195
SiO_2	42.2	45.6	43.3	35.8	38.2
TiO_2	0.63	0.61	0.79	0.91	0.55
Al_2O_3	11.7	10.6	10.8	10.6	10.3
Fe_2O_3	6.63	4.23	6.56	4.55	1.77
Fe_3O_4	28.65	27.32	26.99	29.64	34.95
MnO	0.01	0.01	0.02	0.05	0.05
MgO	1.56	2.54	2.02	9.04	4.14
CaO	1.01	1.18	1.18	0.93	1.60
BaO	0.02	<0.01	—	—	—
Na_2O	5.90	5.12	5.53	3.17	4.60
K_2O	0.44	1.04	0.87	4.00	2.02
P_2O_5	0.08	0.46	0.44	0.02	0.07
V_2O_5	0.12	0.09	0.10	0.09	0.12
F	0.09	—	—	—	—
Cl	0.02	—	—	—	—
CO_2	0.33	0.98	1.47	0.64	1.10
S	0.011	0.005	0.015	0.012	0.006
CuO	0.02	<0.01	<0.01	<0.01	0.01
Σ	99.42	99.78	100.08	99.45	99.48

1—5 = west of Syväjärvi

TABLE 6. Chemical analyses of syenite-porphyry (weight %)

	1	2	3	4	5	6
SiO_2	45.2	47.3	48.5	57.1	60.0	60.8
TiO_2	1.28	1.29	1.12	0.78	0.62	1.12
Al_2O_3	15.3	15.1	16.1	16.7	17.3	16.4
Fe_2O_3	3.15	2.70	2.32	0.23	0.74	1.42
Fe_3O_4	21.15	19.07	20.73	10.08	3.44	3.44
MnO	0.06	0.12	0.08	0.02	0.02	0.02
MgO	0.51	1.19	0.60	0.48	1.99	2.25
CaO	2.88	2.52	0.98	2.24	3.16	3.10
BaO	0.02	0.03	0.02	0.01	—	<0.01
Na_2O	7.40	5.60	8.00	8.40	8.52	8.20
K_2O	0.08	1.08	0.20	0.72	1.05	0.46
P_2O_5	1.26	0.89	0.46	0.50	0.53	0.53
F	0.02	0.01	0.01	0.15	—	0.19
CO_2	1.21	2.75	0.31	1.14	2.00	1.34
S	0.130	0.008	0.011	0.020	0.007	0.003
CuO	0.03	0.01	<0.01	0.03	<0.01	0.03
Σ	99.68	99.66	99.44	98.60	99.37	99.30

1—3 = syenite-porphyry with nodules of magnetite
4—6 = nodular syenite-porphyry
1 = drill hole 483—84 m, 2 = drill hole 484—8 m, 3 = drill hole 485—56 m,
4 = drill hole 486—58 m, 5 = drill hole 486—95 m, 6 = drill hole 597—21 m

TABLE 7. Chemical analyses of ore fragments and apatite from the quartz-bearing porphyry (weight %)

	1	2	3
Fe_3O_4	5.14	6.09	0.46
Fe_2O_3	54.89	47.33	2.63
SiO_2	30.8	3.25	4.55
MnO	0.03	0.06	0.18
CaO	0.12	22.2	50.5
MgO	1.57	0.27	0.14
P_2O_5	<0.01	16.8	38.3
Al_2O_3	4.25	1.09	0.54
TiO_2	0.58	0.43	0.05
V_2O_5	0.07	0.07	<0.01
CuO	<0.01	0.59	<1.43
Na_2O	0.88	0.10	0.13
K_2O	0.93	0.30	0.23
CO_2	0.59	0.28	0.22
Fe	42.11	37.51	2.17
P	0.004	7.33	16.7
Fe^{2+}	1.24	1.47	0.11
S	0.002	0.020	0.031
F	0.021	0.16	3.40
Cl	0.023	0.039	0.03
Σ	99.89	99.07	101.39

1 = west of the Rektorn ore
2 = west of drill hole 189
3 = apatite-mass, west of drill hole 189

TABLE 8. Chemical analyses of anhydrite (weight %)

SO_3	55.4
F	0.01
Cl	0.02
Fe_3O_4	0.41
Fe_2O_3	0.71
MnO	0.02
MgO	0.21
Na_2O	0.03
K_2O	0.07
CaO	38.8
Al_2O_3	0.22
SiO_2	0.70
TiO_2	0.03
V_2O_5	0.01
P_2O_5	0.02
CO_2	2.01
CuO	0.01
BaO	0.01
Σ	98.69

Loss of ignition = 0.63

TABLE 9. Chemical analyses of quartz-bearing porphyry (weight %)

	Kiirunavaara										
	1	1a	2	3	4	5	6	7	8	9	10
SiO_2	67.42	4.03	70.0	76.5	57.9	69.3	66.7	67.1	69.2	68.2	71.6
TiO_2	0.35	0.12	0.04	0.02	0.50	0.42	0.62	0.62	0.43	0.20	0.30
Al_2O_3	13.49	1.05	10.1	10.6	13.7	14.2	16.0	14.0	12.1	13.2	14.8
Fe_2O_3	3.50	1.07	11.7	0.53	12.63	3.00	3.99	4.76	2.95	6.96	1.33
Fe_3O_4	2.49	0.98	0.12	2.11	1.45	1.45	0.12	0.12	0.95	—	1.45
MnO	0.06	0.06	0.19	—	0.03	0.01	0.01	0.09	0.02	0.10	0.02
MgO	1.70	1.71	0.49	0.28	0.38	0.25	0.33	0.46	1.88	1.49	0.47
CaO	1.55	1.77	0.18	1.12	1.19	0.20	0.88	0.96	2.11	1.88	0.38
BaO	0.04	0.01	0.05	0.12	0.07	<0.01	0.08	—	<0.01	0.05	0.04
Na_2O	5.51	1.01	0.08	2.09	1.13	4.60	4.20	2.59	6.10	0.38	5.03
K_2O	2.91	1.21	7.17	5.51	9.11	5.80	6.20	6.42	0.72	5.77	3.22
P_2O_5	0.04	0.03	0.05	0.46	0.19	0.10	0.25	0.21	0.15	0.11	0.05
F	0.07	0.04	0.05	0.05	0.05	—	0.06	—	0.17	0.05	0.01
CO_2	0.80	0.50	0.31	0.39	1.36	0.25	0.23	0.37	1.36	1.48	0.85
S	0.26	0.53	0.002	0.180	0.022	0.032	0.005	0.005	0.007	0.001	0.004
CuO	—	—	0.07	<0.01	0.03	0.01	0.04	0.03	0.05	<0.01	0.01
Σ	100.19	—	100.60	99.96	99.74	99.62	99.71	97.73	98.19	99.87	99.56

1 = average of 25 analyses, 1a = standard deviation, 2 = Haukivaara, 3—4 = Lappmalmen, 5 = Henry, 6—7 = drill holes at Kurravaara road, 8 = Syväjärvi, 9 = Välivaara, 10 = Hopukka

TABLE 10. Chemical analyses of meta-dolerite (meta-diabase) (weight %)

SiO_2	50.1
TiO_2	2.18
Al_2O_3	15.9
Fe_2O_3	4.84
Fe_3O_4	14.06
MnO	0.03
MgO	3.17
CaO	0.68
Na_2O	4.70
K_2O	2.90
P_2O_5	0.46
V_2O_5	0.08
CO_2	0.23
CuO	0.01
S	0.01
Σ	99.35

East of Luossavaara's ore body

TABLE 11. Chemical analyses of detritus of porphyry (weight %)

	1 Dh 70	2 Dh 479	3 Dh 246–10	4 Dh 246–80	5 Dh 1179	6 Dh 1130	7 Rektorn
SiO_2	64.5	65.0	58.7	56.1	76.5	57.9	54.1
TiO_2	0.06	0.11	0.10	0.10	0.02	0.50	0.33
Al_2O_3	17.4	16.6	8.55	12.5	10.6	13.7	8.40
Fe_2O_3	2.59	2.80	5.43	3.03	0.53	12.63	9.06
Fe_3O_4	0.12	0.12	9.41	1.24	2.11	1.45	20.03
MnO	0.08	0.13	0.06	0.09	—	0.03	0.04
MgO	0.40	1.39	1.11	2.76	0.28	0.38	0.22
CaO	3.80	1.96	4.34	9.16	1.12	1.19	0.44
BaO	0.15	0.05	0.04	0.50	0.12	0.07	<0.01
Na_2O	0.40	2.92	1.22	3.46	2.09	1.13	1.04
K_2O	7.10	5.80	5.02	3.34	5.51	9.11	4.60
P_2O_5	2.86	0.11	2.80	3.23	0.46	0.19	0.04
F	0.03	0.01	0.20	0.20	0.05	0.05	0.02
CO_2	0.32	2.72	1.58	4.03	0.39	1.36	0.54
S	0.004	0.001	0.008	0.020	0.180	0.022	0.031
CuO	<0.01	<0.01	—	—	<0.01	0.03	0.03
Σ	99.81	99.72	98.56	99.76	99.96	99.74	98.92

1 = grey with reddish spherolites, 2 = red, homogenous, 3 = grey-red, 4 = grey-red with spherolites, 5 = red, 6 = red, hematite impregnated, 7 = red-grey banded

TABLE 12. Chemical analyses of syenite-porphyry of Hauki type (weight %)

	Henry Dh 370	Henry Dh 226	Nukutusv. Dh 1129	Nukutusv. Dh 958	Rektorn Dh 478	Syväjärvi Dh 910	Rektorn Dh 1281
SiO_2	46.4	52.9	54.7	43.7	47.6	52.8	45.2
TiO_2	1.30	1.30	0.57	0.16	1.33	1.18	1.22
Al_2O_3	21.0	16.9	18.7	13.0	19.5	19.1	17.0
Fe_2O_3	12.22	10.79	14.14	9.22	12.25	4.92	11.08
Fe_3O_4	0.46	4.77	0.12	21.35	0.46	6.22	—
MnO	0.20	0.03	—	0.02	0.11	0.11	0.11
MgO	1.92	2.22	1.52	3.80	1.89	4.74	1.35
CaO	3.78	1.12	0.98	1.03	3.73	1.82	9.93
BaO	0.13	0.02	0.19	0.11	0.12	0.10	0.14
Na_2O	2.40	4.00	0.16	0.54	3.08	2.24	0.92
K_2O	5.29	3.10	7.66	5.94	4.72	4.20	4.83
P_2O_5	0.64	0.57	0.73	0.71	0.60	1.15	0.53
F	0.02	0.08	0.05	0.06	0.02	0.03	0.04
CO_2	3.80	0.35	0.21	0.30	2.77	0.53	7.41
S	0.003	0.020	0.008	0.026	<0.001	0.005	0.003
CuO	<0.01	0.01	<0.01	0.02	0.01	0.07	0.01
Σ	99.56	98.18	99.73	99.98	98.19	99.21	99.72

TABLE 13. Chemical analyses of sericite quartzite (weight %)

	Dh 910 m 44	Dh 910 m 45	Dh 142	Dh 724	Syväjärvi hand sp.		Dh 755
SiO_2	77.4	80.3	84.8	76.9	78.1	79.5	45.8
TiO_2	0.22	0.25	0.06	0.07	0.14	0.23	1.04
Al_2O_3	13.2	11.0	7.65	4.73	9.86	4.14	13.1
Fe_2O_3	1.30	1.32	0.43	2.86	4.05	13.45	20.15
Fe_3O_4	—	—	0.46	0.40	0.12	0.12	1.12
MnO	0.08	0.02	<0.01	<0.01	<0.01	<0.01	0.03
MgO	0.61	0.68	0.78	0.08	0.60	0.30	1.16
CaO	0.28	0.38	0.11	0.06	0.21	0.19	5.92
BaO	0.06	<0.01	—	—	—	—	0.43
Na_2O	0.16	0.10	0.04	0.38	0.11	0.05	0.58
K_2O	5.55	2.70	2.65	3.70	3.01	1.25	4.52
P_2O_5	0.01	0.18	0.018	0.02	0.016	0.018	0.25
F	<0.01	0.07	—	—	—	—	0.03
CO_2	0.30	0.18	0.42	—	0.37	0.43	4.67
S	0.004	0.012	0.005	0.77	0.004	0.007	0.036
CuO	0.01	0.02	<0.01	—	<0.01	<0.01	<0.01
Σ	99.18	97.21	97.42	89.97	96.58	99.67	98.83

TABLE 14. Chemical analyses of greywacke (weight %)

	Rektorn	Nukutus-vaara	Dh 479	Syväjärvi North	Syväjärvi North
SiO_2	65.2	60.2	48.6	55.4	57.3
TiO_2	0.90	0.90	1.04	0.53	0.90
Al_2O_3	14.0	13.1	13.2	12.3	13.9
Fe_2O_3	7.75	13.01	23.59	26.74	17.73
Fe_3O_4	1.70	—	—	—	—
MnO	0.14	0.12	0.16	<0.01	0.05
MgO	0.63	0.51	0.72	0.20	0.88
CaO	1.57	1.98	3.95	0.11	2.13
BaO	0.21	0.19	0.15	0.36	0.17
Na_2O	1.03	1.00	0.65	0.38	0.22
K_2O	4.49	4.49	3.51	2.70	4.28
P_2O_5	0.48	0.60	0.73	0.09	0.60
F	0.03	0.04	0.05	<0.01	0.04
CO_2	1.23	3.79	2.99	0.68	1.33
S	0.012	0.012	0.003	0.014	0.082
CuO	0.01	0.01	0.01	0.01	0.01
Σ	99.38	99.95	99.35	99.51	99.62

TABLE 15. Chemical analyses of phyllite (weight %)

	Dh 577	Dh 478	Dh 630	Dh 479
SiO_2	63.2	55.3	50.9	61.5
TiO_2	0.79	0.63	0.77	0.32
Al_2O_3	18.4	22.2	26.3	18.0
Fe_2O_3	4.89	9.17	5.75	9.42
Fe_3O_4	0.46	0.12	0.79	0.46
MnO	0.04	0.05	0.08	0.08
MgO	3.15	3.68	2.62	3.88
CaO	0.43	0.40	0.21	0.36
BaO	0.06	0.02	0.09	0.07
Na_2O	0.16	0.16	0.16	0.10
K_2O	5.80	5.70	8.20	5.02
P_2O_5	0.19	0.15	0.18	0.13
F	0.06	0.11	0.01	0.05
CO_2	0.36	0.16	0.36	0.24
S	0.020	0.78	<0.001	0.010
CuO	0.06	0.02	<0.01	<0.01
Σ	98.07	98.65	96.42	99.64

TABLE 16. Chemical analyses of quartzitic sandstone (weight %)

	Dh 346 Σ 50 m	Dh 916 Σ 100 m	Dh 913 Σ 100 m	Dh 914 Σ 100 m	Dh 915 Σ 100 m	Dh 954 Σ 100 m
SiO_2	92.2	89.2	86.4	88.0	88.4	86.1
TiO_2	0.09	0.11	0.10	0.11	0.12	0.11
Al_2O_3	2.38	5.19	4.89	5.06	5.40	6.10
Fe_2O_3	0.61	—	—	—	—	—
Fe_3O_4	1.12	0.68	0.62	0.80	0.83	0.73
MnO	0.03	—	0.03	0.028	0.004	0.026
MgO	0.13	—	0.18	0.17	0.04	0.10
CaO	0.24	0.55	0.29	0.60	0.18	0.52
BaO	—	0.03	0.04	0.03	0.01	—
Na_2O	0.32	0.48	0.54	0.64	0.42	0.60
K_2O	1.63	2.23	2.07	2.11	1.97	2.13
P_2O_5	0.06	0.03	0.03	0.03	0.02	0.03
V_2O_5	0.01	—	0.03	0.00	0.00	0.00
F	0.01	—	0.009	0.009	0.007	0.013
Cl	0.03	—	0.01	0.00	0.02	0.01
S	0.012	—	0.004	0.004	0.004	0.004
Σ	98.87	98.50	95.23	97.57	97.41	96.46

TABLE 17. Chemical analyses of ores from Kiirunavaara, Luossavaara and Luossajärvi (weight %)

	Kiirunavaara					Luossavaara		Luossajärvi			
Fe_3O_4	86.03	82.71	87.69	82.71	3.11	90.68	81.72	74.42	36.28	30.97	8.42
Fe_2O_3	9.78	1.73	3.76	2.76	73.62	0.66	4.90	0.84	53.46	59.21	84.23
SiO_2	2.06	1.21	3.65	0.72	10.4	2.57	6.15	1.18	2.00	0.49	0.91
MnO	0.04	0.06	0.09	0.04	0.02	0.04	0.11	0.06	0.01	0.01	<0.01
CaO	0.50	7.05	1.02	6.86	4.85	1.33	1.88	11.5	3.45	4.70	3.26
MgO	0.42	0.47	1.63	0.39	4.13	1.34	1.79	0.74	0.32	0.17	0.07
P_2O_5	0.10	5.20	0.02	4.86	2.18	0.78	0.04	9.51	2.80	3.69	2.47
Al_2O_3	0.19	0.24	0.60	0.13	0.20	1.06	0.54	0.02	0.74	0.14	0.12
TiO_2	0.22	0.26	0.86	0.02	0.03	0.92	1.55	0.01	0.03	0.02	0.01
V_2O_5	0.13	0.23	0.20	0.13	0.23	0.18	0.23	0.17	0.18	0.11	0.16
Na_2O	0.07	0.05	0.03	0.09	0.06	0.03	0.10	0.04	0.03	0.05	0.05
K_2O	0.20	0.13	0.20	0.11	0.02	0.23	0.26	0.05	0.04	0.05	0.01
CuO	0.004	<0.001	<0.001	0.002	0.002	<0.001	0.009	<0.001	0.040	<0.001	<0.001
BaO	0.004	0.003	0.001	0.002	0.002	0.003	0.003	0.003	0.001	0.001	0.003
CO_2	0.20	0.14	0.14	0.40	0.15	0.11	0.11	0.38	0.10	0.12	0.10
Fe	69.09	61.06	66.08	61.78	53.74	66.07	62.56	54.44	63.64	63.82	65.00
Fe^{2+}	20.75	19.95	21.15	19.95	0.75	21.87	19.71	17.95	8.75	7.47	2.03
P	0.045	2.27	0.010	2.12	0.95	0.34	0.018	4.15	1.22	1.61	1.08
S	0.11	0.012	0.007	0.074	0.040	0.042	0.014	0.010	0.062	0.020	0.057
F	0.04	0.37	0.01	0.42	0.16	0.08	0.05	0.66	0.19	0.30	0.28
Cl	0.04	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.01	0.02	0.02
Σ	100.13	99.88	99.93	99.74	99.23	100.07	99.46	99.61	99.74	100.07	100.16

TABLE 17 a. Chemical analyses of ores from Tuolluvaara (weight %)

	Tuolluvaara			
Fe_3O_4	86.03	44.90	3.44	1.45
Fe_2O_3	2.19	22.46	90.91	77.71
SiO_2	0.76	11.5	0.48	3.24
MnO	0.06	0.03	<0.01	<0.01
CaO	5.16	7.61	2.43	8.92
MgO	0.74	2.13	0.19	0.10
P_2O_5	4.03	5.73	1.95	6.65
Al_2O_3	0.09	2.14	0.24	0.24
TiO_2	0.07	1.28	0.30	0.26
V_2O_5	0.10	0.11	0.07	0.04
Na_2O	0.03	0.29	0.03	0.07
K_2O	0.07	0.05	0.01	0.01
CuO	0.004	<0.001	<0.001	<0.001
BaO	0.003	0.003	0.002	0.003
CO_2	0.21	0.15	0.10	0.10
Fe	63.78	48.20	66.07	55.40
Fe^{2+}	20.75	10.83	0.83	0.35
P	1.76	2.50	0.85	2.90
S	0.007	0.006	0.003	0.011
F	0.20	0.43	0.14	0.51
Cl	0.11	0.03	0.02	0.02
Σ	99.85	99.84	100.31	99.33

TABLE 18. Chemical analyses of iron ore from Haukivaara (weight %)

	1 Dh 235 m 36	2 Dh 235 m 45	3 Dh 236 m 51	4 Dh 236 m 9	5 Dh 236 m 21	6 Dh 236 m 44	7 Dh 237 m 70	8 Dh 237 m 73	9 Dh 238 m 5	10 Dh 238 m 14
Fe_3O_4	2.86	2.20	2.53	2.53	5.06	5.72	4.44	12.07	2.53	3.19
Fe_2O_3	89.18	81.86	75.91	77.24	68.39	71.96	69.57	72.29	87.63	66.93
SiO_2	1.02	0.66	1.03	12.0	17.5	0.69	4.60	0.84	8.48	21.5
MnO	0.02	0.03	0.06	0.15	0.10	0.17	0.18	0.20	0.13	0.10
CaO	3.28	6.15	8.45	2.95	4.20	11.8	12.2	7.70	0.20	3.50
MgO	0.03	0.09	0.06	0.05	0.05	0.05	0.20	0.45	0.05	0.10
P_2O_5	2.61	4.08	7.56	1.97	2.82	8.32	5.27	3.73	0.09	2.64
Al_2O_3	0.00	0.10	0.26	2.20	0.95	0.75	0.75	0.90	0.70	1.70
TiO_2	0.35	0.32	0.61	0.22	0.20	0.33	0.28	0.50	0.22	0.20
V_2O_5	0.18	0.13	0.23	0.17	0.12	0.16	0.22	0.25	0.14	0.12
CO_2	0.27	0.20	0.20	0.30	0.70	0.26	2.72	1.65	0.42	0.22
Na_2O	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.03
K_2O	0.02	0.04	0.08	0.51	0.19	0.08	0.06	0.11	0.08	0.37
CuO	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.02	0.03	0.02
BaO	0.01	0.01	0.01	0.01	<0.01	0.01	0.01	0.01	0.01	0.02
Fe	64.44	58.84	54.92	55.85	51.49	54.47	51.84	59.29	63.12	49.12
Fe^{2+}	0.69	0.53	0.61	0.61	1.22	1.38	1.07	2.91	0.61	0.77
P	1.14	1.78	3.30	0.86	1.23	3.63	2.30	1.63	0.038	1.15
S	0.009	0.009	0.010	0.007	0.010	0.007	0.016	0.026	0.006	0.006
F	0.21	0.31	0.60	0.16	0.23	0.70	0.41	0.29	<0.005	0.21
Cl	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.01	0.01	<0.01
Σ	100.09	96.23	97.66	100.53	100.59	101.07	101.00	101.06	100.73	100.85

Fe, Fe^{2+}, P, S, CO_2, F, Cl, Na, K = wet chemical methods (otherwise spectrographic analysis)

TABLE 19. Chemical analyses of iron ore from Rektorn (weight %)

	1 Dh 4— 17 m	2 Dh 4— 39 m	3 Dh 11— 15 m	4 Dh 12— 4 m	5 Dh 16— 25 m	6 Dh 16— 31 m
Fe_3O_4	18.41	25.37	24.75	32.88	11.28	3.81
Fe_2O_3	56.32	22.51	15.20	33.81	19.60	70.88
SiO_2	12.6	25.1	4.20	2.98	18.6	3.60
MnO	0.10	0.06	0.04	0.04	0.04	0.05
CaO	3.95	9.75	29.3	15.7	23.4	11.0
MgO	1.93	1.10	0.50	0.40	0.78	0.48
P_2O_5	0.59	6.03	21.40	11.20	16.59	5.80
Al_2O_3	1.05	4.45	0.63	0.35	3.50	0.33
TiO_2	0.82	0.32	0.53	0.31	0.33	0.63
V_2O_5	0.20	0.10	0.08	0.14	0.06	0.19
CO_2	3.64	1.12	1.42	0.94	1.70	2.08
Na_2O	0.02	1.06	0.04	0.05	0.28	0.03
K_2O	0.36	1.95	0.13	0.14	1.45	0.09
CuO	0.08	0.02	0.03	0.02	0.01	0.03
BaO	0.01	0.06	0.01	0.02	0.01	0.01
Fe	52.71	34.10	28.54	47.44	21.87	52.33
Fe^{2+}	4.44	6.12	5.97	7.93	2.72	0.92
P	0.259	2.63	9.34	4.89	7.24	2.53
S	0.053	0.039	0.107	0.047	0.038	0.056
F	0.043	0.47	1.80	0.56	1.46	0.43
Cl	0.01	0.01	0.02	0.02	0.02	<0.01
Σ	100.18	99.51	100.18	99.60	99.14	99.49

TABLE 20. Chemical analyses of iron ore from Henry (weight %)

	Dh 263— 87 m	Dh 263— 96 m	Dh 263— 102 m	Dh 264— 172 m	Dh 264— 183 m
Fe_3O_4	26.00	31.72	54.60	54.56	30.43
Fe_2O_3	57.11	16.81	11.37	6.95	19.96
SiO_2	1.06	5.28	2.18	6.59	3.38
MnO	0.05	0.08	0.06	0.05	0.07
CaO	8.10	23.30	15.70	15.0	23.9
MgO	0.30	1.00	0.70	1.57	0.40
P_2O_5	5.96	15.81	10.91	11.39	16.96
Al_2O_3	0.45	0.90	0.35	1.42	0.50
TiO_2	0.31	0.29	0.23	0.34	0.33
V_2O_5	0.19	0.11	0.18	0.16	0.13
CO_2	0.22	2.44	1.64	0.50	1.16
Na_2O	0.03	0.26	0.06	0.18	0.04
K_2O	0.09	0.31	0.09	0.36	0.06
CuO	0.02	0.02	0.02	0.02	0.02
BaO	0.07	0.07	0.09	0.02	0.07
Fe	58.75	34.71	47.46	44.34	35.98
Fe^{2+}	6.27	7.65	13.17	13.16	7.34
P	2.60	6.90	4.76	4.97	7.40
S	0.010	0.060	0.240	0.019	0.035
F	0.31	1.38	0.95	0.99	1.48
Cl	0.02	0.01	0.01	0.03	0.03
Σ	100.30	99.85	99.38	100.14	98.95

TABLE 21. Chemical analyses of iron ore from Nukutusvaara (weight %)

	1 Dh 248— 435 m	2 Dh 252— 579 m	3 Dh 252— 597 m	4 Dh 244— 331 m	5 Dh 269— 23 m	6 Dh 257— 965 m	7 Dh 257— 976 m
Fe_3O_4	7.92	58.67	64.06	54.60	57.71	6.68	11.73
Fe_2O_3	63.78	11.72	12.93	9.37	1.49	72.18	52.42
SiO_2	5.30	5.54	8.52	5.10	27.8	7.08	7.56
MnO	0.08	0.06	0.07	0.05	0.05	0.05	0.03
CaO	13.2	11.1	3.60	16.0	1.50	6.00	12.4
MgO	0.43	0.68	2.10	0.90	0.70	0.30	2.20
P_2O_5	5.27	6.42	0.108	10.17	0.24	4.35	9.37
Al_2O_3	0.44	0.65	2.75	0.70	4.55	0.70	0.30
TiO_2	0.45	0.77	0.82	0.43	0.47	0.66	0.58
V_2O_5	0.15	0.21	0.22	0.12	0.11	0.18	0.25
CO_2	0.84	1.92	2.02	2.00	0.10	0.28	0.62
Na_2O	0.03	0.05	0.06	0.06	3.60	0.03	0.05
K_2O	0.09	0.25	1.12	0.20	0.08	0.09	0.25
CuO	0.02	0.05	0.05	0.03	0.02	0.02	0.02
BaO	0.02	0.02	0.03	0.01	0.03	<0.01	0.01
Fe	50.34	50.65	55.39	46.06	42.80	55.31	45.15
Fe^{2+}	1.91	14.15	15.45	13.17	13.92	1.61	2.83
P	2.30	2.80	0.047	4.44	0.106	1.90	4.09
S	0.018	0.018	0.019	0.017	0.011	0.014	0.030
F	0.44	0.52	0.031	0.80	0.020	0.37	0.88
Cl	<0.01	0.02	0.01	<0.01	0.03	0.02	0.01
Σ	98.47	98.66	98.51	100.55	98.51	99.00	98.71

TABLE 22. Chemical analyses of iron ore from Lappmalmen (weight %)

	1 Dh 1130 900 m	2 Dh 1130 942 m	3 Dh 333 896 m	4 Dh 333 1160 m	5 Dh 333 1260 m	6 Dh 333 1332 m
Fe_3O_4	55.18	2.45	4.52	20.69	69.16	59.29
Fe_20_3	3.82	77.16	75.66	21.93	3.53	0.03
SiO_2	0.92	1.55	11.4	9.88	1.00	25.4
MnO	—	0.06	0.03	0.14	0.03	0.08
CaO	21.3	8.40	2.52	20.5	13.3	3.60
MgO	0.08	0.55	0.36	2.12	0.34	1.63
P_2O_5	15.15	5.73	0.23	7.10	10.1	0.34
Al_2O_3	0.60	0.57	1.75	2.19	0.12	2.55
TiO_2	0.02	0.35	0.46	0.18	0.12	0.38
V_2O_5	0.04	0.16	0.21	0.08	0.12	0.11
CO_2	0.30	2.04	2.30	8.30	1.31	4.35
Na_2O	0.04	0.02	0.10	0.04	0.04	0.14
K_2O	0.07	0.06	0.60	0.07	0.07	0.75
CuO	<0.01	0.01	<0.01	0.07	<0.01	<0.01
BaO	0.04	0.02	0.01	0.02	0.01	0.03
Fe	42.61	55.74	56.19	30.31	52.51	42.92
Fe^{2+}	13.31	0.59	1.09	4.99	16.68	14.30
P	7.05	2.50	0.10	3.10	4.40	0.15
S	0.015	0.153	0.07	1.19	0.08	0.55
F	1.35	0.52	0.02	0.48	0.80	0.02
Cl	0.02	0.01	0.02	0.01	0.01	0.04
Σ	98.94	99.81	100.26	94.10	100.14	99.29

TABLE 23. Chemical analyses of Hauki hematite (weight %)

	1	2	3	4	5	6	7	8	9
Fe_3O_4	1.45	3.3	6.6	3.7	2.5	1.7	6.47	0.95	1.16
Fe_2O_3	38.02	37.6	34.0	49.8	65.3	41.3	32.38	42.26	34.03
SiO_2	44.4	52.0	49.7	35.0	23.0	47.7	32.8	52.8	48.4
MnO	0.03	—	—	—	—	—	0.03	0.02	0.01
CaO	2.15	0.24	0.44	0.42	1.99	0.58	4.25	0.17	0.06
MgO	0.21	0.14	0.12	0.14	0.20	0.12	0.67	0.10	0.60
P_2O_5	0.30	0.11	0.23	0.10	1.53	0.44	2.50	0.10	0.04
Al_2O_3	2.00	1.84	2.85	2.57	2.77	2.43	9.97	0.78	7.91
TiO_2	0.13	0.20	0.24	0.24	0.18	0.20	1.30	0.14	0.45
V_2O_5	0.01	—	—	—	—	—	0.06	0.01	0.01
CO_2	2.90	—	—	—	—	—	1.61	0.20	0.22
Na_2O	0.34	0.07	0.10	0.04	0.08	0.11	1.09	0.03	0.06
K_2O	0.18	0.32	0.42	0.51	0.71	0.40	5.66	0.35	3.80
CuO	0.01	—	—	—	—	—	0.01	—	—
BaO	6.42	1.64	1.98	3.85	0.12	1.75	—	2.13	0.04
Fe	27.64	28.7	28.6	37.5	47.5	30.1	27.33	30.2	24.64
Fe^{2+}	0.35	0.8	1.6	0.9	0.6	0.4	1.56	0.23	0.28
P	0.13	0.048	0.009	0.044	0.67	0.19	1.09	0.043	0.016
S	1.27	0.37	0.42	0.78	0.016	0.37	0.15	0.44	0.006
F	0.032	0.014	0.022	0.010	0.122	0.029	0.22	0.007	0.006
Cl	—	—	<0.01	0.01	—	0.01	0.04	0.04	0.01
Σ	99.85	97.84	97.12	97.17	98.51	97.13	99.21	100.52	96.80

1—6 = Syväjärvi North, 7 = Lappmalmen, 8 = Kiruna city, 9 = Kiruna city

TABLE 24. Median values of Cu in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	80	40
2. Hauki hematite	—	60
3. Sericite quartzite	20	60
4. Syenite-porphyry (Hauki type)	16	110
5. Detritus of porphyry	15	40
6. Per Geijer ores	15	30
7. Quartz-bearing porphyry	10	30
8a. Kiirunavaara ore 320 m level	40	70
8b. Kiirunavaara ore 800 m level	10	—
9. Luossavaara ore	4	—
10. Luossajärvi ore	10	30
11. Tuolluvaara ore	20	30
12. Syenite-porphyry	10	—
13. Magnetite-syenite-porphyry	0	—
14. Kurravaara conglomerate, matrix	10	—
15. Kurravaara conglomerate, pebbles	20	—
16. Kiruna greenstone	10	—

TABLE 25. Median values of Zn in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	40	60
2. Hauki hematite	—	55
3. Sericite quartzite	30	60
4. Syenite-porphyry (Hauki type)	40	90
5. Detritus of porphyry	40	80
6. Per Geijer ores	40	60
7. Quartz-bearing porphyry	10	30
8a. Kiirunavaara ore 320 m level	50	40
8b. Kiirunavaara ore 800 m level	40	—
9. Luossavaara ore	60	—
10. Luossajärvi ore	30	20
11. Tuolluvaara ore	20	30
12. Syenite-porphyry	40	—
13. Magnetite-syenite-porphyry	40	—
14. Kurravaara conglomerate, matrix	40	—
15. Kurravaara conglomerate, pebbles	100	—
16. Kiruna greenstone	60	—

TABLE 26. Median values of Ti in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	650	2 300
2. Hauki hematite	—	1 950
3. Sericite quartzite	3 600	3 200
4. Syenite-porphyry (Hauki type)	1 500	4 400
5. Detritus of porphyry	570	3 000
6. Per Geijer ores	950	2 950
7. Quartz-bearing porphyry	1 750	4 300
8a. Kiirunavaara ore 320 m level	700	300
8b. Kiirunavaara ore 800 m level	300	—
9. Luossavaara ore	800	—
10. Luossajärvi ore	100	200
11. Tuolluvaara ore	300	1 400
12. Syenite-porphyry	1 100	—
13. Magnetite-syenite-porphyry	300	—
14. Kurravaara conglomerate, matrix	400	—
15. Kurravaara conglomerate, pebbles	300	—
16. Kiruna greenstone	2 300	—

TABLE 27. Median values of Zr in the magnetites and hematites of the Kiruna area (ppm)

Sample group		M=in magnetite H=in hematite
1. Vakko sedimentary rocks	31 specimens	M=140 H=110, 180, 80
2. Hauki hematite	4 specimens	H=90, 50
3. Sericite quartzite	12 specimens	H=70, 50
4. Syenite-porphyry (Hauki type)	20 specimens	M=0 H=0
5. Detritus of porphyry	36 specimens	M=70 H=110
6. Per Geijer ores	74 specimens	M=70 H=0
7. Quartz-bearing porphyry	25 specimens	M=60, 1 100, 140, 230, 300 H=0
8a. Kiirunavaara ore 320 m level	22 specimens	M=0 H=0
8b. Kiirunavaara ore 800 m level	14 specimens	M=0
9. Luossavaara ore	22 specimens	M=70, 60, 180
10. Luossajärvi ore	23 specimens	M=0 H=0
11. Tuolluvaara ore	18 specimens	M=0 H=0
12. Syenite-porphyry	15 specimens	M=280, 290, 110, 190, 50
13. Magnetite-syenite-porphyry	9 specimens	M=50, 90, 140, 140, 150, 140, 90
14. Kurravaara conglomerate, matrix	8 specimens	M=110, 70, 80, 90
15. Kurravaara conglomerate, pebbles	10 specimens	M=50, 80, 50, 50
16. Kiruna greenstone	3 specimens	M=0

TABLE 28. Median values of V in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	820	450
2. Hauki hematite	—	110
3. Sericite quartzite	980	460
4. Syenite-porphyry (Hauki type)	1 100	1 400
5. Detritus of porphyry	880	1 200
6. Per Geijer ores	960	1 200
7. Quartz-bearing porphyry	855	1 200
8a. Kiirunavaara ore 320 m level	1 400	1 600
8b. Kiirunavaara ore 800 m level	1 300	—
9. Luossavaara ore	1 200	—
10. Luossajärvi ore	990	1 200
11. Tuolluvaara ore	780	510
12. Syenite-porphyry	1 300	—
13. Magnetite-syenite-porphyry	1 100	—
14. Kurravaara conglomerate, matrix	1 100	—
15. Kurravaara conglomerate, pebbles	1 200	—
16. Kiruna greenstone	1 300	—

TABLE 29. Median values of Cr in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	55	20
2. Hauki hematite	—	50
3. Sericite quartzite	20	30
4. Syenite-porphyry (Hauki type)	20	20
5. Detritus of porphyry	20	20
6. Per Geijer ores	3	—
7. Quartz-bearing porphyry	20	—
8a. Kiirunavaara ore 320 m level	0	0
8b. Kiirunavaara ore 800 m level	0	—
9. Luossavaara ore	5	—
10. Luossajärvi ore	0	0
11. Tuolluvaara ore	0	0
12. Syenite-porphyry	90	—
13. Magnetite-syenite-porphyry	30	—
14. Kurravaara conglomerate, matrix	550	—
15. Kurravaara conglomerate, pebbles	345	—
16. Kiruna greenstone	1 400	—

TABLE 30. Median values of Mn in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	120	30
2. Hauki hematite	—	10
3. Sericite quartzite	40	30
4. Syenite-porphyry (Hauki type)	130	40
5. Detritus of porphyry	75	35
6. Per Geijer ores	175	70
7. Quartz-bearing porphyry	135	50
8a. Kiirunavaara ore 320 m level	720	770
8b. Kiirunavaara ore 800 m level	805	—
9. Luossavaara ore	440	—
10. Luossajärvi ore	370	20
11. Tuolluvaara ore	220	0
12. Syenite-porphyry	90	—
13. Magnetite-syenite-porphyry	150	—
14. Kurravaara conglomerate, matrix	310	—
15. Kurravaara conglomerate, pebbles	825	—
16. Kiruna greenstone	130	—

TABLE 31. Median values of Co in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	65	0
2. Hauki hematite	—	0
3. Sericite quartzite	40	10
4. Syenite-porphyry (Hauki type)	50	40
5. Detritus of porphyry	65	25
6. Per Geijer ores	80	20
7. Quartz-bearing porphyry	50	30
8a. Kiirunavaara ore 320 m level	120	80
8b. Kiirunavaara ore 800 m level	120	—
9. Luossavaara ore	60	—
10. Luossajärvi ore	85	0
11. Tuolluvaara ore	50	0
12. Syenite-porphyry	60	—
13. Magnetite-syenite-porphyry	30	—
14. Kurravaara conglomerate, matrix	30	—
15. Kurravaara conglomerate, pebbles	110	—
16. Kiruna greenstone	40	—

TABLE 32. Median values of Ni in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	425	0
2. Hauki hematite	—	20
3. Sericite quartzite	330	20
4. Syenite-porphyry (Hauki type)	470	40
5. Detritus of porphyry	505	25
6. Per Geijer ores	400	40
7. Quartz-bearing porphyry	130	20
8a. Kiirunavaara ore 320 m level	300	180
8b. Kiirunavaara ore 800 m level	265	—
9. Luossavaara ore	135	—
10. Luossajärvi ore	220	0
11. Tuolluvaara ore	240	0
12. Syenite-porphyry	110	—
13. Magnetite-syenite-porphyry	100	—
14. Kurravaara conglomerate, matrix	60	—
15. Kurravaara conglomerate, pebbles	170	—
16. Kiruna greenstone	210	—

TABLE 33. Median values of Al in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	300	900
2. Hauki hematite	—	600
3. Sericite quartzite	600	500
4. Syenite-porphyry (Hauki type)	700	500
5. Detritus of porphyry	300	550
6. Per Geijer ores	350	500
7. Quartz-bearing porphyry	600	700
8a. Kiirunavaara ore 320 m level	200	800
8b. Kiirunavaara ore 800 m level	100	—
9. Luossavaara ore	200	—
10. Luossajärvi ore	100	400
11. Tuolluvaara ore	600	400
12. Syenite-porphyry	1 200	—
13. Magnetite-syenite-porphyry	1 200	—
14. Kurravaara conglomerate, matrix	1 400	—
15. Kurravaara conglomerate, pebbles	1 300	—
16. Kiruna greenstone	600	—

TABLE 34. Median values of Mg in the magnetites and hematites of the Kiruna area (ppm)

Sample group	Magnetite	Hematite
1. Vakko sedimentary rocks	100	100
2. Hauki hematite	—	0
3. Sericite quartzite	100	100
4. Syenite-porphyry (Hauki type)	300	100
5. Detritus of porphyry	100	150
6. Per Geijer ores	100	100
7. Quartz-bearing porphyry	550	200
8a. Kiirunavaara ore 320 m level	700	700
8b. Kiirunavaara ore 800 m level	650	—
9. Luossavaara ore	400	—
10. Luossajärvi ore	700	300
11. Tuolluvaara ore	1 200	100
12. Syenite-porphyry	800	—
13. Magnetite-syenite-porphyry	300	—
14. Kurravaara conglomerate, matrix	950	—
15. Kurravaara conglomerate, pebbles	400	—
16. Kiruna greenstone	400	—

TABLE 35. Median values of some trace elements in P-rich and P-poor ores (magnetite+hematite) (ppm)

		n	Cu	Zn	Ti	V	Mn	Co	Ni	Al	Mg
Kiirunavaara	P-rich	10	40	50	200	1 550	735	120	305	150	700
320 m level	P-poor	12	45	55	950	1 300	790	115	275	250	650
Kiirunavaara	P-rich	6	10	35	150	1 300	985	115	245	100	700
800 m level	P-poor	8	10	50	700	1 350	660	120	280	150	600
Luossavaara	P-rich	1	—	—	—	—	—	—	—	—	—
	P-poor	21	4	60	800	1 200	440	60	135	200	400
Luossajärvi	P-rich	13	10	30	100	1 100	300	60	160	300	300
	P-poor	10	10	20	350	1 200	360	85	220	150	750
Tuolluvaara	P-rich	9	20	30	600	600	90	20	30	500	100
	P-poor	9	30	30	300	680	240	60	240	500	1 200
Per Geijer	P-rich	64	20	50	1 250	1 000	135	60	190	400	100
ores	P-poor	10	72	35	1 600	1 200	200	70	135	750	200

n = number

TABLE 36. Median values of some trace elements in P-rich and P-poor magnetite ore and hematite ore from the Per Geijer ores (ppm)

		n	Cu	Zn	Ti	V	Mn	Co	Ni	Al	Mg
Magnetite ore	P-rich	37	12	40	800	890	170	80	470	300	100
	P-poor	7	90	30	1 400	1 200	280	80	160	800	600
Hematite ore	P-rich	27	30	60	3 100	1 300	80	20	40	500	100
	P-poor	3	30	60	2 200	800	40	20	20	700	100

n = number

TABLE 37. Median values of some trace elements in all ore specimens of P-rich type (number = 103) and P-poor type (number = 70) (ppm)

	n	Cu	Zn	Ti	V	Mn	Co	Ni	Al	Mg
P-rich magnetite	65	12	40	400	980	260	90	300	200	400
P-rich hematite	38	30	60	2 200	1 200	65	20	20	450	100
P-poor magnetite	63	20	50	800	1 200	400	80	220	200	600
P-poor hematite	7	90	40	1 700	1 200	40	20	20	700	300

n = number

TABLE 38. The content (median values) of trace elements of all magnetites and hematites (ppm)

	n	Cu	Zn	Ti	V	Mn	Co	Ni	Al	Mg
P-rich	103	20	50	800	1 200	400	80	205	200	600
P-poor	70	20	40	700	1 100	170	60	200	300	200

n = number

TABLE 39. Median values of trace elements in co-existing magnetite and hematite (ppm)

Hematite	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Vakko sedimentary rocks	70	40	800	0	960	60	0	120	60	430	300	100
Sericite quartzite	20	30	3600	0	980	20	0	40	40	330	600	100
Syenite-porphyry (Hauki type)	40	35	1100	0	930	30	0	105	45	515	450	100
Detritus of porphyry	30	40	500	0	860	20	0	80	40	520	300	100
Per Geijer ores	30	40	750	0	900	0	0	180	60	730	300	50
Quartz-bearing porphyry	20	40	300	0	1000	0	0	150	60	450	300	200
Luossajärvi ore	10	20	0	0	670	0	0	310	50	160	100	200
Tuolluvaara ores	50	30	0	0	600	0	0	120	20	120	100	900

Magnetite	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Vakko sedimentary rocks	40	80	2900	0	1100	20	0	110	0	30	700	200
Sericite quartzite	30	40	7600	0	1400	0	0	70	60	30	300	200
Syenite-porphyry (Hauki type)	85	90	5300	0	1400	10	0	55	60	35	400	50
Detritus of porphyry	40	80	3100	0	1200	20	0	40	30	30	600	100
Per Geijer ores	25	60	3300	0	1250	0	0	75	25	40	500	100
Quartz-bearing porphyry	10	80	5600	0	1200	0	0	50	40	20	700	100
Luossajärvi ore	30	20	200	0	1200	0	0	20	0	0	400	300
Tuolluvaara ores	20	20	700	0	680	0	0	10	0	0	400	100

TABLE 40. The content of trace elements in the co-existing magnetite and hematite ore concentrates from the profile between Rektorn and Lappmalmen (see Fig. 37)

Magnetite	%		ppm											
	Fe	P	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Dh 346— 9	71.2	0.20	150	—	239	—	428	2 200	—	320	130	1 900	688	121
—11	68.6	0.20	90	—	4 076	—	1 100	170	—	70	70	180	1 217	784
—12	67.9	0.20	60	—	5 875	—	1 000	600	—	140	50	160	1 798	784
—13	69.6	0.20	70	—	4 556	—	1 400	40	—	130	60	180	1 164	1 327
—15	69.0	0.35	40	—	4 556	—	960	30	—	160	30	210	1 693	1 327
—16	65.9	0.31	50	—	2 997	—	1 200	80	—	220	40	110	4 233	4 021
—17	69.3	0.47	70	—	4 600	—	1 200	50	—	230	—	210	794	241
Dh 186— 1	69.3	0.025	100	—	2 817	—	600	980	—	140	60	900	1 375	181
— 2	71.5	0.011	170	—	299	70	500	1 700	—	250	70	3 600	793	241
— 3	68.1	0.010	180	—	112	80	440	2 000	—	280	260	1 800	3 174	2 292
— 7	71.7	0.050	200	—	239	7	820	1 700	—	260	90	2 600	688	181
— 8	71.5	0.12	80	—	590	—	560	800	—	140	90	960	317	63
—10	58.4	0.25	140	—	5 275	—	480	1 100	—	110	60	190	9 259	1 025
Dh 314— 1	67.6	0.009	130	—	4 676	—	620	600	—	130	—	170	3 597	2 533
— 2	70.2	0.003	150	—	2 517	—	590	520	—	110	40	250	1 746	952
— 3	71.7	0.060	110	—	1 139	—	770	60	—	70	30	240	846	361
— 4	71.8	0.11	110	—	179	—	370	70	—	150	60	180	476	121
— 5	72.0	0.007	40	—	1 260	—	400	40	—	70	20	140	105	—
— 6	71.1	—	28	150	959	—	570	~6 000	520	570	100	230	741	302
— 8	71.6	0.043	130	—	1 918	—	890	60	—	120	60	210	370	241
— 9	71.3	0.061	100	—	659	—	970	50	—	120	20	170	370	361
—11	71.4	0.012	70	—	419	—	640	40	—	110	50	200	635	361
—12	61.0	0.076	160	—	1 378	220	740	1 400	140	180	30	90	9 871	4 041

Hematite	%		ppm											
	Fe	P	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Dh 346— 9	67.2	0.66	120	—	659	—	530	20	—	60	—	—	952	121
—11	59.3	0.67	350	—	14 807	—	1 400	40	—	130	20	20	3 439	2 292
—12	59.3	0.42	100	—	21 343	—	1 200	90	—	200	30	30	3 705	1 689
—13	57.9	0.82	190	—	29 975	—	1 500	10	—	200	240	30	4 497	4 584
—15	59.0	1.11	190	—	21 402	—	1 400	—	—	170	60	30	4 869	3 558
—16	52.2	1.44	170	—	15 227	—	1 400	30	—	190	—	40	10 264	10 676
—17	63.8	0.84	150	—	14 567	—	1 200	—	—	100	—	20	1 798	422
Dh 186— 1	67.1	0.035	170	—	6 294	—	760	40	—	20	70	40	2 433	241
— 2	68.8	0.031	110	—	1 798	—	650	40	—	70	—	—	1 322	241
— 3	66.7	0.040	160	—	4 196	—	650	60	—	70	30	40	3 174	1 387
— 7	68.8	0.15	130	—	1 139	220	1 100	30	—	20	30	20	688	181
— 8	65.3	0.85	150	—	659	—	680	10	—	10	—	—	1 005	121
—10	47.0	0.19	140	—	8 693	150	400	90	—	30	30	30	20 899	2 171
Dh 314— 1	65.9	0.012	170	—	8 093	—	840	50	—	90	20	50	3 650	1 628
— 2	65.3	0.007	180	—	12 769	—	820	30	—	100	20	30	4 391	1 568
— 3	66.2	0.31	250	—	4 736	—	1 000	30	—	90	20	30	3 915	1 680
— 4	68.5	0.25	340	—	2 698	—	380	20	—	20	30	20	899	362
— 5	68.1	0.062	180	—	7 254	—	550	20	—	30	20	20	1 164	351
— 6	69.6	0.028	100	—	5 455	—	320	170	—	70	30	20	794	102
— 8	64.3	0.12	510	—	28 476	—	1 300	30	—	120	420	20	1 534	630
— 9	66.0	0.46	230	—	3 357	—	1 500	20	—	180	510	140	952	603
—11	62.8	0.18	650	—	4 556	—	800	40	—	140	3 200	60	5 608	3 619
—12	49.7	0.23	360	—	3 057	300	700	350	—	130	130	60	17 777	4 222

TABLE 41. Median values of trace elements in the "mono-type" magnetite and hematite (ppm)

Magnetite	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Vakko sedimentary rocks	280	60	600	0	700	40	0	220	130	110	500	300
Sericite quartzite	only hematite											
Syenite-porphyry (Hauki type)	12	50	2 500	0	1 400	20	0	170	80	240	900	700
Detritus of porphyry	10	40	600	0	900	30	0	70	90	440	440	100
Per Geijer ores	11	35	1 100	0	1 200	10	0	175	85	200	500	350
Quartz-bearing porphyry	10	40	2 000	0	840	20	0	130	50	120	600	700
Kiirunavaara 320 m level	40	50	700	0	1 400	0	0	720	120	300	200	700
Tuolluvaara ores	20	30	300	0	780	0	0	220	50	240	600	1 200

Hematite	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Vakko sedimentary rocks	30	55	1 950	0	275	25	0	20	0	0	1 050	100
Sericite quartzite	65	65	1 300	0	110	50	0	20	10	20	500	0
Syenite-porphyry (Hauki type)	110	60	3 300	0	1 000	20	0	20	0	50	1 200	100
Detritus of porphyry	40	80	2 600	0	70	40	0	0	0	20	100	300
Per Geijer ores	30	95	2 500	0	980	20	0	60	10	20	650	100
Quartz-bearing porphyry	165	135	850	0	480	10	0	45	15	80	750	350
Kiirunavaara 320 m level	70	40	300	0	1 600	0	0	770	80	180	800	700
Tuolluvara ores	30	20	1 400	0	510	0	0	0	0	0	400	100

TABLE 42. Median values of trace elements in magnetite and hematite from mono-type and co-existing types (ppm)

	Total trace element				Ferrides (Ti, V, Cr, Mn, Co, Ni)			
	co-existing		mono-type		co-existing		mono-type	
	Ma	He	Ma	He	Ma	He	Ma	He
Vakko sedimentary rocks	2 940	5 180	2 940	3 505	2 430	4 160	1 800	2 270
Hauki hematite	—	—	—	2 880	—	—	—	2 140
Sericite quartzite	5 760	9 730	0	2 140	5 010	9 160	0	1 510
Syenite-porphyry (Hauki type)	3 350	7 485	6 072	5 860	2 725	6 860	4 410	4 390
Detritus of porphyry	2 490	5 240	2 680	3 250	2 020	4 420	2 130	2 730
Per Geijer ores	3 040	5 375	3 666	4 465	2 620	4 690	2 770	3 590
Quartz-bearing porphyry	2 520	7 800	4 510	2 880	1 960	6 910	3 160	1 480
Kiirunavaara 320 m	—	—	4 230	4 540	—	—	3 240	2 930
Kiirunavaara 800 m	—	—	3 590	—	—	—	2 790	—
Luossavaara ore	—	—	3 304	—	—	—	2 640	—
Luossajärvi ore	1 510	2 170	3 100	—	1 180	1 420	2 160	—
Tuolluvara ores	1 940	1 930	3 440	2 520	860	1 390	1 590	1 970
Syenite-porphyry	—	—	4 800	—	—	—	2 750	—
Magnetite-syenite-porphyry	—	—	3 340	—	—	—	1 710	—
Kurravara conglomerate, matrix	—	—	4 850	—	—	—	2 450	—
Kurravara conglomerate, pebbles	—	—	4 770	—	—	—	2 950	—
Kiruna greenstone	—	—	6 450	—	—	—	5 380	—

Ma = magnetite, He = hematite

TABLE 43. Ti, V, Cr, Mn, Co, Ni in per cent of total trace element contents in co-existing and mono-type magnetites and hematites

Testgroups	Co-existing-type		Mono-type	
	magnetite	hematite	magnetite	hematite
Vakko sedimentary rocks	82.7	80.3	61.2	64.8
Sericite quartzite	87.0	94.1	—	70.6
Syenite-porphyry (Hauki type)	81.3	91.6	72.6	74.9
Detritus of porphyry	81.1	84.4	79.5	84.0
Per Geijer ores	86.2	87.3	75.6	80.4
Quartz-bearing porphyry	77.8	88.6	70.1	51.4
Kiirunavaara 320 m level	—	—	76.6	64.5
Luossajärvi ore	78.1	65.4	69.7	—
Tuolluvaara ores	44.3	72.0	46.2	78.2

TABLE 44. Median values of trace elements in magnetites and hematites from the Kiruna iron ores and from the wall-rocks of the ores (ppm)

	Cu	Zn	Ti	V	Cr	Mo	Mn	Co	Ni	Al	Mg
Syenite-porphyry	10	40	1 100	1 300	90	0	90	60	110	1 200	800
Magnetite-syenite-porphyry	0	40	300	1 100	30	0	150	30	100	1 200	300
Quartz-bearing porphyry	10	10	1 750	855	20	0	135	50	130	600	550
	(30)	(30)	(4 300)	(1 200)	(0)		(50)	(30)	(20)	(700)	(200)
Detritus of porphyry	15	40	570	880	20	0	75	65	505	300	100
	(40)	(80)	(3 000)	(1 200)	(20)		(35)	(25)	(25)	(550)	(150)
Syenite-porphyry (Hauki type)	16	40	1 500	1 100	20	0	130	50	470	700	300
	(110)	(90)	(4 400)	(1 400)	(20)		(40)	(40)	(40)	(500)	(100)
Kiirunavaara ore 320 m level	40	50	700	1 400	0	0	720	120	300	200	700
	(70)	(40)	(300)	(1 600)	—		(770)	(80)	(180)	(800)	(700)
Kiirunavaara ore 800 m level	10	40	300	1 300	0	0	805	120	265	700	650
Luossavaara ore	4	60	800	1 200	5	0	440	60	135	200	400
Luossajärvi ore	10	30	100	990	0	0	370	85	220	100	700
	(30)	(20)	(200)	(1 200)	—		(20)	(0)	(0)	(400)	(300)
Tuolluvaara ores	20	20	300	780	0	0	220	50	240	600	1 200
	(30)	(30)	(1 400)	(510)	—		(0)	(0)	(0)	(400)	(100)
Per Geijer ores	15	40	950	960	3	0	175	80	400	350	700
	(30)	(60)	(2 950)	(1 200)	(0)		(70)	(20)	(40)	(500)	(100)
Hauki hematite	(60)	(55)	(1 950)	(110)	(50)	(0)	(10)	(0)	(20)	(600)	(0)

( ) = hematite

TABLE 45. Hydrothermal alteration of lava from Ebeko, USSR (weight %)

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	P_2O_5	H_2O+	H_2O-	CO_2	S:a
1	52.50	1.15	21.22	4.0	3.94	0.10	7.20	3.40	2.90	1.90	0.27	0.42	1.42	0.57	100.79
2	96.60	1.11	1.43	0.02	0.21	trace	0.40	0.05	0.03	0.05	no	no	0.30	0.06	100.26

1 = non-altered lava, 2 = same lava altered by the termalflow. After Zelenov, 1960
Anal. by Sisova

TABLE 46. Chemical analyses of limonite from the islands of Ituruo and Kunasjir, USSR (per cent)

	Iturup		Kunasjir	
	Lake Tyhoe	Limonite Cascade	Kislijrucej	Lesnaja
SiO_2	1.61	0.36	8.53	1.87
TiO_2	0.06	trace	0.36	0.33
Al_2O_3	1.29	0.55	3.02	0.62
Fe_2O_3	56.73	72.92	61.56	70.62
FeO	10.75	4.06	2.82	1.49
CaO	0.27	0.13	0.19	0.11
MgO	0.23	0.14	0.05	0.03
Na_2O	1.48	0.09	0.11	0.08
K_2O	0.23	0.15	0.15	0.13
P_2O_5	1.33	0.93	0.25	0.32
SO_3	7.78	5.14	8.12	8.20
S	—	—	1.15	0.30
Cl	0.01	—	trace	trace
H_2O+	16.89	13.29	14.13	13.87
CO_2	0.85	0.19	0.14	0.43
C	0.06	1.50	0.70	1.80
S:a	99.58	99.48	101.28	100.20
O = S	—	—	0.51	0.15
S:a 2	—	—	100.71	100.05
H_2O-	71.51	24.82	52.97	64.33

After Zelenov, 1960. Anal. by Sisova

TABLE 47. Locallity, ore type, and content of iron and phosphorous of samples used for the trace element determination

Hau = Haukivaara, Rek = Rektorn, Lap = Lappmalmen, Hen = Henry, Nuk = Nukutusvaara, Kii = Kiirunavaara, Luo = Luossavaara, Luj = Luossajärvi, Tuo = Tuolluvaara, Kur = Kurravaara, Syv. N = Syväjärvi, North, Syv. W = Syväjärvi, West, Hen. W = Henry, West. M = magnetite, H = hematite.

No.	Local	Drill hole	Type	Fe^{tot} %	P %
	1. Vakko sedimentary rocks				
1	Hau —	34—30	M+H	35.3	0.99
2	„ —				
3	„ —	238—120	H	33.4	2.17
4	Rek —	23—60	M+H	29.4	0.04
5	„ —				
6	„ —	478—315	M	32.4	0.15
7	„ —	4—40	M+H	18.3	0.12
8	„ —				
9	„ —	4—70	M+H	17.5	0.24
10	„ —				
11	„ —	480—130	M+H	15.0	0.29
12	„ —				
13	„ —	480—180	H	26.5	0.18
14	Lap —	333—960	H	27.5	0.04
15	Rek—Hen	142—70	H	23.8	0.39
16	„ —	142—110	H	19.8	0.42
17	„ —	142—160	H	23.6	0.04
18	Hen —	226—18	M+H	57.0	0.16
19	„ —				
20	„ —	226—107	H	20.6	0.08
21	„ —	226—130	M+H	30.4	0.05
22	„ —				
23	„ —	336—78	M	5.5	0.30
24	„ —	336—148	H	12.4	0.22
25	„ —	189—35	H	33.2	0.31
26	„ —	189—55	H	18.7	0.10
27	„ —	189—65	H	28.6	0.06
28	Nuk —	246—10	M	9.8	1.04
29	„ —	273—20	H	21.0	0.26
30	„ —	273—30	H	26.2	0.17
31	Syv. N	724—145	H	27.4	0.08
	2. Hauki hematite				
32	Rek—Hen	142—70	H	28.3	0.09
33	Syv. N	724—158	H	32.0	0.03
34	„	724—175	H	31.2	0.26
35	„	755—50	H	58.4	0.01

No.	Local	Drill hole	Type	Fe^{tot} %	P %
		3. Sericite-quartzite			
36	Hau —	235—90	H	22.2	2.65
37	„ —	235—200	M+H	29.9	2.49
38	„ —				
39	Rek —	4—140	M+H	46.4	0.80
40	„ —				
41	Hen —	189—75	H	24.1	0.01
42	Nuk —	253—10	M+H	47.5	1.44
43	„ —				
44	Syv. N	910—78	H	34.1	0.01
45	„ —	910—155	H	48.4	0.08
46	„ —	755—95	H	31.3	0.03
47	„ —	753—40	H	45.0	0.01
		4. Syenite-porphyry of Hauki type			
48	Hau —	235—140	M+H	41.5	6.94
49	„ —				
50	„ —	235—170	M+H	39.6	6.68
51	„ —				
52	Rek —	478—330	M+H	37.0	0.90
53	„ —				
54	„ —	4—90	M+H	36.0	0.73
55	„ —				
56	„ —	4—100	M+H	30.3	0.14
57	„ —				
58	„ —	4—120	M	38.0	0.38
59	Lap —	333—1050	H	30.0	2.48
60	Hen —	336—230	H	34.1	0.06
61	„ —	278—25	H	34.0	2.35
62	„ —	278—35	M+H	11.5	2.63
63	„ —				
64	Nuk —	253—20	M	47.5	1.14
65	„ —	253—30	M	25.1	1.10
66	„ —	253—40	M	37.5	1.23
67	„ —	273—120	M	16.6	0.91
		5. Detritus of porphyry			
68	Hau —	34—40	M	38.7	3.52
69	„ —	34—70	M+H	23.9	2.49
70	„ —				
71	„ —	34—88	M+H	47.8	4.05
72	„ —				
73	„ —	235—230	M	29.6	2.95
74	„ —	235—255	M	34.4	1.49

No.	Local	Drill hole	Type	Fe^{tot} %	P %
75	„ —	235—285	M+H	23.7	0.31
76	„ —				
77	„ —	235—320	M+H	31.5	1.41
78	„ —				
79	„ —	235—350	M	8.0	0.005
80	„ —	235—390	M	41.3	1.77
81	„ —	34—45	H	26.3	0.50
82	„ —	238—230	M+H	50.6	0.77
83	„ —				
84	„ —	238—270	M+H	16.1	4.90
85	„ —				
86	„ —	238—385	M	27.3	5.56
87	Rek —	16—25	M+H	25.3	1.18
88	„ —				
89	„ —	16—40	M+H	30.3	0.87
90	„ —				
91	„ —	4—148	M	8.5	3.23
92	„ —	480—250	M+H	26.3	0.25
93	„ —				
94	„ —	480—275	M	18.3	0.23
95	Rek—Hen	577—203	H	31.1	0.03
96	„ —	577—209	H	46.5	0.16
97	„ —	142—180	M+H	42.4	0.42
98	„ —				
99	„ —	142—190	M+H	16.9	4.20
100	„ —				
101	Hen —	278—45	M	39.4	2.36
102	Nuk —	246—20	M	24.7	4.75
103	„ —	190—100	M	32.7	1.99

6. Per Geijer ores

104	Hau —	34—50	M+H	51.0	3.92
105	„ —				
106	„ —	235—70	H	58.2	1.57
107	„ —	235—110	H	58.8	0.53
108	„ —	238—250	H	48.7	2.63
109	„ —	238—290	M+H	14.6	10.60
110	„ —				
111	„ —	238—320	M+H	52.2	2.01
112	„ —				
113	„ —	238—350	M+H	45.9	5.26
114	„ —				
115	„ —	238—400	M+H	35.2	5.33
116	„ —				
117	Rek —	23—100	M+H	38.4	5.56
118	„ —				
119	„ —	23—110	M	47.3	3.05

No.	Local	Drill hole	Type	Fetot %	P %
120	„ —	16—10	M+H	49.0	0.60
121	„ —				
122	„ —	16—60	M	21.5	5.70
123	„ —	16—70	H	52.3	2.57
124	Lap —	333—1090	M+H	42.3	4.65
125	„ —				
126	„ —	333—1160	M+H	53.8	2.60
127	„ —				
128	„ —	333—1220	M	39.5	3.80
129	„ —	333—1300	M	53.1	4.25
130	„ —	333—1320	M	47.1	3.25
131	Hen —	189—85	H	49.6	0.90
132	„ —	189—95	M+H	42.9	4.23
133	„ —				
134	„ —	278—55	M+H	45.7	5.77
135	„ —				
136	„ —	278—65		34.2	7.38
137	„ —	278—75	M+H	44.1	6.17
138	„ —				
139	„ —	276—10	H	45.7	2.10
140	„ —	276—20	M+H	44.6	5.94
141	„ —				
142	„ —	276—30	M+H	52.5	3.46
143	„ —				
144	„ —	276—40	M+H	50.6	4.26
145	„ —				
146	„ —	276—50	M+H	39.6	7.06
147	„ —				
148	„ —	276—60	M+H	50.8	2.05
149	„ —				
150	„ —	276—70	M+H	53.2	3.99
151	„ —				
152	„ —	270—18	M+H	43.1	5.93
153	„ —				
154	„ —	270—30	M+H	53.7	3.59
155	„ —				
156	„ —	270—50	M+H	52.6	4.05
157	„ —				
158	„ —	270—70	M+H	48.1	4.88
159	„ —				
160	„ —	264—40	M	44.0	5.05
161	Nuk —	269—35	M	50.3	0.28
162	„ —	269—45	M	48.9	0.05
163	„ —	269—55	M	60.1	0.03
164	„ —	243—20	M	61.4	0.03
165	„ —	243—30	M	56.9	0.18
166	„ —	243—40	M	36.6	0.47
167	„ —	243—50	M	39.7	4.63

No.	Local	Drill hole	Type	Fe^{tot} %	P %
168	„ —	246—30	M	45.8	2.15
169	„ —	246—40	M	42.0	3.61
170	„ —	246—50	M	37.8	3.49
171	„ —	190—110	M	41.3	3.35
172	„ —	190—130	M	37.6	3.24
173	„ —	253—70	M	36.7	5.61
174	„ —	253—80	M	43.8	4.79
175	„ —	273—130	M	29.1	6.90
176	„ —	273—140	M	33.5	3.88
177	Syv. N	755—134	H	42.6	1.10
		7. Quartz-bearing porphyry			
178	Luo —	19—150	M	60.7	1.76
179	„ —	54—30	M	14.9	0.01
180	„ —	47—25	M	20.5	0.06
181	Hau —	238—418	M	30.3	3.75
182	Rek —	23—130	M	24.8	4.13
183	„ —	23—150	M+H	23.4	4.71
184	„ —				
185	„ —	16—80	M+H	15.6	3.00
186	„ —				
187	„ —	16—103	M	8.1	1.44
188	„ —	478—350	H	37.0	0.90
189	„ —	478—380	M	14.8	5.65
190	„ —	478—385	M	25.8	6.75
191	„ —	478—390	M	24.5	2.16
192	Hen —	226—145	M	8.3	5.50
193	„ —	336—275	M	6.4	0.64
194	„ —	336—290	H	15.7	0.94
195	„ —	189—105	M+H	39.0	7.15
196	„ —				
197	„ —	264—70	M	28.3	7.11
198	Nuk —	269—75	M	6.9	1.46
199	„ —	269—85	M	22.0	0.05
200	„ —	243—60	M	35.5	0.76
201	„ —	265—65	M	6.8	0.54
202	„ —	253—120	M	17.2	6.06
		8a. Kiirunavaara 320 m level			
203	Y —	14.5	M	69.2	0.05
204	Y —	17.5	M	63.2	0.04
205	Y —	21.5	M	67.8	0.58
206	Y —	23.5	M	46.4	5.30
207	Y —	25.5	M	63.6	1.38
208	Y —	27.0	M	52.2	4.60

No.	Local	Drill hole		Type	Fe^{tot} %	P %
209	Y —	29.0		M	67.7	0.15
210	Y —	31.0		M	58.7	2.70
211	Y —	33.0		M	48.9	5.20
212	Y —	35.0		M	70.5	0.02
213	Y —	37.0		M	47.6	5.30
214	Y —	39.0		M	66.1	0.13
215	Y —	41.5		M	63.2	0.02
216	Y —	44.0		M	62.6	0.06
217	Y —	45.5		M	67.7	0.07
218	Y —	49.0		M	51.1	5.05
219	Y —	52.0		M	53.6	0.11
220	Y —	28.4		H	59.1	1.80
221	Y —	37.8		H	66.6	0.003
222	Y —	38.6		H	46.4	4.56
223	Y —	37.6		H	68.3	0.04
224	Y —	28.1		H	38.5	6.80
		8 b. Kiirunavaara 800 m level				
225	Y —	20	22—676	M	53.5	4.38
226	Y —	20	22—678	M	59.3	2.04
227	Y —	20	22—690	M	67.8	0.02
228	Y —	20	8—485	M	67.9	0.07
229	Y —	27.9	291—624	M	68.1	0.02
230	Y —	27.9	290—716	M	69.3	0.02
231	Y —	37.1	295—560	M	68.8	0.03
232	Y —	37.1	295—604	M	48.9	1.97
233	Y —	44.9	128—556	M	66.8	0.78
234	Y —	44.9	128—655	M	62.3	0.08
235	Y —	44.9	128—556a	M	60.9	1.98
236	Y —	44.8	188—576	M	61.4	0.02
237	Y —	44.8	188—578	M	42.8	6.62
238	Y —	44.8	188—594	M	51.9	4.56
		9. Luossavaara ore				
239		19—160		M	55.6	2.88
240		22—400		M	38.1	0.01
241		54—45		M	56.9	0.01
242		54—60		M	51.3	0.01
243		54—75		M	68.5	0.01
244		54—99		M	59.5	0.01
245		19—167		M	20.2	0.27
246		19—197		M	18.8	0.01
247		22—410		M	18.7	0.02
248		27—10		M	65.4	0.01
249		27—50		M	21.4	0.01

No.	Local	Drill hole	Type	Fe^{tot} %	P %
250		27—85	M	31.4	0.005
251		54—125	M	24.1	0.10
252		23—10	M	32.3	0.01
253		23—21	M	38.9	0.01
254		23—38	M	35.2	0.02
255		23—50	M	25.4	0.02
256		23—70	M	22.4	0.03
257		47—40	M	23.4	0.01
258		47—60	M	22.7	0.02
259		47—80	M	10.7	0.02
260		47—100	M	23.1	0.02
		10. Luossajärvi ore			
261		225—615	M	68.6	0.03
262		225—642	M	69.7	0.05
263		225—644	M	68.2	0.01
264		225—656	M	49.2	4.96
265		225—676	M	67.8	0.10
266		225—690	M	61.1	1.95
267		225—698	M	55.7	2.22
268		225—718	M	53.4	3.47
269		331—702	M	64.3	0.15
270		331—712	M	33.7	7.26
271		331—720	M+H	60.7	2.42
272					
273		331—728	M+H	59.9	2.42
274					
275		331—737	M+H	62.3	1.72
276					
277		331—740	M+H	65.6	0.81
278					
279		331—748	M+H	60.4	1.48
280					
281		331—766	M	65.2	0.03
282		331—785	M	68.4	0.03
283		331—788	M	66.9	0.11
		11. Tuolluvaara ores			
284		149—49	M	62.6	0.98
285		210—16	M	67.6	0.09
286		217—2	M	68.3	0.01
287		217—18	M	69.4	0.02
288		226—36	M	59.8	2.60
289		231—117	M	59.9	0.06
290		246—43	M	50.4	2.56

No.	Local	Drill hole	Type	Fe^{tot} %	P %
291		249—28	M	68.7	0.05
292		handspecimen	M+H	68.6	0.01
293					
294		11—158	M	69.7	0.002
295		11—245	M	56.6	1.22
296		11—304	M+H	60.3	1.94
297					
298		11—340	M+H	58.4	1.94
299					
300		11—318	H	59.4	2.28
301		11—310	H	49.5	4.40
		12. Syenite-porphyry			
302	Hen —	264—20	M	30.6	8.35
303	„ —	264—30	M	9.9	2.26
304	„ —	264—50	M	17.0	4.22
305	„ —	264—60	M	6.5	4.04
306	Hen. W	484—2	M	18.3	2.30
307	„ —	483—20	M	17.5	0.36
308	„ —	483—120	M	27.4	1.48
309	Syv. W	486—18	M	13.2	0.36
310	„ —	486—40	M	8.4	0.24
311	„ —	486—114	M	10.5	0.74
312	„ —	486—145	M	6.8	0.40
313	„ —	597—64	M	44.5	0.01
314	„ —	597—161	M	10.4	0.04
315	„ —	597—182	M	24.6	0.01
316	„ —	597—195	M	26.5	0.03
		13. Magnetite-syenite-porphyry			
317	Hen. W	485—50	M	20.7	0.63
318	„ —	485—75	M	19.1	0.37
319	„ —	484—90	M	19.1	0.30
320	Syv. W	597—14	M	23.5	0.30
321	„ —	597—26	M	18.3	0.30
322	„ —	597—39	M	24.1	0.19
323	„ —	597—48	M	10.9	0.09
324	„ —	488—25	M	21.0	2.30
325	„ —	488—44	M	24.5	0.32
		14. Kurravaara conglomerate, matrix			
326	Syv. W	569—24	M	16.8	0.39
327	„	569—24	M	17.2	0.15
328	„	569—75	M	13.3	0.12

No.	Local	Drill hole	Type	Fe^{tot} %	P %
329	„	569—104	M	12.5	0.12
330	„	569—120	M	13.1	0.13
331	„	569—145	M	12.1	0.13
332	„	597—241	M	19.7	0.13
333	„	488—108	M	12.2	0.15
		15. Kurravaara conglomerate, pebbles			
334	Pebble 1		M	17.9	0.05
335	„ 2		M	16.3	0.06
336	„ 3		M	18.9	0.12
337	„ 4		M	21.3	0.10
338	„ 5		M	36.3	0.71
339	„ 6		M	25.8	0.04
340	„ 7		M	19.0	0.15
341	„ 8		M	27.2	0.05
342	„ 9		M	16.0	0.03
343	„ 10		M	23.8	0.15
		16. Kiruna greenstone			
344	Syv. W	487—38	M	9.3	0.12
345	„	487—67	M	15.1	0.18
346	„	487—80	M	11.3	0.62

TABLE 48. Trace element contents of magnetite and hematite from the Kiruna area (ppm)

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
1. Vakko sedimentary rocks												
1.	70	50	900	0	740	150	60	210	60	350	700	200
2.	40	90	3 300	0	1 200	20	0	110	30	80	1 100	100
3.	40	70	400	0	580	0	0	0	0	0	1 500	100
4.	20	30	800	0	1 100	10	0	60	70	430	300	100
5.	40	160	3 700	0	1 200	0	0	70	0	20	1 100	100
6.	500	60	200	0	840	30	0	320	0	100	500	600
7.	20	30	300	0	680	60	0	70	50	420	100	100
8.	70	50	2 900	0	860	10	0	110	0	30	400	200
9.	300	40	1 700	0	800	220	0	80	340	620	300	100
10.	170	50	6 600	0	1 200	20	0	140	0	70	500	100
11.	540	80	400	0	2 100	50	0	720	20	110	800	300
12.	390	100	1 600	0	450	20	0	430	40	20	1 100	800
13.	10	30	1 000	0	1 100	10	0	10	0	40	300	100
14.	10	30	1 400	0	140	20	0	0	0	0	400	0
15.	140	60	3 800	0	760	10	0	100	0	20	1 400	200
16.	20	90	9 000	110	500	100	0	440	20	0	8 400	1 100
17.	50	80	1 700	0	90	20	0	20	0	0	1 300	200
18.	90	40	900	0	960	60	0	120	40	780	100	80
19.	20	80	1 300	0	210	20	0	10	0	0	700	200
20.	30	40	1 000	0	290	40	0	10	0	0	500	0
21.	20	50	500	0	1 200	20	0	120	80	60	100	80
22.	10	50	2 300	0	1 100	30	0	90	30	60	500	200
23.	280	60	600	140	580	40	0	220	130	110	800	300
24.	30	70	2 000	0	380	30	0	30	0	20	500	100
25.	260	50	2 300	0	800	0	0	40	0	0	900	200
26.	90	70	1 900	0	110	30	0	20	0	0	1 600	0
27.	110	30	800	0	70	10	0	10	0	0	700	0
28.	0	-	700	0	700	360	0	50	190	500	0	0
29.	30	30	3 400	180	140	30	0	20	0	0	900	0
30.	30	50	2 900	0	26	40	0	30	0	0	1 400	100
31.	50	80	3 500	80	8	90	40	20	10	20	1 200	0

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
2. Hauki hematite												
32.	60	40	2 000	0	5	20	0	60	0	0	800	0
33.	60	110	1 900	90	5	150	0	10	0	30	400	0
34.	110	70	4 800	50	17	70	0	10	0	20	700	0
35.	40	40	1 300	0	33	30	70	0	10	20	500	0
3. Sericite-quartzite												
36.	20	40	3 200	0	120	10	0	50	20	170	400	0
37.	20	30	700	0	80	0	0	40	40	810	100	60
38.	30	30	5 000	0	140	0	0	30	60	20	300	100
39.	20	30	3 600	0	98	20	0	30	40	330	600	100
40.	100	130	9 400	0	140	0	0	70	90	30	300	200
41.	90	60	390	0	7	30	0	20	0	0	500	0
42.	14	40	4 800	0	180	20	0	340	30	300	1 100	1 000
43.	20	40	7 600	0	180	0	0	440	60	160	1 500	600
44.	60	150	4 100	0	46	100	0	70	0	20	300	100
45.	40	50	1 000	0	10	40	0	20	10	30	900	100
46.	140	100	1 600	70	6	120	40	0	10	20	800	0
47.	70	70	400	50	12	60	100	0	10	20	500	0
4. Syenite-porphyry of Hauki type												
48.	8	30	300	0	56	0	0	40	90	390	100	30
49.	20	30	4 400	0	96	0	0	30	70	20	300	0
50.	30	40	800	0	82	30	0	130	50	1 100	200	100
51.	20	50	2 700	0	160	0	0	10	50	0	200	0
52.	150	40	300	0	110	30	0	350	0	540	800	800
53.	150	100	1 500	0	72	20	0	70	30	180	1 200	700
54.	240	20	2 600	0	940	20	0	80	40	490	100	80
55.	190	90	7 000	0	1 400	0	0	40	90	40	200	0
56.	50	30	1 400	0	920	50	0	70	40	470	700	100
57.	210	90	8 000	0	1 600	20	0	300	140	40	700	300
58.	30	80	1 400	0	1 100	20	0	110	70	470	600	300

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
59.	110	40	3 300	0	1 000	0	0	20	0	50	1 200	100
60.	130	60	1 700	0	70	20	0	10	0	0	500	100
61.	30	90	5 200	0	1 500	30	0	130	40	200	1 400	200
62.	16	60	1 500	0	1 100	30	0	170	50	1 000	800	100
63.	20	110	6 200	0	1 400	30	0	390	20	180	500	100
64.	14	40	4 800	0	1 800	20	0	340	90	300	1 100	1 000
65.	9	60	2 800	0	1 000	40	0	210	80	240	1 200	1 300
66.	12	40	1 700	0	1 500	20	0	170	30	190	700	500
67.	5	50	2 500	0	1 400	0	0	120	90	170	900	700
5. Detritus of porphyry												
68.	50	70	1 400	0	1 300	60	0	220	70	550	500	200
69.	30	50	1 300	0	1 300	7	0	90	70	520	400	200
70.	20	60	2 900	0	1 100	20	0	120	40	310	600	0
71.	40	60	2 500	0	740	20	0	90	40	460	200	100
72.	30	100	6 400	0	1 400	0	0	40	40	30	400	0
73.	10	30	2 200	0	1 000	20	0	20	100	310	1 300	100
74.	7	30	1 300	0	620	30	0	20	70	320	1 300	80
75.	60	30	500	0	860	20	0	70	30	1 000	300	90
76.	40	50	3 100	0	1 500	0	0	40	20	40	600	100
77.	20	50	900	0	860	30	0	80	40	890	700	200
78.	60	50	2 000	0	1 200	20	0	30	50	20	700	100
79.	370	70	400	70	1 100	140	0	350	50	700	400	500
80.	10	50	500	0	900	10	0	50	20	440	200	50
81.	20	60	5 800	0	1 500	0	0	370	30	40	1 500	200
82.	8	30	90	0	840	0	0	30	80	330	300	100
83.	20	80	1 600	0	1 400	0	0	0	20	0	200	0
84.	80	40	2 400	0	540	10	0	100	20	490	300	200
85.	50	120	8 000	0	680	10	0	40	20	20	400	100
86.	10	40	1 400	0	1 100	6	0	100	50	440	100	30
87.	30	30	500	0	1 000	10	0	40	60	660	200	80
88.	80	90	5 600	0	1 600	20	0	20	40	40	900	200

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
89.	60	30	1 100	0	920	20	0	60	30	570	200	100
90.	90	100	5 600	0	1 400	20	0	30	50	30	400	100
91.	40	20	800	80	1 100	0	0	60	110	790	1 400	200
92.	40	40	300	0	2 400	50	0	700	30	180	300	600
93.	60	40	2 600	110	400	20	0	20	30	0	1 400	200
94.	0	30	600	0	900	60	0	50	160	290	200	100
95.	110	160	1 300	0	50	270	30	0	0	20	100	400
96.	40	80	2 600	0	70	40	0	0	0	20	100	300
97.	10	60	50	0	340	30	0	110	80	1 100	200	0
98.	20	80	1 800	0	580	10	0	110	0	20	500	200
99.	10	60	200	0	710	20	0	70	40	520	400	400
100.	10	60	6 400	0	1 200	20	0	60	20	100	700	200
101.	10	90	100	0	810	80	0	280	90	2 100	400	200
102.	0	60	540	0	600	650	0	70	250	320	0	0
103.	0	-	30	0	620	30	0	100	210	300	0	0
6. Per Geijer ores												
104.	540	30	1 300	0	1 000	30	0	260	30	300	400	1 000
105.	20	60	1 700	0	740	20	0	40	20	100	300	0
106.	10	80	600	0	1 100	20	0	40	0	80	300	0
107.	200	100	1 100	0	860	20	0	50	0	0	700	100
108.	20	60	1 700	0	800	10	0	20	20	20	200	100
109.	20	40	1 400	0	540	20	0	90	20	1 400	500	300
110.	10	40	1 900	0	540	10	0	30	0	20	200	0
111.	120	50	700	0	700	30	0	170	20	1 600	300	300
112.	40	60	1 200	0	840	10	0	20	0	0	300	100
113.	30	40	1 100	0	840	10	0	40	30	760	400	100
114.	20	80	2 500	0	1 300	20	0	20	0	0	300	0
115.	110	40	4 000	0	1 200	6	0	120	50	240	700	400
116.	150	100	8 600	0	1 100	10	0	60	20	30	1 200	300
117.	10	30	400	0	1 000	5	0	50	60	750	100	50
118.	20	40	2 300	0	1 500	0	0	60	20	0	500	200

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
151.	20	60	3 900	0	1 500	0	0	90	50	50	700	0
152.	20	40	2 500	0	840	0	0	190	140	280	200	70
153.	50	70	6 400	0	1 100	0	0	180	40	70	700	200
154.	5	30	1 200	0	880	0	0	80	70	400	100	40
155.	20	60	4 800	0	1 600	0	0	30	40	110	200	0
156.	10	30	1 200	0	1 000	5	0	80	30	470	200	40
157.	30	60	3 500	0	1 500	0	0	40	30	100	400	0
158.	50	30	800	0	1 000	0	0	310	40	400	200	60
159.	100	70	3 100	0	1 200	0	0	480	70	60	500	100
160.	8	30	1 100	0	1 400	0	0	200	80	200	400	300
161.	54	40	1 400	0	1 200	0	0	270	80	140	800	900
162.	25	30	800	0	1 300	20	0	300	80	170	700	300
163.	15	30	1 500	70	1 200	20	0	280	70	160	100	800
164.	270	60	2 500	0	1 000	0	0	320	120	200	1 100	100
165.	90	50	1 900	0	1 500	0	0	320	70	160	1 000	900
166.	280	20	1 100	0	1 300	20	0	70	40	140	900	600
167.	6	20	1 200	0	1 400	10	0	180	80	130	1 000	900
168.	0	40	30	0	560	600	0	90	110	720	0	0
169.	0	-	140	0	720	210	0	170	150	420	0	0
170.	0	-	110	0	720	7	0	90	140	550	0	0
171.	0	-	460	0	840	25	0	80	400	650	0	0
172.	0	-	9	0	860	26	0	140	120	660	0	0
173.	6	60	1 300	0	1 300	0	0	120	90	260	300	400
174.	33	40	1 400	0	1 400	10	0	250	100	260	500	100
175.	12	50	1 400	0	1 600	40	0	230	100	170	500	600
176.	0	80	3 700	0	1 700	40	0	210	100	240	500	600
177.	80	130	6 400	0	3 100	30	0	70	0	20	1 500	900
7. Quartz-bearing porphyry												
178.	0	50	1 600	0	1 100	0	0	260	40	150	400	1 200
179.	10	50	700	0	1 200	20	0	370	40	80	100	400
180.	7	50	400	60	900	20	0	260	60	90	1 000	1 100

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
181.	20	40	2 700	0	800	10	0	120	50	170	400	600
182.	10	30	2 400	0	340	150	0	120	70	80	3 000	3 000
183.	20	30	1 700	0	1 200	0	0	100	70	450	600	200
184.	10	80	7 400	0	1 200	0	0	50	20	20	700	800
185.	190	40	300	0	1 000	60	0	150	20	430	100	200
186.	5	60	5 600	0	1 300	10	0	40	40	20	400	100
187.	70	30	3 800	0	490	20	0	140	40	180	700	700
188.	160	110	700	0	100	0	0	20	30	0	600	200
189.	20	80	1 300	0	820	20	0	130	30	230	300	400
190.	7	30	6 000	0	840	6	0	150	30	130	300	200
191.	8	30	1 800	0	760	20	0	150	40	70	1 600	1 800
192.	30	40	2 000	0	780	30	0	80	50	470	300	80
193.	610	30	3 400	0	520	8	0	20	50	130	600	200
194.	170	160	1 000	0	860	20	0	70	0	160	900	500
195.	10	50	100	0	710	0	0	340	60	690	300	0
196.	30	160	4 300	0	1 200	0	0	1 000	100	50	1 000	100
197.	10	60	2 600	1 100	1 100	0	0	80	90	120	700	800
198.	10	30	2 000	140	790	20	0	110	50	60	600	1 000
199.	0	40	200	230	940	10	0	210	50	70	900	1 400
200.	0	50	800	0	1 200	50	0	160	110	140	700	500
201.	8	60	100	300	1 100	0	0	130	60	90	600	700
202.	0	30	2 300	0	870	20	0	0	60	110	500	300
8a.	Kiirunavaara 320 m level											
203.	40	50	700	0	880	0	0	370	50	250	100	500
204.	250	80	700	0	1 200	10	0	630	120	260	200	700
205.	70	30	900	0	1 000	0	0	320	90	290	100	500
206.	30	50	100	0	1 400	0	0	530	120	300	200	1 000
207.	40	50	600	0	1 500	0	0	780	120	320	200	700
208.	50	50	600	0	1 500	0	0	700	120	270	200	800
209.	30	50	400	0	1 700	0	0	900	150	320	100	600
210.	40	50	600	0	1 600	0	0	820	140	340	100	400

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
211.	30	80	200	0	1 400	0	0	990	160	330	200	800
212.	25	90	1 000	0	1 600	0	0	720	100	320	200	400
213.	50	80	200	0	1 600	0	0	1 200	170	320	100	900
214.	40	60	800	0	1 300	0	0	920	150	270	100	600
215.	190	40	700	0	1 300	9	0	860	140	280	300	1 100
216.	40	100	2 300	0	1 400	12	0	690	110	270	700	700
217.	20	60	2 000	0	1 400	0	0	1 000	190	310	400	1 100
218.	20	30	70	0	980	0	0	350	60	310	100	600
219.	50	60	3 200	0	1 100	8	0	130	20	220	500	500
220.	70	30	200	0	1 700	10	0	80	20	20	100	400
221.	180	50	1 400	0	1 300	0	0	1 100	580	290	1 400	800
222.	10	40	300	0	1 600	0	0	770	80	250	800	700
223.	90	40	1 900	0	1 200	0	0	1 200	110	180	3 400	1 000
224.	70	40	200	0	1 800	0	0	70	10	0	100	700
8b. Kiirunavaara 800 m level												
225.	10	40	100	0	1 600	0	0	970	120	260	100	600
226.	0	30	200	0	1 000	0	0	1 100	120	240	100	900
227.	10	40	500	0	950	0	0	370	70	230	400	1 400
228.	20	50	3 100	0	1 200	0	0	600	120	280	200	1 200
229.	20	40	600	0	1 500	0	0	890	90	280	100	500
230.	8	100	800	0	1 400	0	0	430	190	320	500	1 800
231.	10	80	400	0	1 400	0	0	920	120	320	100	500
232.	10	100	60	0	1 300	0	0	1 000	170	320	100	600
233.	8	50	200	0	1 100	0	0	1 300	120	270	100	300
234.	8	50	1 500	0	1 400	0	0	520	90	310	100	200
235.	10	30	200	0	1 400	0	0	1 100	110	250	400	600
236.	10	40	1 700	0	1 300	0	0	720	120	230	200	700
237.	20	30	200	0	1 200	0	0	470	60	200	300	800
238.	20	40	100	0	1 300	0	0	400	60	200	100	1 900
9. Luossavaara ore												
239.	0	60	300	0	1 100	0	0	380	40	190	100	500
240.	0	60	370	0	980	0	0	480	150	110	0	0

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
241.	0	60	800	0	1 400	0	0	400	40	170	200	400
242.	0	80	1 100	0	1 200	0	0	360	50	180	100	200
243.	0	60	1 100	0	1 200	0	0	400	50	170	100	400
244.	0	60	400	0	1 200	0	0	360	60	90	100	700
245.	0	40	1 200	0	1 100	0	0	320	30	100	300	1 200
246.	0	40	500	70	1 100	5	0	380	70	50	500	1 000
247.	0	0	310	0	130	15	0	1 500	270	220	0	0
248.	80	80	2 700	0	1 300	9	0	380	50	160	200	400
249.	8	50	300	60	1 200	50	0	400	60	110	3 100	800
250.	10	60	900	0	1 400	0	0	490	60	140	100	100
251.	0	50	200	180	1 100	5	0	370	130	120	200	200
252.	20	210	800	0	1 500	0	0	700	80	250	100	200
253.	50	50	1 800	0	1 400	5	0	620	80	210	200	400
254.	10	60	1 300	0	1 200	10	0	740	70	110	800	700
255.	30	40	1 100	0	1 400	20	0	760	110	180	1 600	800
256.	40	60	1 100	0	920	8	0	700	50	120	300	400
257.	0	60	700	0	780	10	0	400	40	50	600	700
258.	9	60	2 100	0	1 100	0	0	700	60	200	200	200
259.	20	60	400	0	1 100	40	0	600	90	110	1 100	400
260.	8	60	600	0	1 200	40	0	520	60	130	300	100
10. Luossajärvi ore												
261.	20	50	1 300	0	1 600	0	0	350	120	360	100	1 100
262.	10	30	100	0	1 000	0	0	370	80	220	200	600
263.	10	20	100	0	980	0	0	400	90	200	100	700
264.	20	30	25	0	1 200	0	0	690	140	300	100	1 300
265.	10	30	200	0	1 400	0	0	570	110	220	100	600
266.	10	40	500	0	950	0	0	370	70	230	400	1 400
267.	20	50	100	0	1 400	0	0	890	150	290	100	700
268.	20	80	200	0	1 400	0	0	1 500	180	300	100	2 100
269.	10	20	1 400	0	700	10	0	480	90	200	700	800
270.	10	30	100	0	510	0	0	450	130	210	400	500

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
271.	10	30	25	0	570	0	0	360	60	160	100	100
272.	10	20	100	0	1 100	0	0	0	0	0	400	100
273.	10	30	0	0	670	0	0	300	40	170	100	25
274.	20	20	100	0	1 100	0	0	0	0	0	300	100
275.	10	20	0	0	820	0	0	290	60	160	300	200
276.	30	10	300	0	1 200	0	0	30	0	0	400	300
277.	10	20	0	0	610	0	0	310	50	200	100	200
278.	290	20	200	0	1 400	0	0	20	20	0	700	300
279.	10	20	0	0	810	0	0	290	50	110	300	300
280.	240	20	1 700	0	1 300	0	0	30	10	0	500	300
281.	0	20	500	0	1 100	0	0	350	80	280	300	800
282.	20	50	1 300	0	1 600	0	0	350	120	360	100	1 100
283.	20	20	3 300	0	1 300	10	0	380	80	250	500	800
11. Tuolluvaara ore												
284.	50	30	300	0	620	10	0	220	40	210	1 300	1 800
285.	30	40	200	0	980	0	0	240	60	280	800	1 500
286.	10	40	300	0	950	0	0	630	180	300	100	1 200
287.	10	20	1 000	0	1 000	0	0	450	140	240	100	200
288.	10	40	300	0	800	0	0	650	150	260	100	1 700
289.	10	20	300	0	780	10	0	150	30	180	1 000	1 200
290.	60	30	500	0	990	0	0	130	30	220	1 300	1 900
291.	70	30	400	0	580	0	0	320	180	260	500	2 500
292.	70	40	300	0	630	0	0	500	130	290	100	1 100
293.	70	40	300	0	680	0	0	40	10	10	100	800
294.	20	30	400	0	560	0	0	70	40	180	600	200
295.	10	30	600	0	1 300	0	0	90	50	260	900	600
296.	50	20	0	0	390	10	0	120	20	120	900	900
297.	10	20	2 200	0	450	0	0	10	0	0	500	100
298.	20	30	0	0	600	20	0	100	20	30	100	100
299.	20	20	700	0	800	0	0	0	0	0	400	100
300.	30	30	1 400	0	480	0	0	0	0	0	300	25
301.	30	10	1 900	0	510	0	0	0	0	0	500	100

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
12. Syenite-porphyry												
302.	12	40	2 000	0	1 200	0	0	80	60	130	900	700
303.	36	30	1 600	0	1 100	0	0	190	80	110	1 800	1 900
304.	58	40	3 800	0	1 500	0	0	70	80	100	1 200	700
305.	29	–	4 700	0	1 800	0	0	90	100	220	800	600
306.	20	60	100	60	1 100	390	0	390	50	130	1 200	300
307.	50	40	2 900	0	1 300	270	0	60	110	270	900	800
308.	30	40	2 100	0	1 500	180	0	130	60	250	800	500
309.	10	40	1 100	280	1 300	90	0	360	100	110	2 800	1 100
310.	10	40	4 500	290	900	60	0	20	70	30	2 000	700
311.	9	60	400	110	960	40	0	60	30	100	1 200	1 000
312.	8	40	400	0	620	20	0	90	30	50	400	300
313.	0	50	600	190	1 300	840	0	20	20	210	1 200	1 500
314.	6	40	100	50	1 200	1 800	0	220	40	90	1 200	900
315.	0	40	200	0	1 500	500	0	260	30	90	1 000	1 300
316.	0	30	200	0	1 500	480	0	380	50	90	600	800
13. Magnetite-syenite-porphyry												
317.	20	70	300	50	1 500	250	0	410	60	210	500	100
318.	10	50	1 100	0	1 700	100	0	400	70	190	700	200
319.	0	30	500	90	1 400	70	0	160	50	160	1 100	300
320.	0	30	80	140	940	10	0	230	30	100	2 000	300
321.	0	60	200	140	1 000	20	0	20	20	100	1 900	500
322.	6	40	300	150	1 000	30	0	30	30	90	1 500	400
323.	0	40	60	140	1 100	30	0	10	0	130	1 200	100
324.	0	30	300	90	1 200	0	0	50	30	90	700	600
325.	0	30	300	0	1 100	1 700	0	150	40	100	1 800	2 200
14. Kurravaara conglomerate, matrix												
326.	7	60	800	110	700	960	0	300	20	40	1 900	600
327.	10	40	400	70	1 300	740	0	450	30	90	1 000	700

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
119.	10	20	1 000	0	1 400	0	0	130	80	530	600	200
120.	90	30	200	0	1 000	30	0	130	310	710	100	40
121.	160	70	7 000	0	1 200	20	0	40	30	40	700	100
122.	5	20	2 300	0	1 100	0	0	40	0	240	200	200
123.	320	170	6 400	0	1 500	20	0	120	80	20	500	500
124.	0	30	600	0	660	0	0	80	60	400	100	40
125.	10	50	2 800	0	940	0	0	0	0	0	200	0
126.	10	40	1 100	0	710	0	0	80	0	190	1 100	1 200
127.	110	70	7 000	0	1 400	0	0	90	420	40	4 100	4 000
128.	14	50	700	0	890	0	0	140	130	190	1 300	1 200
129.	12	50	900	0	740	0	0	180	70	70	800	900
130.	15	60	300	0	730	20	0	50	60	180	1 500	500
131.	30	30	2 200	0	320	20	0	40	0	0	1 700	100
132.	32	50	70	0	460	0	0	520	0	2 300	400	0
133.	10	40	2 100	0	800	20	0	150	0	20	500	0
134.	37	–	600	0	1 000	0	0	260	210	790	300	50
135.	40	80	810	0	1 600	0	0	530	70	70	800	100
136.	30	90	7 400	0	1 600	0	0	570	130	130	400	100
137.	40	40	500	0	950	40	0	310	160	1 200	200	100
138.	40	50	9 000	0	1 500	0	0	150	70	150	500	100
139.	30	210	2 800	0	680	20	0	420	30	70	1 000	300
140.	30	50	100	0	660	0	0	210	120	590	700	500
141.	40	90	2 200	0	1 100	0	0	70	20	30	1 000	300
142.	12	50	20	0	630	0	0	470	60	2 300	300	30
143.	20	60	2 000	0	1 300	0	0	1 300	20	40	2 000	100
144.	58	50	800	0	940	0	0	630	120	1 400	100	30
145.	30	30	4 900	0	1 400	0	0	360	40	50	300	100
146.	14	30	1 000	0	770	0	0	340	120	1 300	100	30
147.	10	60	4 000	0	1 200	0	0	80	0	20	300	100
148.	33	30	400	0	970	0	0	350	200	1 200	700	0
149.	10	60	4 400	0	1 300	0	0	250	30	50	400	0
150.	12	50	300	0	920	0	0	170	140	660	300	30

No.	Cu	Zn	Ti	Zr	V	Cr	Mo	Mn	Co	Ni	Al	Mg
328.	5	40	100	0	1 300	30	0	390	40	50	1 700	1 900
329.	10	130	400	80	1 000	320	0	280	20	50	3 400	700
330.	10	30	100	0	700	0	0	330	40	80	400	1 100
331.	10	50	300	90	800	450	0	280	30	30	2 500	900
332.	5	40	400	0	1 400	700	0	340	40	100	1 100	700
333.	10	40	700	0	1 200	660	0	50	20	60	800	1 000
15. Kurravaara conglomerate, pebbles												
334.	30	140	300	0	1 100	350	0	790	150	230	1 000	300
335.	20	100	300	0	1 500	1 100	0	670	100	250	2 100	600
336.	20	100	300	0	1 600	1 000	0	670	110	240	1 700	700
337.	8	80	400	0	1 600	580	0	330	80	130	1 400	800
338.	70	140	200	0	1 000	180	0	980	80	70	400	300
339.	7	80	200	50	1 200	330	0	560	80	90	800	500
340.	10	60	300	80	1 000	120	0	860	110	130	4 200	700
341.	20	120	300	0	1 100	250	0	880	120	170	1 200	200
342.	10	100	300	50	1 200	660	0	1 000	110	210	1 500	200
343.	80	140	400	50	1 300	340	0	950	150	170	900	300
16. Kiruna greenstone												
344.	10	70	2 800	0	1 700	500	0	140	40	90	500	400
345.	7	60	2 300	0	1 300	1 500	0	150	50	210	600	400
346.	10	60	1 800	0	1 100	1 400	0	130	40	210	900	600

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[1] О ВЫНОСЕ РАСТВОРЕННОГО ЖЕЛЕЗА В ОХОТСКОЕ МОРЕ ГИДРОТЕРМАМИ ВУЛКАНА ЭБЕКО (о. ПАРАМУШИР)
(Представлено академиком Н. М. Страховым 3 III 1958)

Доклады Академии наук СССР
1958. Том 120, № 5

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[2] ВЫНОС РАСТВОРЕННОГО АЛЮМИНИЯ ТЕРМАЛЬНЫМИ ВОДАМИ КУРИЛЬСКОЙ ГРЯДЫ И НЕКОТОРЫЕ ВОПРОСЫ ОБРАЗОВАНИЯ ГЕОСИНКЛИНАЛЬНЫХ МЕСТОРОЖДЕНИЙ БОКСИТОВ
ИЗВЕСТИЯ АКАДЕМИИ НАУК СССР
Серия геологическая
1960, № 3

Geological map of the Kiruna area

P. Forsell and T. Parák 1972

Scale 1:20000

0 1 2 km

Kurravaara

Hupukka

Syväjärvi

Nukutusvaara

Henry

Sakkaravaara

Valkeasiipivaara

Luossajärvi

Rektorn

Luossavaara

Neptunus

Haukivaara

Tuolluvaara

KIRUNA TOWNSITE

Kiirunavaara

Päron

Konsuln

- Granite
- Vakko sedimentary rocks
- Lower Hauki rocks
- Dikes of quartz-porphyry
- Dikes of porphyry
- Beds of tuff in the syenite-porphyry at Kiirunavaara
- Intermediate andesitic rocks (partly amphibolitic)
- Quartz-bearing porphyry
- Syenite
- Syenite-porphyry
- Kurravaara conglomerate
- Sedimentary beds in the Kiruna greenstones
- Kiruna-greenstones

- Ores
- Ore breccias
- Drill hole
- Boundary of rocks
- Fault
- Dip
- Rock exposures (partly after Offerberg, 1967)
- Cross section (fig. 35 in the description)

Godkänd ur sekretessynpunkt för spridning. Rikets allmänna kartverk 1974.09.12.

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