SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 807 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 79 NR 1

RUDYARD FRIETSCH

THE LANNAVAARA IRON ORES NORTHERN SWEDEN

UPPSALA 1985

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 807 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 79 NR 1

RUDYARD FRIETSCH

THE LANNAVAARA IRON ORES NORTHERN SWEDEN

UPPSALA 1985

ISBN 91-7158-314-9
ISSN 0082-0024

Kartan på s. 6 godkänd ur sekretessynpunkt för spridning.
Statens lantmäteriverk 1984-02-05

Address:
Rudyard Frietsch
Luleå University
S-951 87 LULEÅ

Schmidts Boktryckeri AB
Helsingborg 1985

CONTENTS

ABSTRACT

Frietsch, Rudyard, 1985: The Lannavaara iron ores, northern Sweden. Sveriges geologiska undersökning, Ser. C, No. 807, pp. 1–55. Uppsala 1985.

The iron ore deposits Kevus, Sattavaara and Teltaja at Lannavaara in northern Sweden occur in Early Proterozoic supracrustals rocks. The Sattavaara ore is made up of a skarn-magnetite layered chert lying in basic tuffs, limestones-dolomites and graphite-bearing schists, all belonging to the older Greenstone group. The skarn silicates are rich in ferrous iron and manganese. Manganese is in addition enriched in ilmenite coexisting with magnetite. Barium is a conspicuous element found in hyalophane and biotite. The Sattavaara ore resembles some other magnetite layered siliceous ores, partly with manganese-bearing silicates, in the Greenstone group in northern Sweden, and like these has a volcano-sedimentary origin. The association iron — manganese — barium in Sattavaara indicates a close kinship to metalliferous sediments formed in Recent basins by submarine volcanism along active ocean ridges or rift zones. The Kevus and Teltaja ores have a unique composition and do not have any counterparts among the iron ores in northern Sweden. They occur as massive bodies, veins or impregnations in trachytes belonging to the younger Porphyry group. The trachytes consist of albite — (microcline — quartz) rocks with varying amounts of mica. In Teltaja there are tuffites rich in mica and garnet. In both deposits the ore is

epigenetic, veining the wall rock. The ore, magnetite in Kevus and magnetite-hematite in Teltaja, is mainly accompanied by diopside, hornblende, tremolite and scapolite. In Teltaja the ore is accompanied by quartz. Subordinate minerals in both deposits are biotite, calcite, epidote, garnet and, less usually, chlorite and serpentine. In the Kevus ore a relatively coarse albite is common. In both deposits there are small or accessory amounts of apatite, tourmaline, sphene, fluorite and analcime. The occurrence of scapolite and small amounts of tourmaline, fluorite and analcime indicate formation by hydrothermal, metasomatic processes rich in volatile components. In both deposits the main product was iron oxides, in the Teltaja deposit also quartz. Small amounts of pyrrhotite, pyrite and traces of chalcopyrite are associated with the iron ore in the Kevus deposit, whereas they are of little importance in the Teltaja deposit. The ore formation in connection with scapolitization and tourmalinization relates Kevus and Teltaja to the pyrite-pyrrhotite-chalcopyrite-magnetite deposits Gruvberget, Nautanen, Aitik and Liikavaara Östra in northern Sweden. However, the content of magnetite, in these deposits is low, and only Nautanen has magnetite impregnations. Possibly they all are volcanic-exhalative formations formed in connection with a silica-intermediate volcanism. The host for all these deposits is albite — (microcline — quartz) rocks with varying amounts of mica, amphibole and pyroxene, similar in composition to the trachytes of Kevus and Teltaja.

According to Ambros (1977, 1980) there is a major hiatus between the older (stratigraphically lower) Greenstone and younger (stratigraphically higher) Porphyry groups in the Lannavaara area. After the regional metamorphism and the intrusion of the synkinematic Haparanda suite the Porphyry group was deposited, partly as an erosional product, on the Greenstone group. The both groups are in parts interlayered by metasediments of the Pahakurkkio group. The current results show that no such hiatus exists. The groups are possibly coeval. In a regional context both are involved in the same tectonic pattern and radiometric determinations show similar ages.

INTRODUCTION

The Lannavaara iron ore deposits Kevus, Sattavaara and Teltaja in northern Sweden are situated about 76 km ENE of Kiruna and about 5 km ESE of the Lannavaara village (Fig. 1). The ores were discovered in 1920–1921 by magnetic measurements (Högbom 1924). Kevus and Teltaja were subsequently investigated by four short drill-holes, which, however, only served to make concessions possible. In connection with a general investigation in the 1960's of the iron ores in Norrbotten county in northern Sweden, financed by the Government and carried out by the Geological Survey, the Lannavaara ores were more thoroughly investigated. In 1967 magnetometric and gravimetric field work was done. In 1970–71 drillings were made on Kevus and Teltaja and prospecting trenches were made over Sattavaara. In 1971 a minor electro-magnetic measurement was made over the Sattavaara occurrence. This work was initiated because of a moraine boulder of a sphalerite-bearing limestone discovered half-way between the Sattavaara and Teltaja deposits (Fig. 2). Later LKAB Prospektering AB made an intense search for this ore type and found west of the iron ores a wide limestone-dolomite bed in which there is a skarn horizon containing sphalerite. In the following description, however, only the iron ore deposits will be treated.

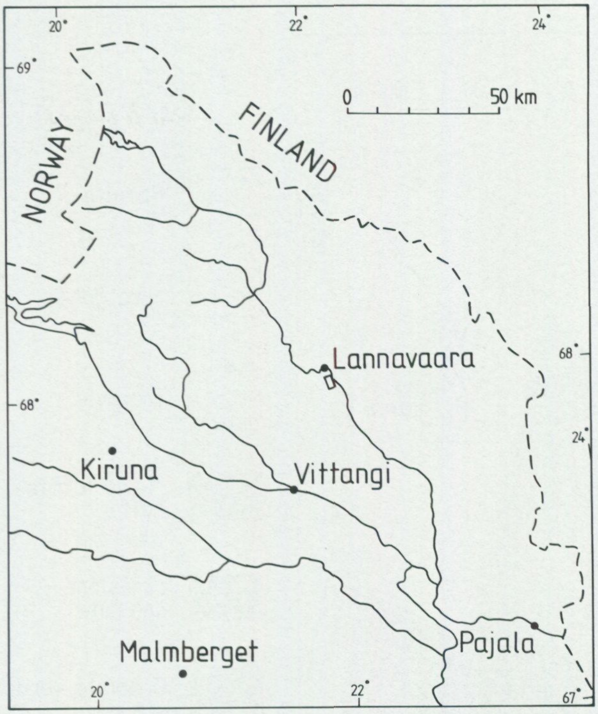


Fig. 1. Map showing the site of the Lannavaara iron ore deposits.

An extensive report of the results of the iron ore investigations made in 1967–71 is given by Ambros (1977). This material has largely been used here although a far-reaching reinterpretation is made of the rock types. This is based on study of thin sections, polished sections, and drill-cores which in more crucial parts have been remapped. The ore quantity for the Kevus deposit given here, is also somewhat different from that given by Ambros (ibid.). In addition, a rough estimate of the ore quantity in the Teltaja deposit, not previously given, is presented.

The map of the Lannavaara area on Fig. 2 is based on data obtained from the drilling and from geophysical measurements, mainly magnetometric ones. For Sattavaara Ambros' (1977) mapping of trenches and outcrops has been used. The western part of the map, mainly comprising limestone-dolomite, mica schist and granite, is entirely based on data delivered by LKAB Prospektering AB. The extent of the limestone-dolomite is known from a great number of drill-holes (not shown on the map). The delineation of adjacent graphite-bearing schists is based on electro-magnetic measurements made by LKAB Prospektering AB.

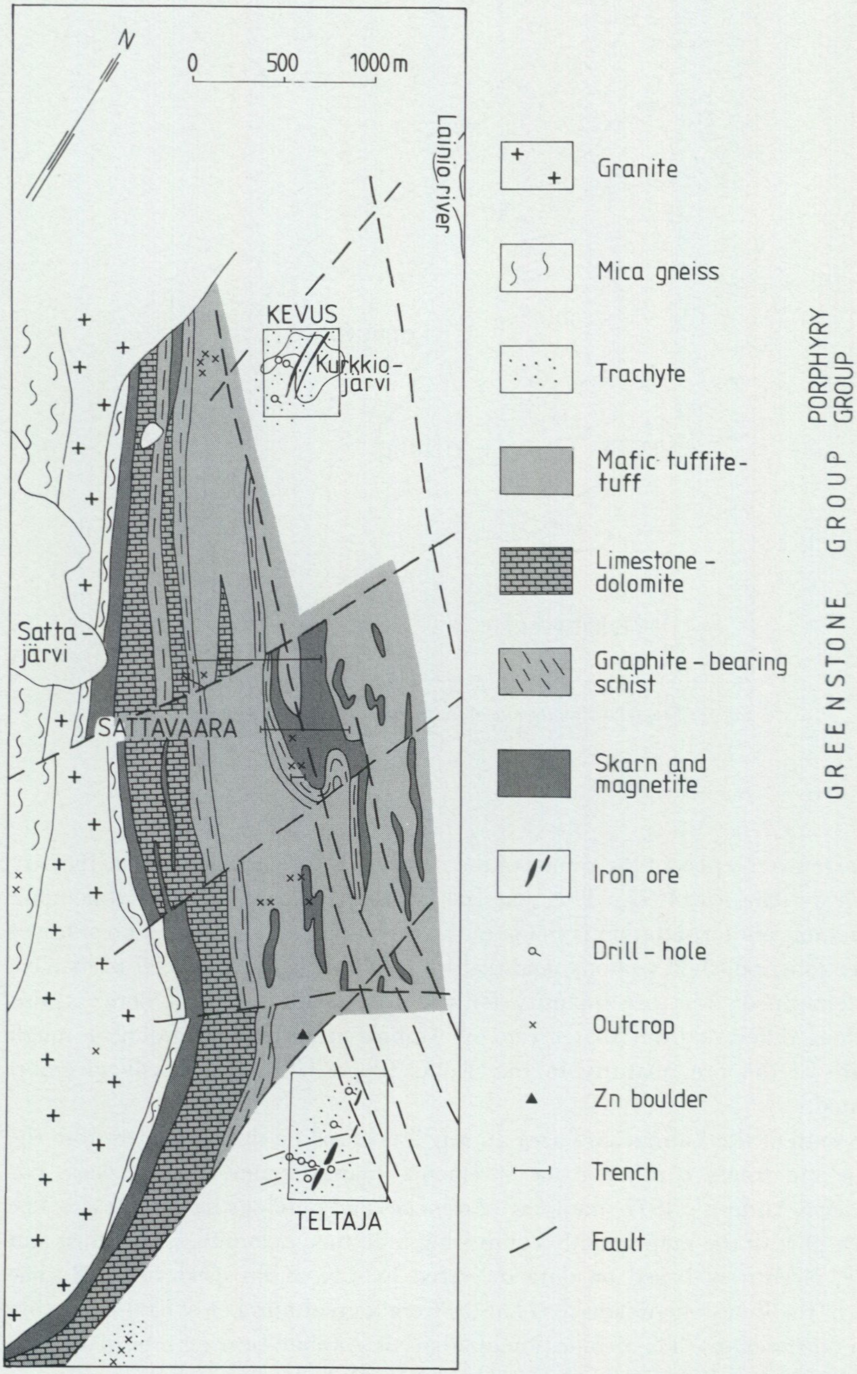


Fig. 2. Geological map of the Lannavaara iron ore deposits. The position of outcrops and trenches are taken from Ambros (1977). The western part of the map is mainly based on investigations made by LKAB Prospektering AB.

GEOLOGICAL SETTING

According to Ambros (1977, 1980) the rock units which cover the Lannavaara area are composed of the older Kiruna Greenstone group and the younger Kiruna Porphyry group. The Greenstone group consists of basaltic greenstones (''Greenstone formation'') and metasediments (''Sedimentary formation''). The greenstones are described as having uniform mineralogical composition with albite-andesine plagioclase, hornblende, sphene, calcite and magnetite as the main components. Common accessories are scapolite, epidote and biotite. The ''Sedimentary formation'' is composed of basaltic greenstone interlayered with skarn, limestone, iron ore, biotite schist and graphitic schists. According to Ambros (ibid.) the Lannavaara iron ores all occur in the rocks of the Greenstone group. The Porphyry group, found att Teltaja and towards the southwest, is made up of a syenite porphyry composed of alkali feldspar (microcline being subordinate), small amounts of quartz and some additional biotite and magnetite. In the syenite porphyry there are conglomeratic parts with pebbles of the porphyry rock.

The rocks of the Greenstone group are overlain by the Pahakurkkio group which comprises a thick sequence of quartzites and schists. The Greenstone and the Pahakurkkio groups are intruded by the ''Haparanda series'', which is a synkinematic differentiated suite mainly comprising granodiorites and gabbros. The youngest intrusive rocks belong to the ''syenite series'' with gabbros and perthite monzonites, and ''migmatite granite series'' with potassic granites and associated pegmatites.

According to Ambros (ibid.) the major structural elements that characterize the region around Lannavaara are: 1, an anticline in which the Greenstone group is exposed and 2, a syncline with rocks of the Pahakurkkio group. As the rocks of the Porphyry group occur in the direction of the axial dip against the south, the Porphyry group is considered as younger than both the other supracrustal units. The conglomerates at the base of the Porphyry group indicate an important hiatus. The Greenstone group, the Pahakurkkio group and the igneous rocks of the ''Haparanda series'' were folded and eroded before extrusion of the Porphyry group.

The geological setting given by Ambros (1977, 1980) is here revised in many respects.

The three iron ore deposits differ geologically and geophysically. The magnetic anomalies are homogeneous over Kevus and Teltaja whereas they show an irregular pattern over Sattavaara. Sattavaara lies within a large, positive gravimetric anomaly from which Kevus and Teltaja are separated. The host rocks and the ore types differ among the deposits. Kevus and Teltaja lie in trachytes of the Porphyry group, whereas Sattavaara occurs in mafic metavolcanics and metasediments of the Greenstone group (Fig. 2). In Sattavaara there is a Fe^{2+}-Mn silicate-magnetite banded chert which probably is stratabound. By contrast the Kevus magnetite ore and the Teltaja magnetite-hematite ore rich in quartz, both show epigenetic traits and are associated with secondary alterations such as scapolitization and tourmalinization. It must, however, be emphasized that the internal relationships of the three deposits are not clear. The details of the bedrock in the ore-bearing area are poorly known, mainly due to the scarcity of outcrops. In addition, intense faulting seems to have obliterated primary structural features (Fig. 2). The aeromagnetic map indicates that there are fault systems to NW and NE. The NE fault half-ways between Sattavaara and Teltaja is obvious from the magnetic ground measurement. Even if the map in Fig. 2 is schematic, it indicates that the contact relation between the Greenstone and Porphyry groups is largely influenced by tectonic disturbances. There is, however, no reason to anticipate the existence of an important hiatus between the two groups.

KEVUS

THE ORE

The Kevus iron ore which is the northernmost of the Lannavaara deposits, has no outcrop and runs beneath Lake Kurkkiojärvi (Fig. 2). The current knowledge is based on geophysical measurements and on four drill-holes which have a total length of 1078 m. Beyond the drilled area the geophysical measurements (Hesselbom 1977) have indicated some less important mineralizations: 250 m and 500 m east there are narrow magnetite-bearing zones.

The main ore zone is about 600 m long, strikes N–S and dips 80–85 degrees towards west (Fig. 3). In a trachyte there are massive bodies or veins of a skarn- and sulphide-bearing magnetite. In addition the trachyte is locally relatively rich in an even impregnation of magnetite. For technical purposes a division of the ore has been made based on the iron grade. ''Rich ore'' is defined as containing more than 30 % Fe and ''lean ore'' 20–30 % Fe. The boundary is gradational. Two zones, up to 20 m wide, of rich ore are surrounded by lean ore which in the east is up to 50 m wide. In between the ore-bearing parts the trachyte contains magnetite veins and impregnations in varying amounts but the grade does not exceed 20 % Fe.

The rich ore covers an area of 11 000 m^2 and has an average iron content of 39.5 % Fe. The ore contains 1–2 % S, less than 0.1 % Cu, 0.2–0.5 % Mn and 0.01–0.09 % P (occasionally up to 0.2 % P). A chemical analysis of the ore is given in Table 1. The lean ore covers an area of 41 600 m^2 and has an average iron content of 24.3 % Fe. The contents of sulphur, manganese and phosphorus are the same as for the rich ore. Occasionally the sulphur content rises to 2–5 % S. Down to a depth of 200 m below the bedrock surface, the ore reserves are 9.4 million tonnes of rich ore and 29.4 million tonnes of lean ore. In total there are 38.8 million

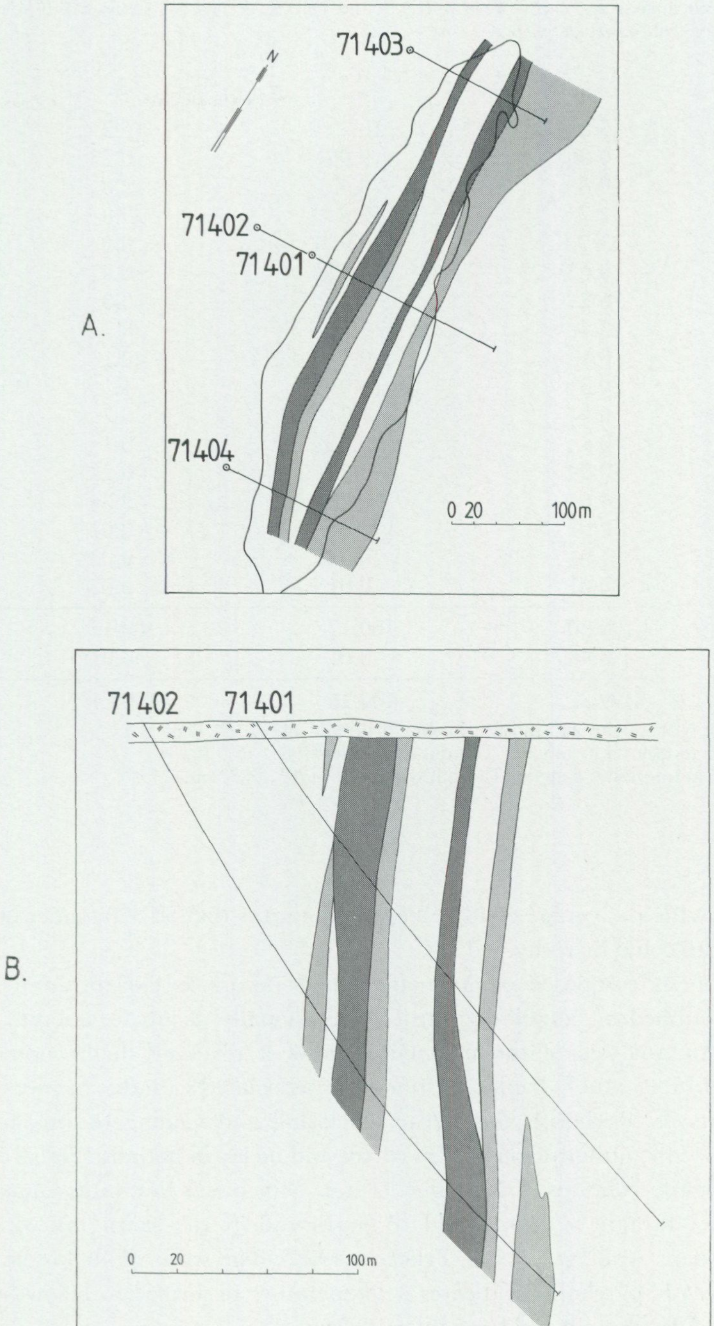


Fig. 3. **The Kevus iron ore. A. Geological map. B. Cross-section of the central part. Dark-grey** = magnetite ore with more than 30 % Fe. Light-grey = magnetite ore with 20–30 % Fe. Heavy solid line on the map delineates magnetic anomalies exceeding 32 000 s. White areas inside this line contain magnetite veins, but the iron content is less than 20 % Fe.

TABLE 1. Chemical analyses of iron ore from Kevus and Teltaja. Weight %. Analyst: G. Svedenbäck, Geological Survey of Sweden.

	1	2	3
SiO_2	5.2	10.2	15.2
TiO_2	0.06	0.06	0.23
Al_2O_3	0.8	0.4	2.0
Fe_2O_3	52.7	55.6	79.8
FeO	23.7	23.9	0.6
MnO	0.63	0.47	0.02
CaO	6.2	4.6	0.3
MgO	3.7	3.7	0.32
Na_2O	$<$ 0.1	$<$ 0.1	$<$ 0.1
K_2O	0.3	0.03	1.1
H_2O^+	0.4	0.2	0.2
H_2O^-	$<$ 0.1	$<$ 0.1	$<$ 0.1
P_2O_5	0.09	0.20	0.22
CO_2	4.6	0.78	0.04
F	0.02	0.03	0.02
S	1.9	$<$ 0.02	$<$ 0.02
BaO	$<$ 0.01	$<$ 0.01	0.07
	100.30	100.17	100.12
−(F, S)	0.48	0.01	0.01
	99.82	100.16	100.11

1. Magnetite ore with calcite and biotite. Kevus, drill-hole 71401, 84.1 m.
2. Magnetite ore in quartzitic gangue. Teltaja, drill-hole 71901, 76.5 m.
3. Hematite ore in quartzitic gangue. Teltaja, drill-hole 71903, 283.2 m.

tonnes of ore with an average of 28 % Fe, which means that 54 320 tonnes of iron per metre depth could be recovered.

The rich ore is composed of magnetite which occurs as 0.05–0.1 mm long, anhedral or subhedral, angular grains, or occasionally as up to 1.5 mm long aggregates. An analysis of the magnetite shows a relatively high content of manganese (0.74 % MnO, Table 2). Commonly associated with the magnetite are small amounts of pyrrhotite and pyrite, enclosing and veining the magnetite. Analyses show low, uniform contents of cobalt and nickel in both minerals (Table 3). The pyrrhotite contains 46.3 atomic % iron, which is a low value compared with 47.2–49.1 atomic % iron found in pyrrhotite in the skarn iron ores in northern Sweden (Annersten 1969, Frietsch 1985). The value of 46.3 atomic % iron in the Kevus pyrrhotite indicates a temperature of formation below 500°C (Arnold 1962, Desborough and Carpenter 1965).

Major constituents in the ore are diopside, hornblende and biotite. Locally the ore is rich in calcite containing small amounts of tremolite. Chlorite occurs in

TABLE 2. Chemical composition of oxide ore minerals from the Lannavaara iron ores. Weight %. Micro probe analyses. Analyst: C. Ålinder, Geological Survey of Sweden

	1 Magnetite	2 Magnetite	3 Hematite	4 Magnetite	5 Ilmenite	6 Ilmenite
SiO_2	0.14	0.12	0.12	0.18	0.05	0.09
TiO_2	0.08	0	0.25	0.15	52.70	52.43
Al_2O_3	0.19	0.12	0.19	0.15	0.11	0.06
Cr_2O_3	0	0.01	0	0.01	0.01	
V_2O_5	0	0.08	0.05	0.32	0.06	
FeO	91.66	92.36	89.44	91.73	36.33	42.18
MnO	0.74	0.42	0	0.11	10.91	4.94
MgO	0.10	0.08	0.05	0.06	0.08	0.05
ZnO	0	0.01	0	0.01		
NiO	0.02	0.05	0	0	0.03	
	92.93	93.25	90.10	92.62	100.28	99.75

Number of ions on basis of

	(32 O)		(32 O)		(6 O)		(32 O)		(6 O)		(6 O)	
Si	0.04	15.93	0.04	15.97	0.01	3.98	0.06	15.91		2.00		1.99
Ti	0.02				0.01		0.03		1.99		1.99	
Al	0.07		0.04		0.01		0.06		0.01			
Fe^{3+}	15.80		15.89		3.95		15.76					
Fe^{2+}	7.83	8.07	7.88	8.03	0.02	0.02	8.04	8.10	1.53	2.01	1.78	1.99.
Mn	0.19		0.11				0.03		0.47		0.21	
Mg	0.05		0.04				0.03		0.01			

Locality: 1. Kevus, drill-hole 71401,65.0 m; 2–3. Teltaja, drill-hole 71903, 243.35 m; 4–5. Sattavaara trench 3500 N/823 W, sample MA 24/2; 6. Sattavaara trench 3500 N/934 W, sample MA 35/2.

small or accessory amounts. Sphene is a common accessory mineral. In the southern part of the western ore horizon, analcime occurs in accessory amounts.

The magnetite veins, which intersect the trachyte abundantly, vary in width from millimetres to centimetres. Locally up to decimetre wide veins have been observed. The veins appear as a network and form a breccia similar to the "ore breccia" in the apatite-bearing iron ores of the Kiruna type. The trachytic wall rock between the veins forms angular, irregular and crushed fragments. Whether the veins have intruded into a tectonized zone or represent the results of forceful injection it is not possible to say. The veins often show a zonation with an outer part of magnetite, passing inwards through skarn silicates into calcite. In skarn — calcite veins lacking magnetite the calcite is always central (Fig. 4).

TABLE 3. Chemical composition of pyrrhotite-pyrite from Kevus iron ore, drill-hole 71401, 65.0 m. Micro probe analyses. Analyst: C. Ålinder, Geolocical Survey of Sweden.

	Pyrrhotite		Pyrite	
	Weight%	Atomic%	Weight%	Atomic%
Fe	59.91	46.33	46.1	33.04
S	39.65	53.39	53.45	66.72
Co	0.14	0.10	0.13	0.09
Ni	0.24	0.18	0.22	0.10
Fe:S	0.87		0.50	

The mineralogical composition of the veins is similar to the rich ore described above. The magnetite is associated with pyrrhotite, pyrite and inferior amounts of chalcopyrite. The sulphides often enclose and brecciate the magnetite. The order of formation is magnetite→pyrite→pyrrhotite and chalcopyrite. The pyrrhotite clearly replaces pyrite. Quite exceptionally the magnetite shows an octahedral martitization.

The gangue minerals of the veins often replace the surrounding trachyte and occur in it as an impregnation (Fig. 5). Most common are diopside, scapolite and hornblende, whereas biotite and calcite are somewhat less abundant. Subordinate in amount are apatite, phlogopite, tremolite, garnet, epidote and serpentine.

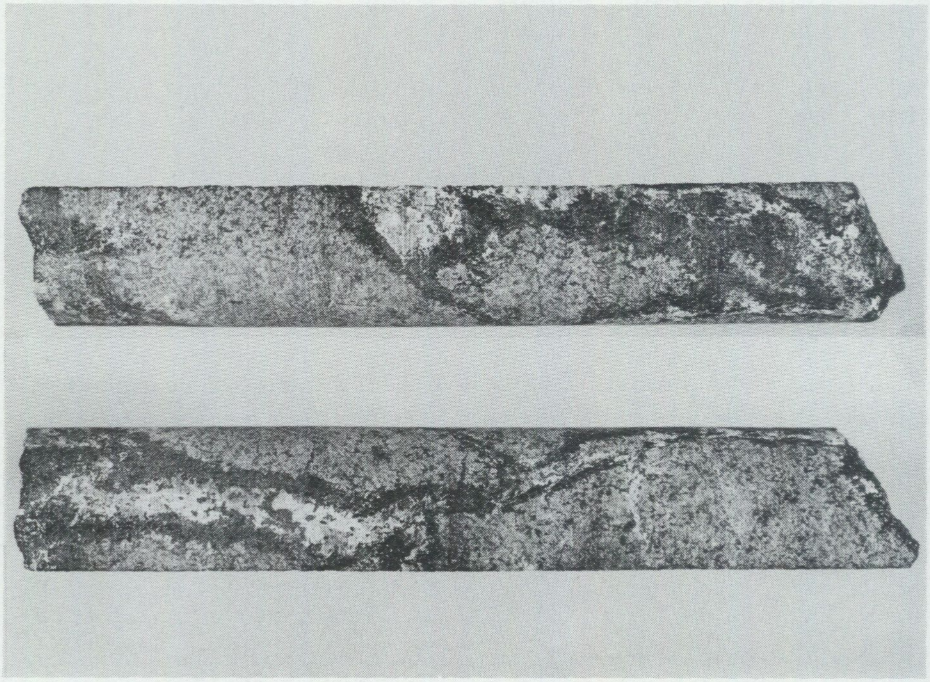


Fig. 4. Veins of magnetite and skarn silicates (black) and calcite (white) in trachyte. Kevus, drill-hole 71401, 233.30 m.

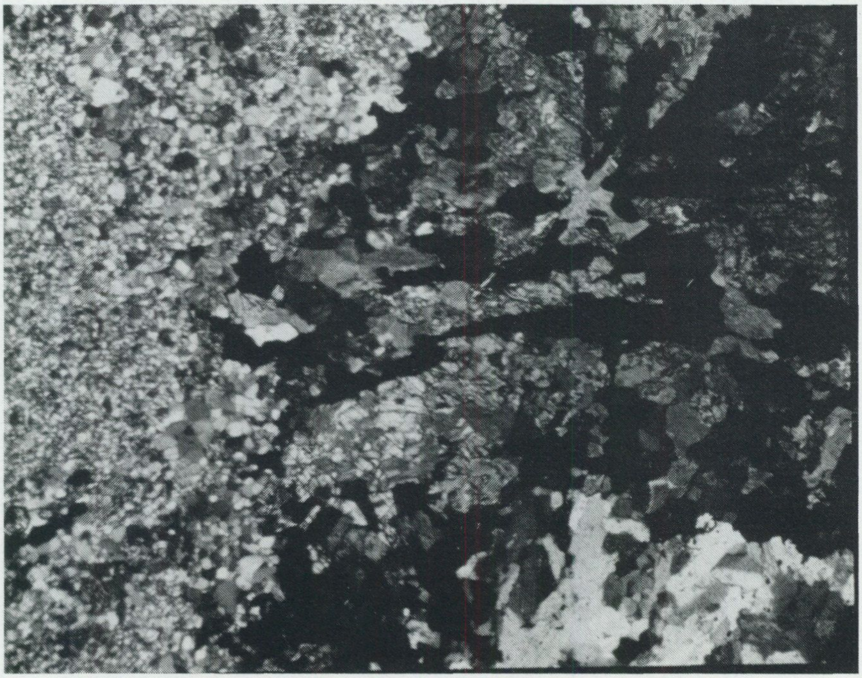


Fig. 5. Vein of magnetite and some pyrite-pyrrhotite (all black), tremolite-diopside (grey with relief), albite (white to grey laths in the right lower corner) and some calcite in a fine-grained trachyte (left part of the picture). Kevus. Drill-hole 71401, 198.67 m. Crossed nicols, × 25.

Albite, tourmaline and sphene occur in small and accessory amounts. Occasionally the trachyte is rich in an even impregnation of tourmaline (Fig. 6) and sphene.

The ore veins are in parts rich in a coarser albite which forms 1–2 mm long laths (Figs 5 and 7). Small amounts of subhedral grains of apatite belong to the association (Fig. 7). The laths are surrounded by an albite-rich trachyte. The coarse-grained albite seems to be formed simultaneously with the magnetite in the veins.

A relatively large part of the ore which has been assigned as rich, i.e. with more than 30 % Fe, comprises a grey, dense, non-schistose, magnetite-rich trachyte. It has small grain size, occasionally 0.005–0.05 mm, and is composed of albite, subordinate microcline, quartz and magnetite (Fig. 8). The latter mineral forms coarser aggregates. This dense trachyte often shows a breccia structure; it contains 1–10 mm long, elongated fragments of a still more fine-grained trachyte consisting of albite, quartz, and some biotite and magnetite.

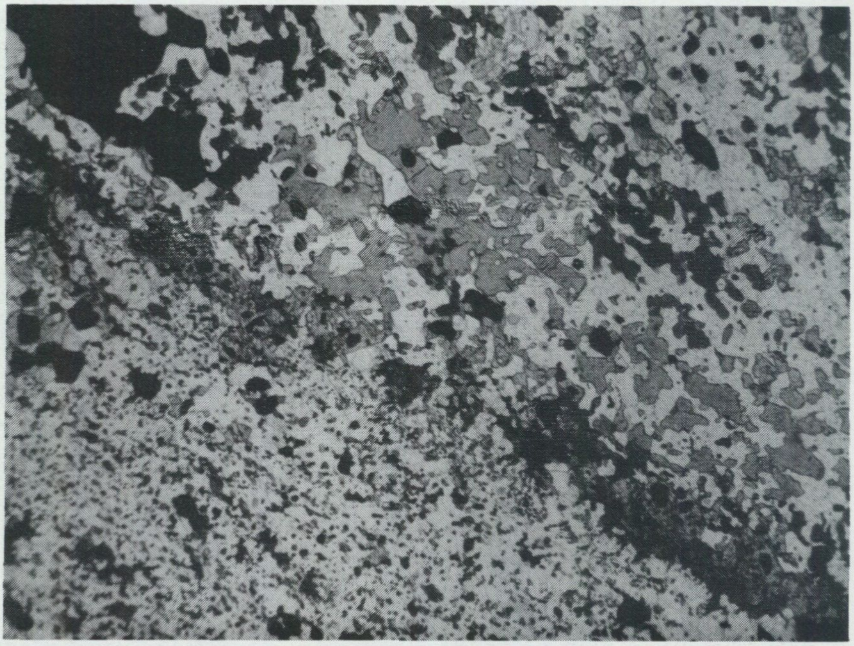


Fig. 6. Magnetite and pyrite (both black) in scapolite (light-grey), diopside-hornblende (grey) in the upper half of the picture. In the lower part a fine-grained trachyte rich in tourmaline (small, grey grains and the elongated aggregate diagonally crossing the picture). Kevus, drill-hole 71404, 95.03 m. Ord. light, × 25.

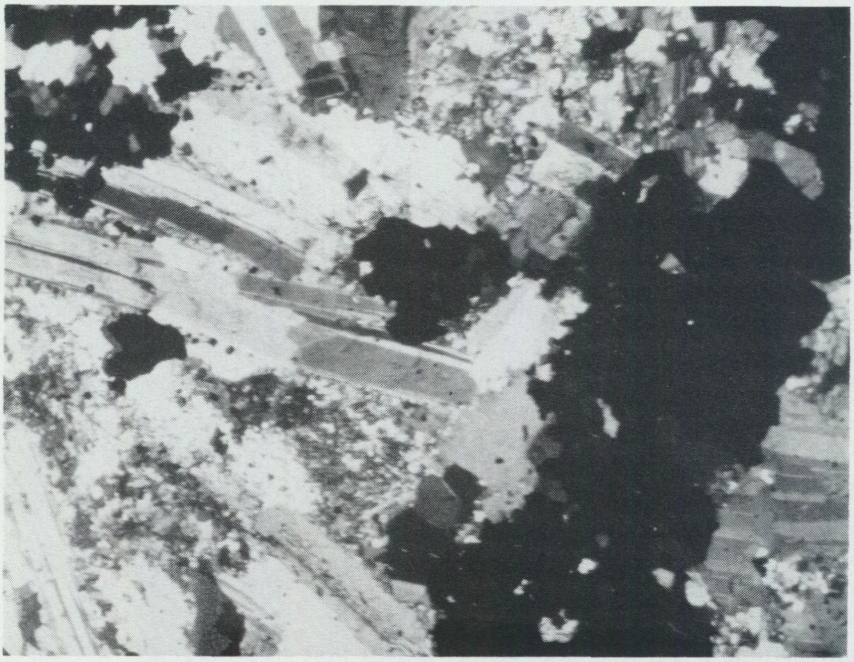


Fig. 7. Magnetite (black) and laths of albite in a fine-grained trachyte. Grey, sub-euhedral grains in the magnetite are made up of apatite. Kevus, drill-hole 71401, 168.63 m. Crossed nicols, × 25.

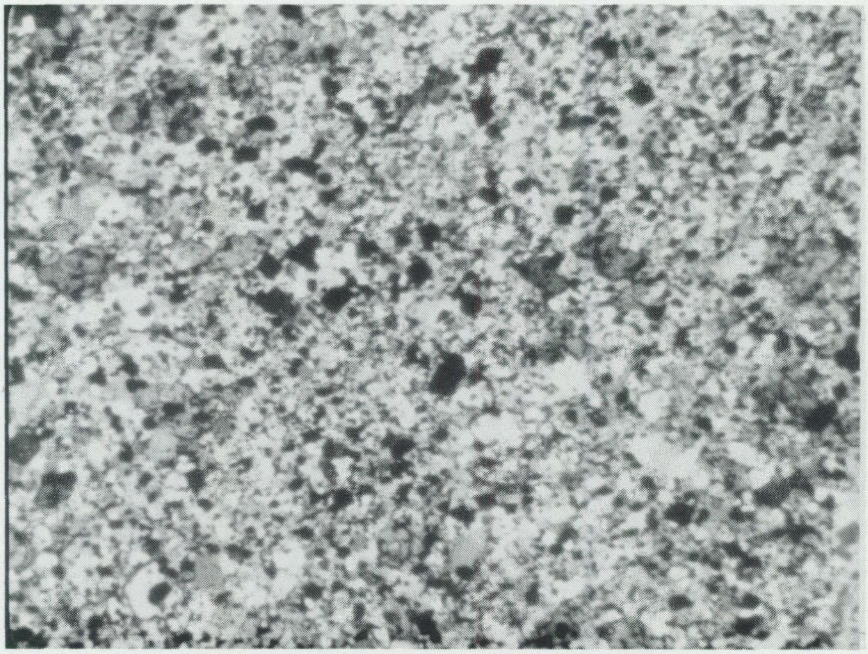


Fig. 8. Trachyte rich in magnetite (black) and with some tremolite-actinolite and biotite (both grey). Kevus, drill-hole 71404, 204.77 m. Crossed nicols, × 40.

THE WALL ROCK

TRACHYTE

The wall rock of the Kevus ore is an intermediate metavolcanite which to a varying degree has been secondarily altered. Geijer (1931) called it an utterly scapolitized leptite. The modal and chemical composition (Table 4) indicate a trachyte.

In the unaltered state the trachyte is a grey, fine-grained, non-schistose or weakly schistose rock which is composed of an even-grained, allotrimorfic aggregate feldspar and quartz. A weak parallel texture is sometimes present. The grain size is mostly 0.01–0.3 mm. The proportion of feldspar to quartz varies somewhat but throughout there is dominance of the feldspar component, which is mostly an albite and to a less extent microcline. Minerals that occur in small amounts are biotite, tremolite, sphene, magnetite, iron sulphides and apatite. Quite exceptionally a porphyritic texture is observed formed by up to 1 mm long, subhedral, lath-shaped phenocrysts of albite (Fig. 9). The phenocrysts are often epidote-chlorite-sericite-biotite altered. The albite surrounding the feldspar phenocrysts is sometimes intersertally arranged. In the porphyry there are exceptionally up to 2 mm long, somewhat elongated or rounded porphyroblasts of chlorite with small amounts of epidote.

TABLE 4. Chemical analyses of metavolcanics and metasediments from Kevus and Teltaja. Weight %. Analyst: G. Svedenbäck, Geological Survey of Sweden.

	1	2	3	4
SiO_2	56.6	62.3	57.4	59.5
TiO_2	0.60	0.58	0.70	0.84
Al_2O_3	17.8	15.8	14.4	11.9
Fe_2O_3	2.9	0.6	2.6	2.5
FeO	4.7	3.9	3.9	12.8
MnO	0.16	0.16	0.18	2.4
CaO	2.9	3.6	6.0	1.3
MgO	3.3	1.98	4.6	2.4
Na_2O	7.8	1.2	4.7	1.0
K_2O	3.1	8.5	3.5	3.4
H_2O^+	0.8	0.8	0.8	1.3
H_2O^-	0.1	$<$ 0.1	0.1	0.1
P_2O_5	0.29	0.44	0.35	0.17
CO_2	0.50	0.27	0.86	0.13
F	0.08	0.10	0.09	0.10
S	0.15	$<$ 0.02	$<$ 0.02	$<$ 0.02
BaO	0.12	0.23	0.10	0.25
	101.80	100.46	100.18	99.99
−(F, S)	0.07	0.04	0.04	0.04
	101.73	100.42	100.14	99.95
si	165	234	169	200
al	30.6	35.0	25.0	23.6
fm	32.5	26.0	36.1	61.2
c	9.1	14.4	18.9	4.6
alk	27.6	24.6	20.0	10.5
t=al−(c+alk)	−6.1	−4.0	−13.9	8.5

1. Trachyte. Kevus, drill-hole 71401, 171.50 m.
2. Trachyte. Teltaja, drill-hole 71903, 181.5 m.
3. Trachyte. Teltaja, drill-hole 70903, 40.0 m.
4. Mica schist. Teltaja, drill-hole 70901, 182.6 m.

In the trachyte there are varieties which are rich in mafic minerals. In parts the trachyte contains hornblende and biotite in a semi-parallel aggregate and the rock somewhat resembles a mica schist (Fig. 10). In other varieties the mafic minerals are more evenly distributed (Fig. 11). The intersertally arranged albite laths are surrounded by scapolite, hornblende, biotite, small amounts of diopside and accessory amounts of sphene, apatite and calcite. The sphene forms up to a few millimetres long aggregates. Possibly the more mafic varieties are the result of intense secondary alteration of the trachyte in connection with the ore formation, but it cannot totally be ruled out that the mafic varieties represent altered metabasites.

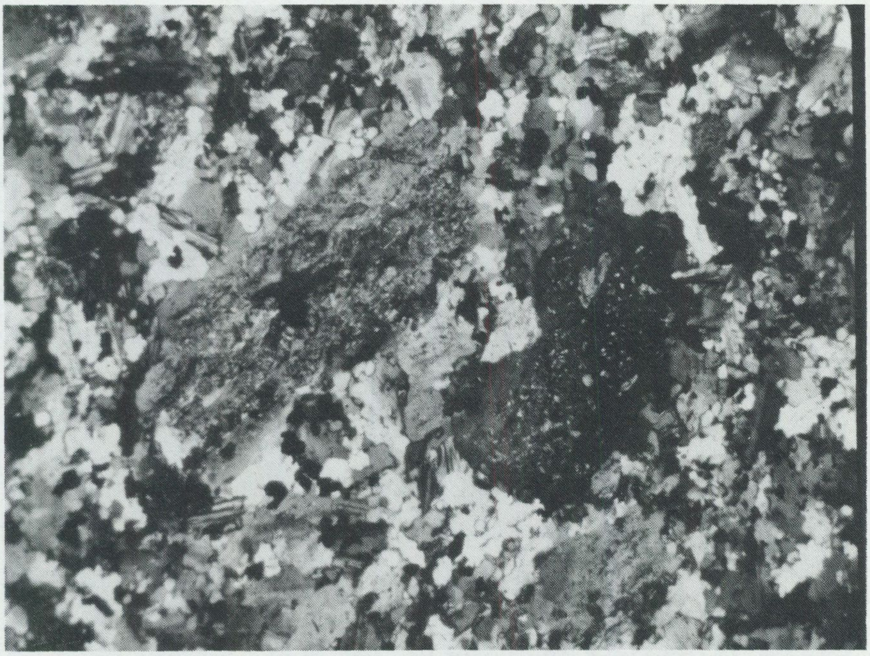


Fig. 9. Trachyte. Phenocrysts of albite in a matrix of albite. Kevus, drill-hole 71401, 261.2 m. Crossed nicols, × 40.

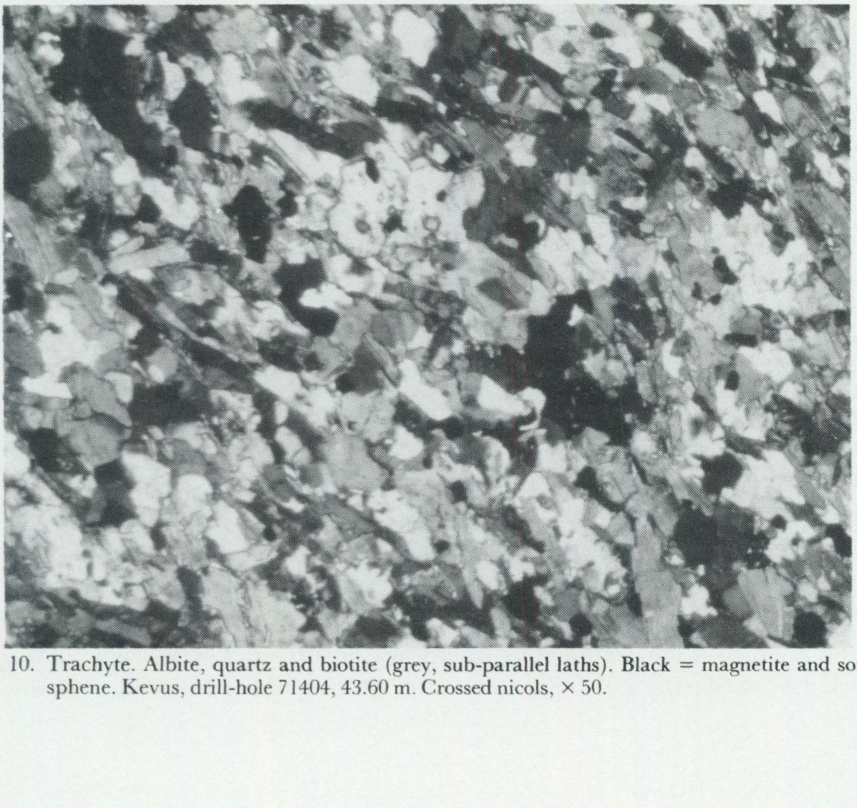


Fig. 10. Trachyte. Albite, quartz and biotite (grey, sub-parallel laths). Black = magnetite and some sphene. Kevus, drill-hole 71404, 43.60 m. Crossed nicols, × 50.

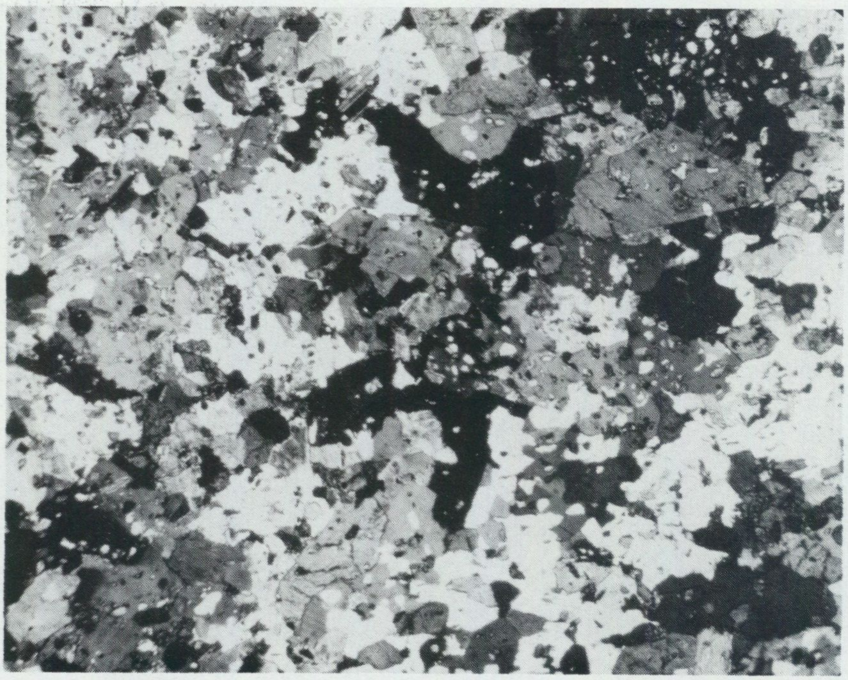


Fig. 11. Trachyte. Albite and scapolite (both white to light-grey) and subordinate amounts of hornblende and biotite (dark-grey to black). Small, black grains are magnetite and sphene. Kevus, drill-hole 71403, 118.06 m. Crossed nicols, × 25.

ALTERED TRACHYTE

Large parts of the trachyte are veined and replaced by the same skarn silicates that are found in the bodies and veins of ore. The difference in composition from the ore-bearing parts is a lower content of magnetite. The skarn veins and replacements contain 0.02–0.2 % P, 1–2 % S and 0.1–0.3 % Mn, contents similar to those in the bodies and veins of ore. The main silicates in the skarn veins are scapolite, diopside and biotite. Scapolite seems here to be somewhat more prominent than in the ore veins. Locally there is an alternation of cm-wide layers of: 1, scapolite with small amounts of magnetite, iron sulphides, hornblende and diopside, and 2, diopside, scapolite and some hornblende (Fig. 12). In parts the content of iron sulphides is relatively high. A "sulphide quartzite" described by Ambros (1977) contains on average 4 % S and 0.1 % Cu. The trachyte here contains up to a few centimetres wide veins of scapolite, hornblende, diopside, pyrrhotite, magnetite and small amounts of albite, quartz and sphene. Locally, as

Fig. 12. Altered trachyte. Scapolite (white to dark-grey) dominant. Diopside (dark-grey, with relief, mainly in the lower part of the picture). Magnetite (black) mainly in the right part of the picture. Kevus, drill-hole 71402, 47.42 m. Crossed nicols, × 25.

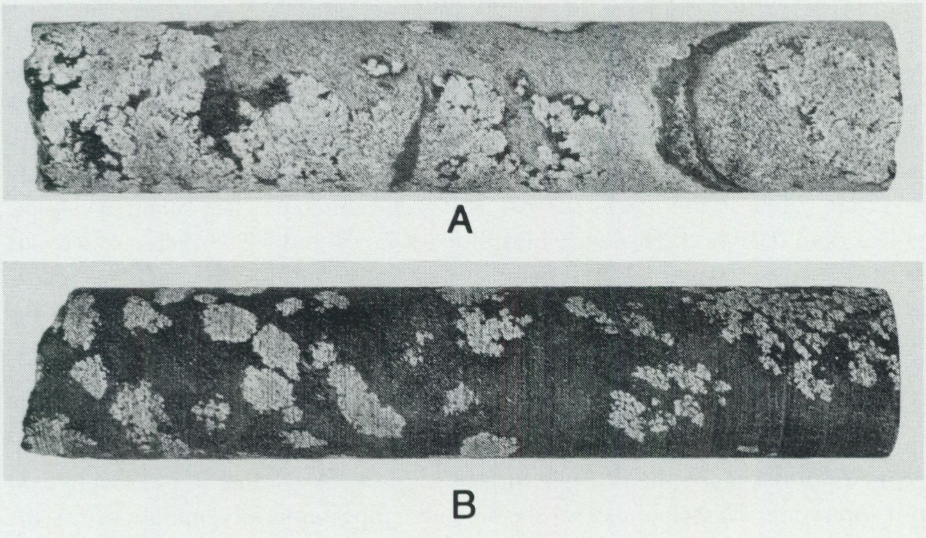


Fig. 13. Alteration of trachyte. Kevus. Upper part of drill-hole 71401. A. Trachyte (grey, mainly in the right and upper part of drill-core) with aggregates and veins of scapolite (white) and hornblende (dark-grey). B. Trachyte totally replaced by hornblende (dark-grey) and scapolite (white).

in drill-hole 71401, there are up to 10 m wide sections in which the trachyte is rich in calcite veins, mostly of limited width but some up to almost one metre. The calcite contains biotite and pseudomorphs of serpentine, possibly after diopside.

In parts the trachyte is intensely replaced by scapolite and hornblende (Fig. 13). The trachyte contains up to 5 cm long concentric aggregates of scapolite which are bordered by a 1–3 mm wide zone of hornblende and some magnetite, biotite and pyrrhotite. The final product of this replacement is an aggregate of hornblende and small amounts of biotite in which 1–2 cm long, irregular aggregates of scapolite have grown.

TELTAJA

THE ORE

The Teltaja ore, the southernmost of the Lannavaara deposits, is covered by glacial drift and the current knowledge of it is based on diamond-drillings, which comprise 7 holes with a total length of 1703 m, and on geophysical surveys. The ore-bearing zone has a geophysically estimated length of about 1 km and encloses two tectonically separated ore bodies which strike NNW–SSE and dip steeply towards the west (Fig. 14). The northern ore is dislocated about 100 m east of the southern ore by an ENE–WSW fault (Hesselbom 1977).

The southern ore body has a length of about 250 m and a width of about 50 m. It contains mostly 30–40 % Fe, in parts up to 50 % Fe. At the southern end, a leaner ore with 20–30 % Fe forms a major part. The ore mineral is magnetite and subordinate hematite. The hematite reaches the surface in the south and forms the eastern half of the ore, whereas in the northern part hematite is found only in the deeper part of the ore. The ore is associated with a quartz-rich rock. Skarn silicates and calcite are present in narrow horizons. The content of phosphorus is mostly less than 0.1 % P, but locally 0.3–0.4 % P is encountered. The content of sulphur is less than 0.01 % S. However, in drill-holes 71903 and 70903 there are sections with several per cent of sulphur, mainly in the leaner ore. The content of manganese is 0.2–0.5 % Mn, but in short sections attains 1–2 % Mn (cf. Fig. 14). All the higher manganese contents seem to be bound to calcitic parts of the ore. A chemical analysis of the magnetite ore is given in Table 1.

The northern ore body seems in principle similar to the southern one. Interpretation of the morphology of the former is hampered because the ore, at least in parts, does not reach the bedrock surface (Fig. 14). According to the geophysical interpretation (Hesselbom 1977) the ore only crops out locally, mainly within the magnetic anomalies exceeding 32 000 γ on the map in Fig. 14. The geophysical interpretation is, however, affected by the relatively large part of the ore that is made up of hematite with magnetite as a subordinate component.

The southern part of the northern ore body consists of a 20 m wide magnetite ore with 33–39 % Fe, 0.01–0.13 % P and 0.08–4.5 % S. Towards the west there are two zones about 5 m wide with leaner ore.

In the northern part of the same body, which is probably cut by an oblique fault (Fig. 14), there is an about 70 m wide ore with 47 % Fe and 0.04–0.28 % P; sulphur and manganese are not present. The eastern half of the body is composed of hematite and the western of magnetite. A chemical analysis of the hematite ore is given in Table 1. West of this rich ore body there is an ore about 5 m wide with 32 % Fe, 0.1–0.2 % P and 0.5–1.15 % S.

The magnetometric map shows that the surface outcrop of the southern ore is 13 000 m^2 and of the northern ore 9 000 m^2 (Hesselbom 1977). Calculations based on the gravimetric results show that the mass excess for the whole deposit corresponds to 17.5 million tonnes iron, which if an average of 41 % Fe is postulated, means an ore reserve of about 43 million tonnes.

Both the magnetite ore and the hematite ore are fine-grained and somewhat schistose. The ore minerals form 0.05–0.5 mm long, subhedral, lath-shaped grains, elongated and aligned in a subparallel texture. In some cases the grains are crushed and tectonized with a jointing at right angles to the subparallel texture. The relationship between magnetite and hematite is not clear. The two ore types pass gradationally into one another. No martitization phenomena are observed. The hematite often forms zones or single grains in the magnetite (Fig. 15). In some of the coarser hematite grains there are small irregular ”remnants” of magnetite. The common impression of any age difference is that hematite postdates magnetite. Chemical analyses show that magnetite by comparison with hematite is enriched in manganese but depleted in titanium (Table 2). The ore is accompanied throughout by a quartzitic gangue composed of 0.05–0.3 mm long, anhedral grains of quartz with irregular borders and with undulating extinction (Fig. 16). Diopside, tremolite and calcite occur in accessory amounts.

The ore minerals occur in the quartz as veins (Fig. 17) or as an even impregnation: in the latter as anhedral grains of the same size as the quartz. In some sections the magnetite and hematite grains are only 0.05 mm across. Mostly the grain size of the iron oxides decreases outwards from the more ”massive” veins (cf. Figs 16 and 17). Occasionally very fine-grained quartz and hematite are intergrown.

In the ore there are narrow intercalations of calcite with some biotite, diopside and tremolite. Accessories are garnet and apatite, the latter in parts forming euhedral, 1–2 mm long grains. The ore is in parts rich in skarn silicates which mainly are scapolite, diopside, hornblende and biotite (Fig. 18). Associated are accessory amounts of chlorite, quartz, biotite and calcite. Apatite is relatively abundant in some skarn sections (Fig. 18).

Outside the massive ore the trachytic host rock is intersected by ore veins which

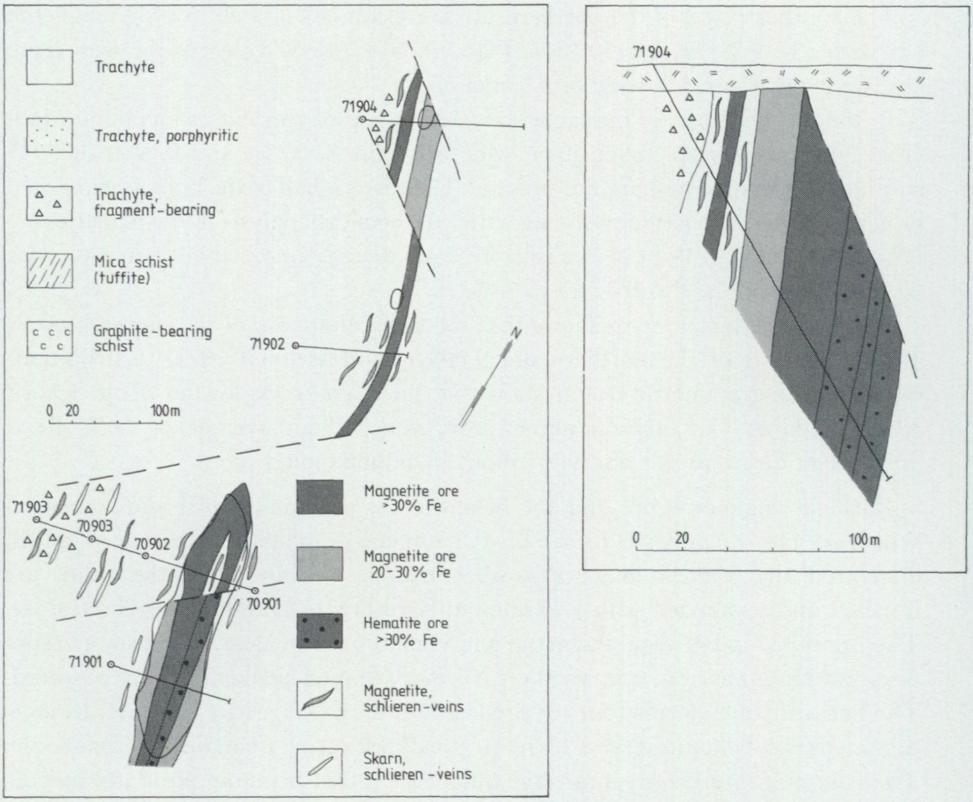
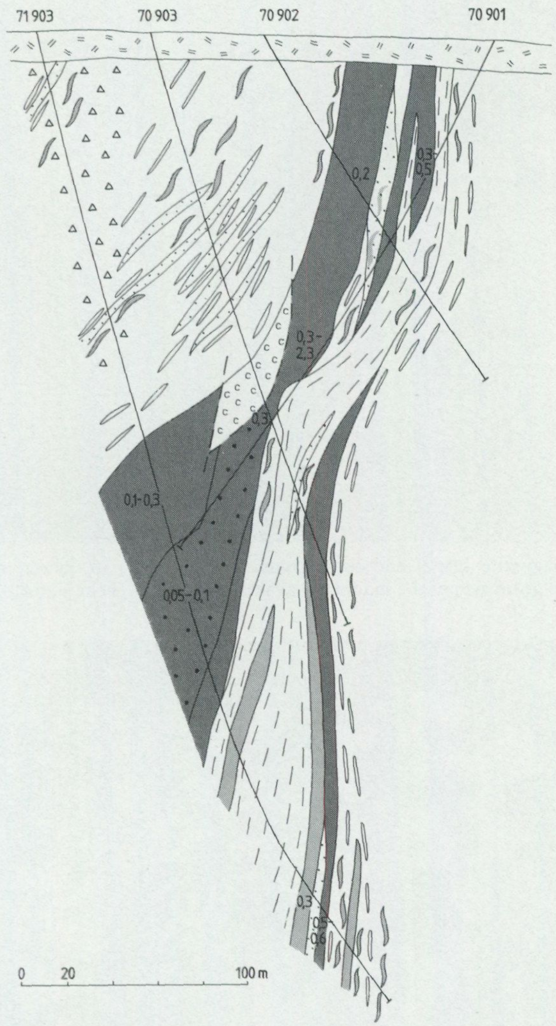


Fig. 14. The Teltaja iron ore. Schematic geological map with the site of the drill-holes, and cross-sections. Figures on the right cross-section denote % Mn in the ore. Heavy solid line on the map encloses magnetic anomalies exceeding 32 000 γ.

mostly have sharp borders (Fig. 19) but also a gradual decrease of the magnetite content towards the trachyte. The trachyte adjacent to these ore veins often contains finely dispersed magnetite. The width of the veins varies from centimetres to decimetres, occasionally upp to metres. The magnetite forms 0.05–0.2 mm long, anhedral grains clustering into elongated aggregates. In the veins the gangue is made up of microcline, quartz and subordinate albite. In small or accessory amounts sphene, allanite, apatite, biotite, muscovite, baryte, analcime and tourmaline occur. Some veins are relatively rich in sphene and tourmaline. Pyrite is a common minor constituent. Occasionally muscovite makes up an important mineral in these veins.

As already described the ore veins are mostly accompanied by skarn silicates. The width of the skarn varies from decimetres to metres, but east of the northern part of the southern ore the skarn has a width of up to 10 metres. The skarn masses



are composed of hornblende, diopside, subordinate scapolite and small amounts of biotite and calcite (Fig. 20). The silicates are often brecciated by 1–20 cm wide veins of magnetite and quartz. Occasionally 1–5 mm wide veins of pyrrhotite and some chalcopyrite occur. Locally the skarn contains small spots of quartz, albite, microcline and some sphene and calcite.

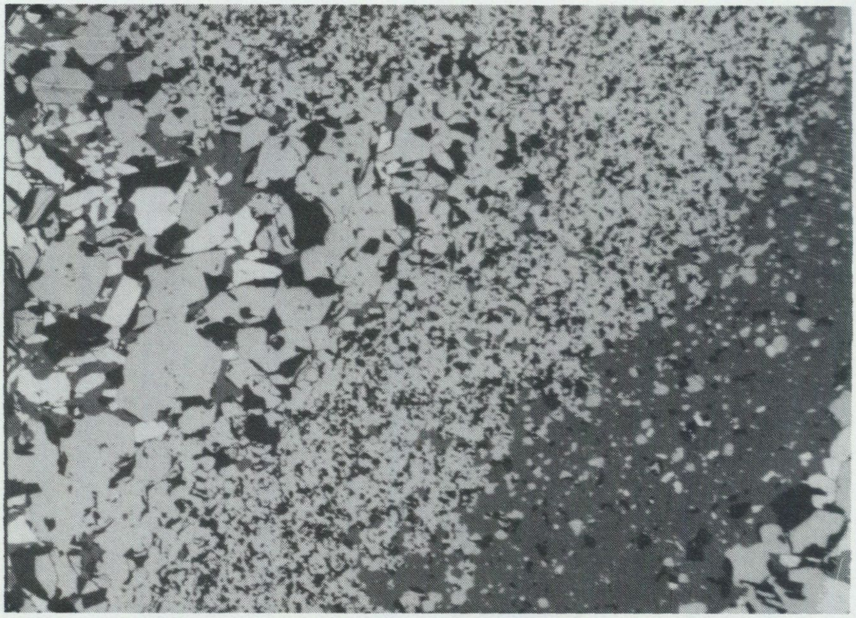


Fig. 15. Vein of magnetite (grey) and some hematite (light-grey) in quartz (dark-grey). Note the decrease in grain size of the magnetite against the quartz. Teltaja, drill-hole 71904, 188.4 m. Ord. light, × 40.

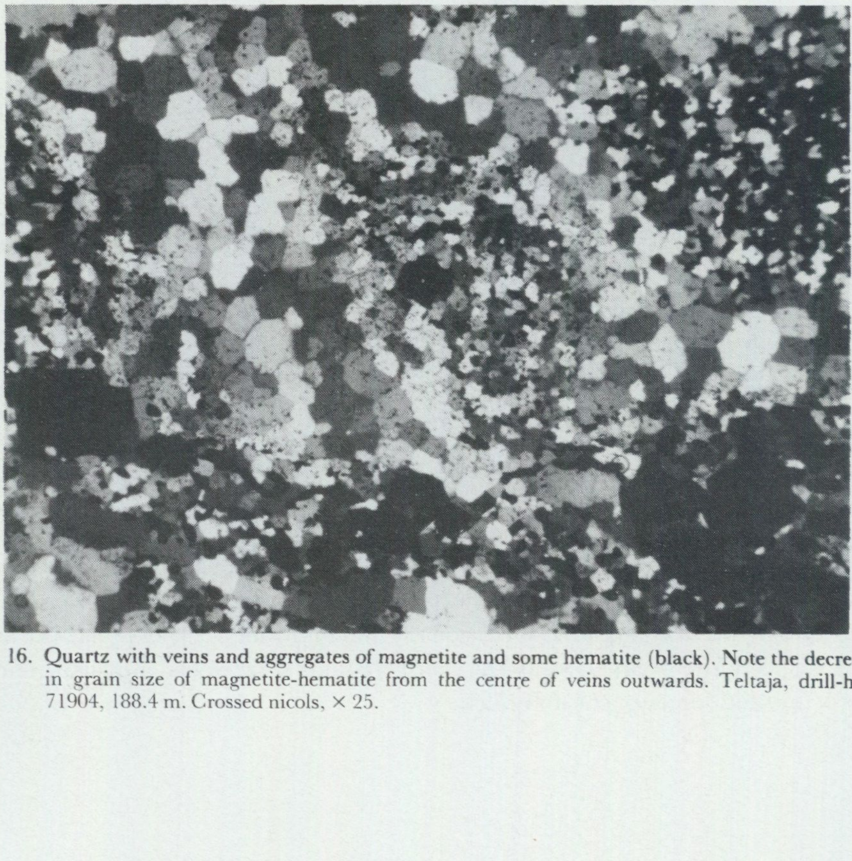


Fig. 16. Quartz with veins and aggregates of magnetite and some hematite (black). Note the decrease in grain size of magnetite-hematite from the centre of veins outwards. Teltaja, drill-hole 71904, 188.4 m. Crossed nicols, × 25.

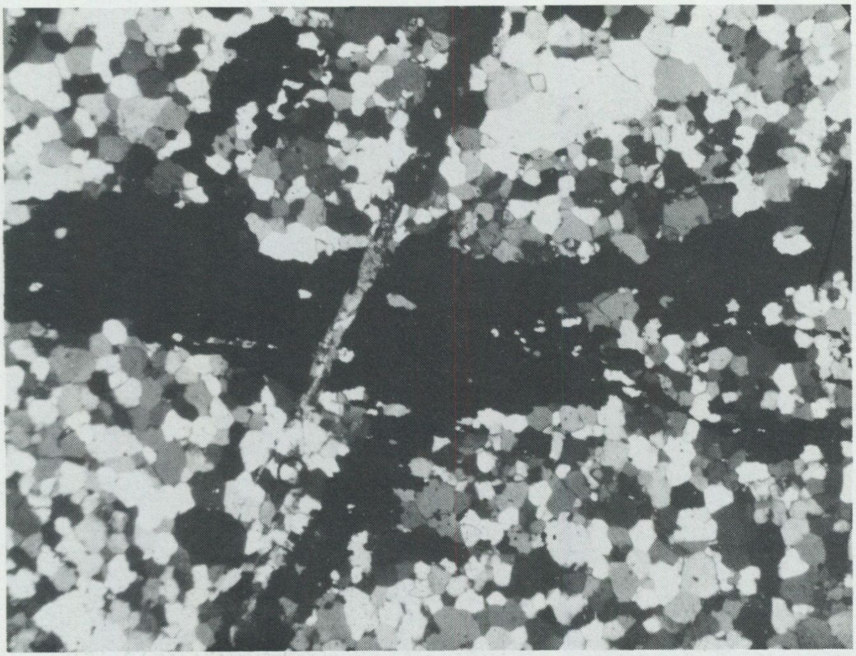


Fig. 17. Veins of magnetite (black) in quartz. Teltaja, drill-hole 70901, 217.53 m. Crossed nicols, × 25.

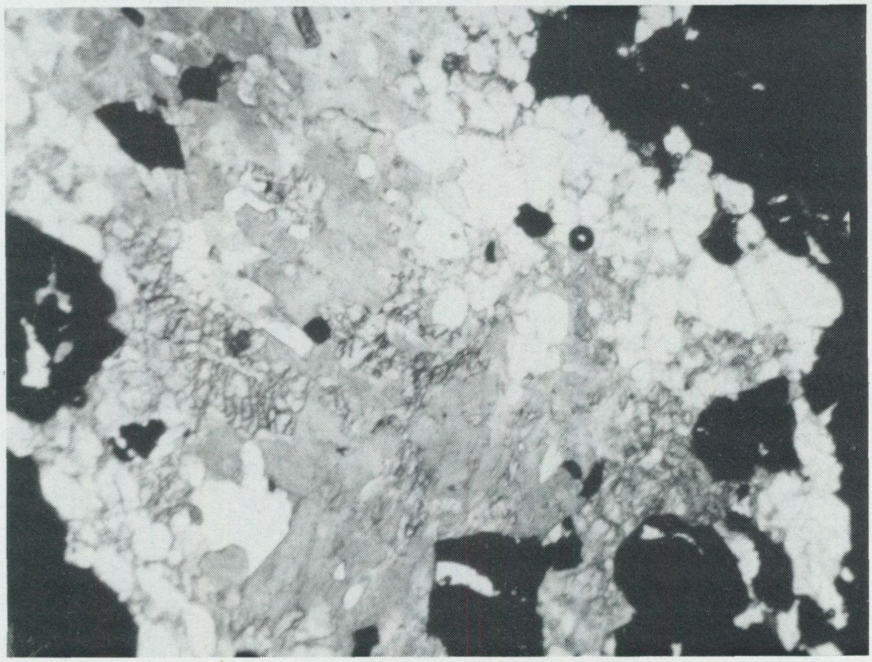


Fig. 18. Magnetite (black), hornblende (grey), some diopside (grey with a high relief) and apatite (white). Teltaja, drill-hole 70901, 70.64 m. Crossed nicols, × 30.

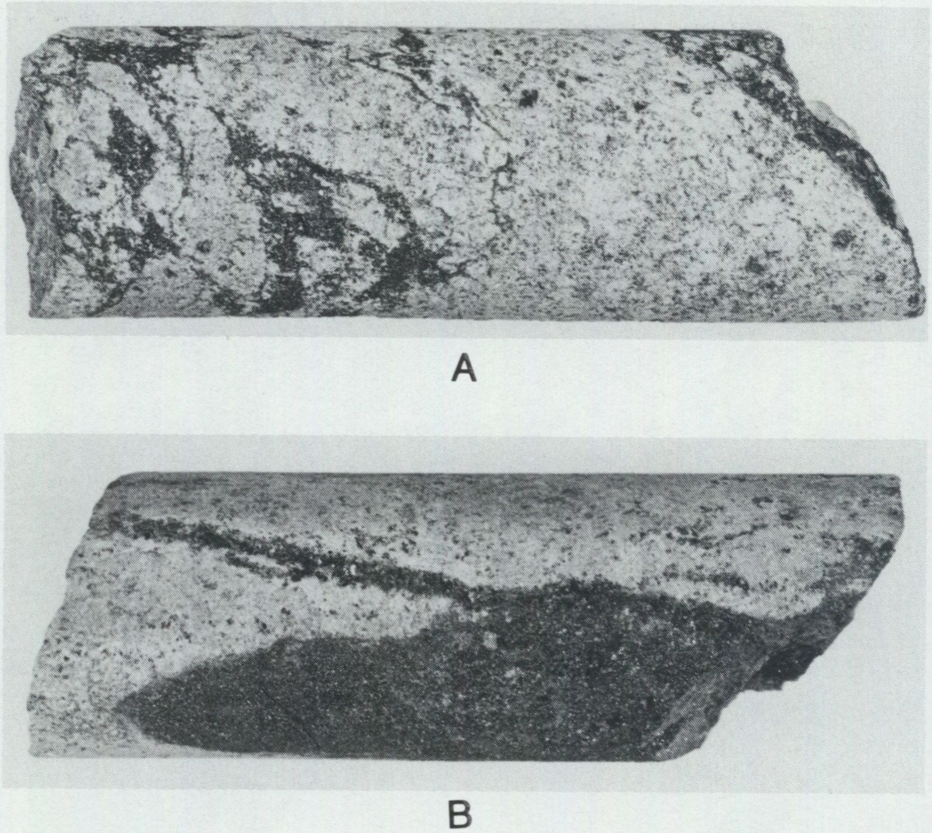


Fig. 19. A. Trachyte veined by magnetite. Teltaja, drill-hole 71904, 72.5 m. B. Fragment-bearing trachyte veined by magnetite. Teltaja, drill-hole 71903, 44.60 m.

THE WALL ROCK

The dominant wall rock at Teltaja is a trachyte (Fig. 15). It resembles the trachyte in the Kevus deposit but differs in being partly fragment-bearing. The Teltaja trachyte is veined and replaced by secondary skarn silicates, in particular east of the ore. At the northern end of the southern ore body there is a horizon of mica schist, which possibly represents a tuffitic bed in the trachyte. The mica schist contains veins of ore and skarn. West of the ore there is at depth a small occurrence of graphite-bearing schist. The presence of this rock is enigmatic. Possibly it belongs to the Greenstone group. Graphite-bearing schists are common in basic volcanics at Sattavaara (Fig. 2). Probably the occurrence of this "alien" rock unit at Teltaja is due to tectonic disturbances which bring rocks of the

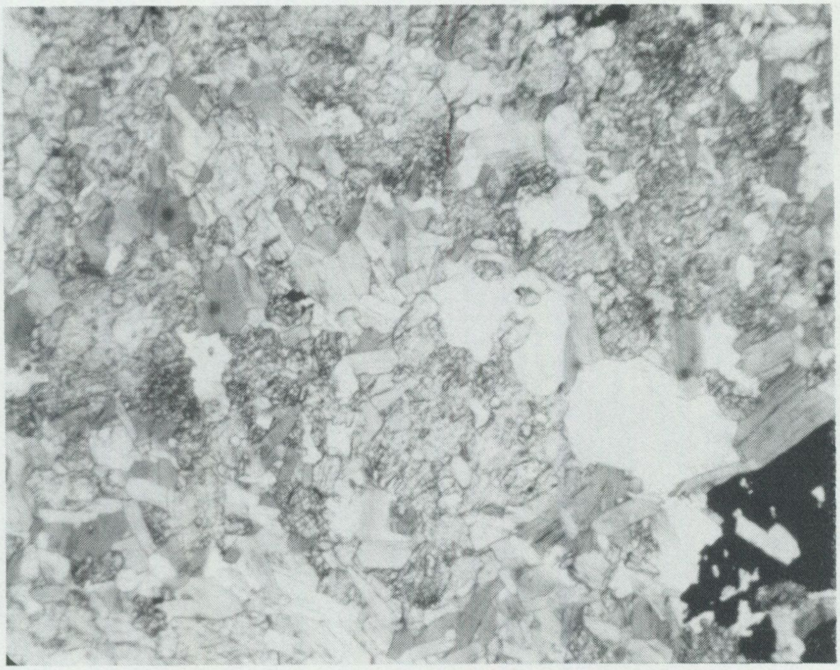


Fig. 20. Skarn consisting of biotite (grey laths, dominating), diopside (grey, with higher relief), calcite (white) and magnetite (black). Teltaja, drill-hole 71903, 437.62 m. Ord. light, × 30.

Porphyry and Greenstone groups into close contact. At the level of the graphite-bearing schist there is possibly a dislocation, cutting the sequence at a low angle. The cross-section in Fig. 15 shows that the ore morphology has obvious differences above and below the graphite-bearing schist. Thus, in the deeper part the ore is wide and in addition contains hematite, which is not found in the upper part.

TRACHYTE

The trachyte is a grey to red-grey, fine-grained, non-schistose to weakly schistose feldspar-quartz rock. The texture is allotrimorphic, exceptionally showing faint parallel features. The grain size is about 0.02–0.05 mm. The main components are albite, microcline and quartz. Feldspar always dominates over quartz, the latter making up roughly 10–20 volume per cent (Fig. 21). Among the feldspars albite mostly dominates but locally there is more microcline. Biotite occurs in small amounts and accessories are magnetite, sphene and tourmaline, which are often associated. Chemical analyses of the trachyte are given in Table 4. They show great variation in sodium and potassium contents, due to variation in the albite-microcline proportions.

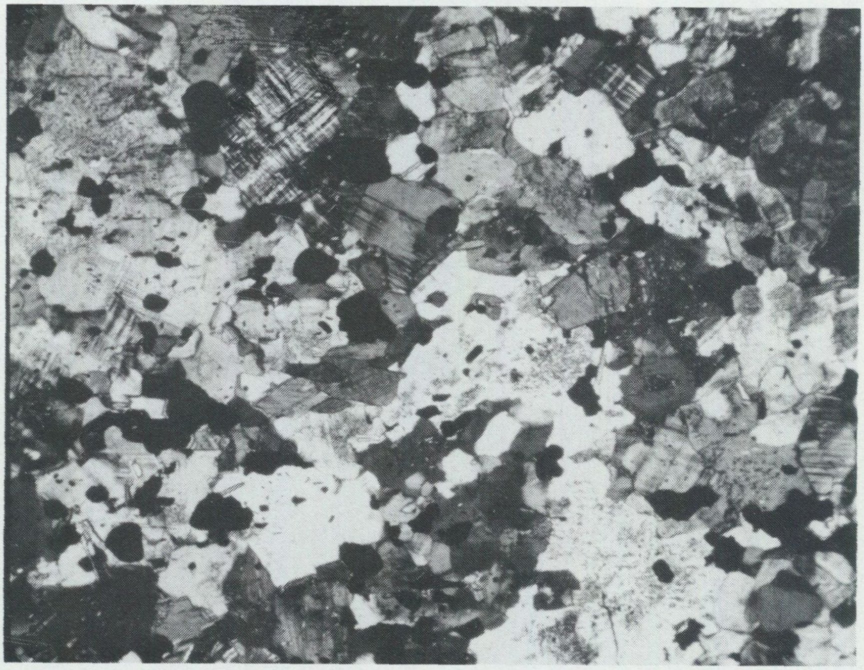


Fig. 21. Trachyte. Microcline, albite and subordinate quartz. Single lath-formed grains with higher relief are biotite. Black is magnetite. Teltaja, drill-hole 70901, 131.90 m. Crossed nicols, × 30.

Within the trachyte porphyritic parts are relatively common. However, it cannot be excluded that some of the porphyritic rocks are dykes which cut the trachyte. The contacts are often masked by crushing. The porphyritic trachyte, which in parts is a reddish, dense rock, contains 1–2 mm long, anhedral-subhedral laths of a somewhat sericite-epidote-altered albite in a feldspar-quartz matrix (Fig. 22). The matrix is composed of 0.05–0.1 mm long grains of albite and quartz, and small amounts of biotite and muscovite in an allotrimorphic or weakly parallel texture. Accessories are magnetite, calcite, apatite, allanite and sphene, the last of these sometimes occurring relatively abundantly. The content of ore minerals is mostly low. However, veins and impregnations of magnetite, pyrite and pyrrhotite occur locally (Fig. 20). Occasionally pyrite is found in relatively large amounts along the schistosity. These relationships indicate that the porphyritic rocks are, at least in parts, older than the ore formation, and possibly coeval with the main part of the trachytes. Secondary alterations such as tourmalinization (cf. Fig. 26) support such an age relationship.

West of the ore zone the trachyte is locally fragment-bearing. Ambros (1980) considered these parts to be similar to the Saarivaara conglomerate, which outcrops about 1.5 km south of the Teltaja deposit (Fig. 2). The nature and origin

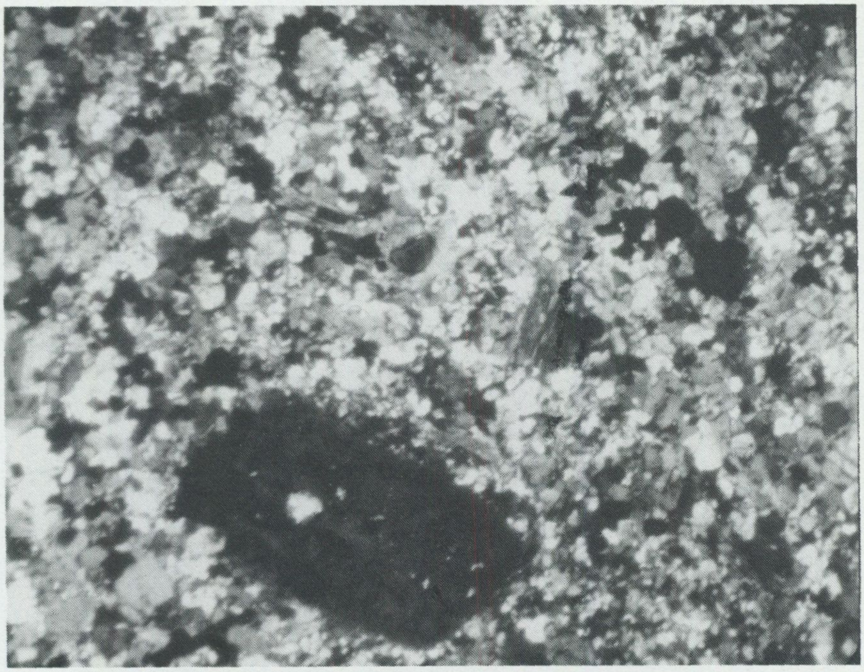


Fig. 22. Trachyte. Albite phenocrysts in a matrix of albite and quartz, small amounts of magnetite and sphene (both black) and single grains of calcite (white). Teltaja, drill-hole 70903, 99.0 m. Crossed nicols, × 30.

of the fragment-bearing trachyte in the Teltaja deposit are however unclear. It is uncertain whether this rock is an erosional product as stated by Ambros (1980), or an agglomerate. In addition a tectonic origin, at least for parts, cannot be ruled out (see below). The fragments, which are 1–20 cm long, angular and elongated in the direction of schistosity, consist almost solely of the same trachyte as the matrix. The rock is fine-grained (grain size 0.05–0.1 mm) and consists of albite, microcline and minor amounts of quartz. Biotite and tremolite are present in small amounts and accessories are sphene, apatite and magnetite. The trachyte of the fragments is often porphyritic with 1–2 mm long laths of albite. The matrix around the fragments is an albite — microcline — (quartz) bearing trachyte which in parts is porphyritic with phenocrysts of albite. The content of secondary minerals in the matrix is mostly relatively high, giving the rock a dark colour. The main minerals are hornblende and diopside. Scapolite and apatite occur as accessories. In some cases the hornblende content is very high and the rock thus resembles a tectonic breccia with hornblende veining the trachyte; the fragment structure is here rather diffuse. There are, however, examples, such as west of the southern ore, where the fragments seem to be clasts, so that the rock should be interpreted as a volcanic breccia.

Of genetic interest is that the fragment-bearing trachyte at several localities is cut by up to a few centimetres wide veins of magnetite with small amounts of sulphides, which most probably have the same provenance as the other ore bodies and veins cutting the trachyte (Fig. 19). The fragment-bearing trachyte adjacent to the magnetite veins is occasionally impregnated with chalcopyrite. The magnetite veins which intersect the fragment-bearing trachyte show that the rock is older than the ore formation, and that the fragment-bearing trachyte cannot, as stated by Ambros (1980), be an erosion product much younger than the trachyte and the ore. The occurrence of hornblende, diopside and accessory amounts of scapolite and apatite in the matrix of the fragment-bearing trachyte support the conclusion.

ALTERED TRACHYTE

The trachyte and its porphyritic parts contain mostly secondary minerals, skarn silicates and calcite, appearing as an even impregnation or as veins varying in width from some centimetres to several metres. The alterations are most intense adjacent to the ore, especially east of it.

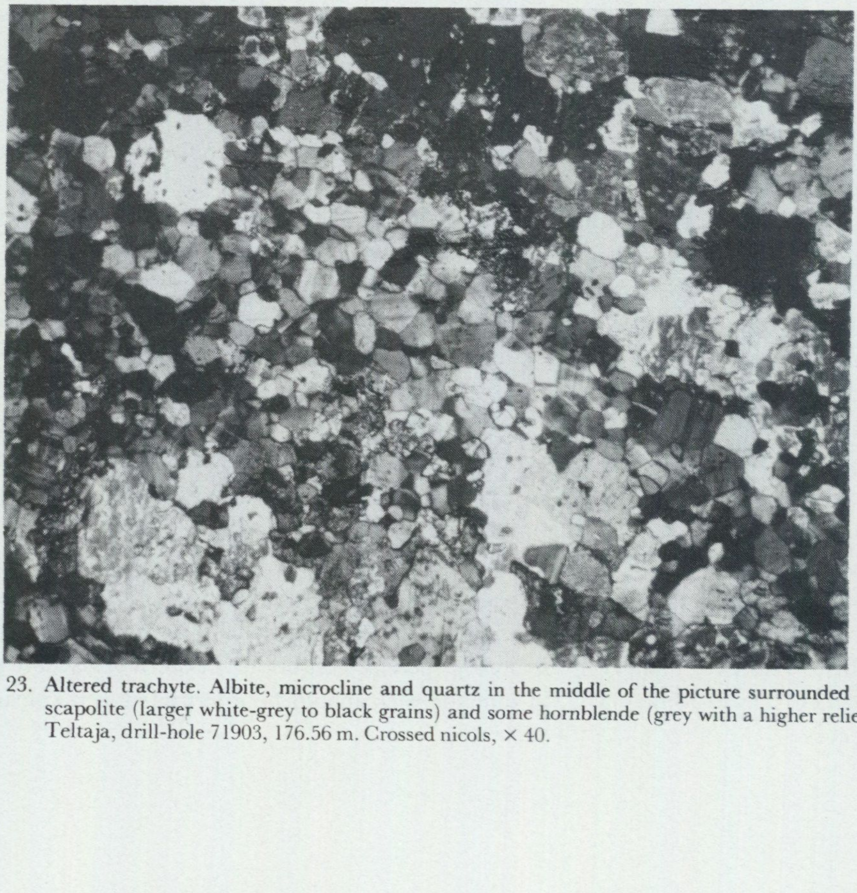


Fig. 23. Altered trachyte. Albite, microcline and quartz in the middle of the picture surrounded by scapolite (larger white-grey to black grains) and some hornblende (grey with a higher relief). Teltaja, drill-hole 71903, 176.56 m. Crossed nicols, × 40.

Fig. 24. Secondary vein in trachyte. Scapolite (white to grey-white) dominates. Epidote (grey) in the upper, right part. The scapolite includes tourmaline (small, grey, lath-shaped grains) and magnetite (large, black grains). Teltaja, drill-hole 70903, 40.0 m. Crossed nicols, × 25.

The most common secondary minerals are scapolite, hornblende and diopside (Fig. 23). Somewhat less common are microcline, quartz, biotite, muscovite and epidote. Small amounts of magnetite, calcite, sphene, apatite, tourmaline, chlorite and sometimes fluorite occur. The sphene is often associated with magnetite. In some cases the trachyte is densely impregnated with tourmaline (Figs 24 and 25). Here and there small amounts of pyrrhotite, pyrite and occasionally also chalcopyrite occur as a fine network. Parts of the trachyte are more or less totally transformed into an aggregate consisting of scapolite, biotite, chlorite and hornblende, with subordinate or small amounts of epidote, sphene, magnetite, iron sulphides and apatite.

MICA SCHIST

East of the northern part of the southern ore at Teltaja there is a horizon of mica schist (Fig. 14). It is possibly a tuffitic intercalation but could also be a metamorphic derivative from the trachyte. The tuffitic forms are represented by a grey to red-grey, fine-grained, somewhat schistose mica-bearing rock. It consists of anhedral grains (0.05–0.2 mm across) of albite, quartz and in some cases microcline

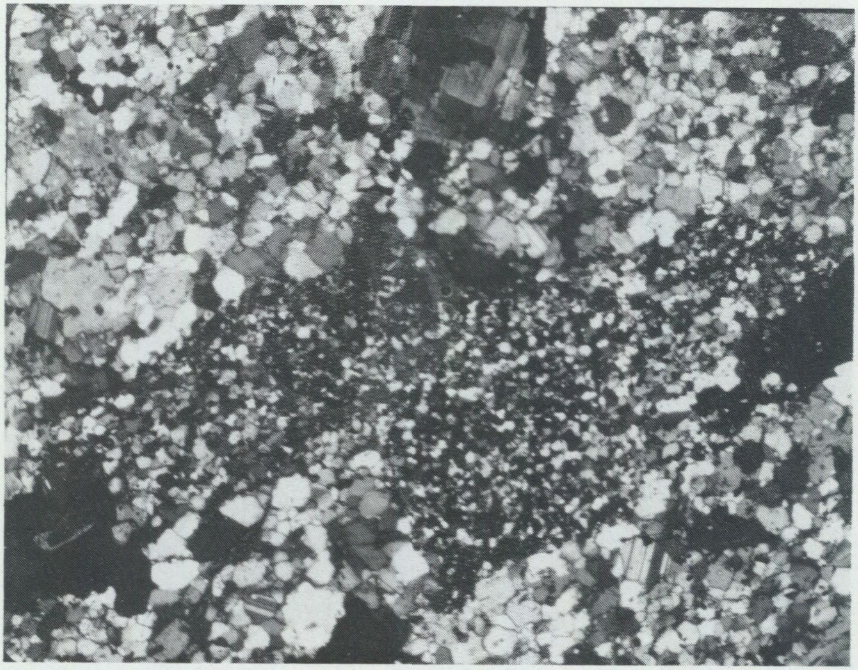


Fig. 25. Porphyritic trachyte with albite phenocrysts cut by a vein of pyrrhotite, some magnetite and pyrite (black, to the right and the left) and tourmaline (small, black grains between the pyrrhotite). Teltaja, drill-hole 70903, 87.76 m. Crossed nicols, × 25.

with a parallel texture. Subordinate or small amounts of biotite or muscovite occur. Evenly distributed, an-subhedral grains (0.5 mm across) of a weakly brownish, often zonated garnet are common (Fig. 26). Other minor constituents are tourmaline, apatite and magnetite, the last of these often elongated along the schistosity planes. The tuffite is cut by 1–5 mm wide veins of magnetite, quartz, subordinate microcline, biotite and small amounts of garnet, pyrite and chalcopyrite. Some of the sedimentary parts have a secondary mineralogical composition. For example in the upper part of drill-hole 70901 there is an interlayering of: 1, fine-grained (grain size 0.02 mm) albite and quartz, some hornblende and scapolite and accessory amounts of magnetite, and 2, still finer grained (grain size 0.005 mm) albite, quartz, some biotite and accessory amounts of magnetite.

However, large parts of the mica schist are made up of a mica-bearing trachyte. The mica content is low and garnet is missing or occurs quite sparsely. The rock is composed of albite, quartz and some biotite. In parts microcline is a major constituent. Relatively coarse aggregates of hornblende with some magnetite, garnet, sphene, apatite and tourmaline are common. Occasionally sillimanite is

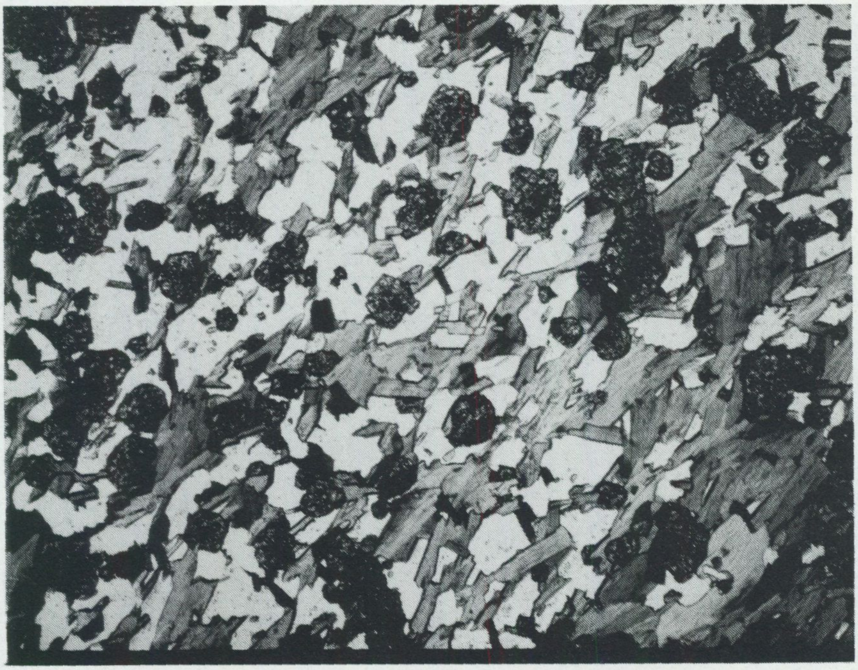


Fig. 26. Mica schist. Albite-quartz (white), biotite (grey laths) and garnet (rounded grains with high relief). Teltaja, drill-hole 71903, 370 m. Ordinary light, × 30.

found. This mica-rich trachyte is in parts also rich in magnetite (Fig. 27). The iron content reaches 20 % Fe or more (Fig. 14). The magnetite occurs as schlieren or is disseminated (Fig. 28). Some of these magnetite-rich parts contain a weak impregnation of iron sulphides. Locally, as in the upper part of the profile in Fig. 14, the mica schist contains some metre wide sections with chalcopyrite, containing 0.1–0.3 % Cu. A chemical analysis of the mica schist is shown in Table 4.

GRAPHITE-BEARING SCHIST

West of the southern ore body in Teltaja there is a ca. 15 m wide graphite-bearing schist which contains some pyrrhotite and occasionally some chalcopyrite (Fig. 14). The schist is bordered to the west by a trachyte veined by quartz and small amounts of pyrrhotite, chalcopyrite and apatite. To the east the graphite-bearing schist grades into a light-grey, weakly schistose, sulphide-bearing rock which is composed of a few millimetres wide layers of quartz and albite with veinlets of pyrrhotite, pyrite, some biotite and tourmaline. This rock passes eastwards into a magnetite ore rich in calcite. As already stated, the presence of the graphite-bearing schist at Teltaja is enigmatic, and possibly due to tectonic disturbances.

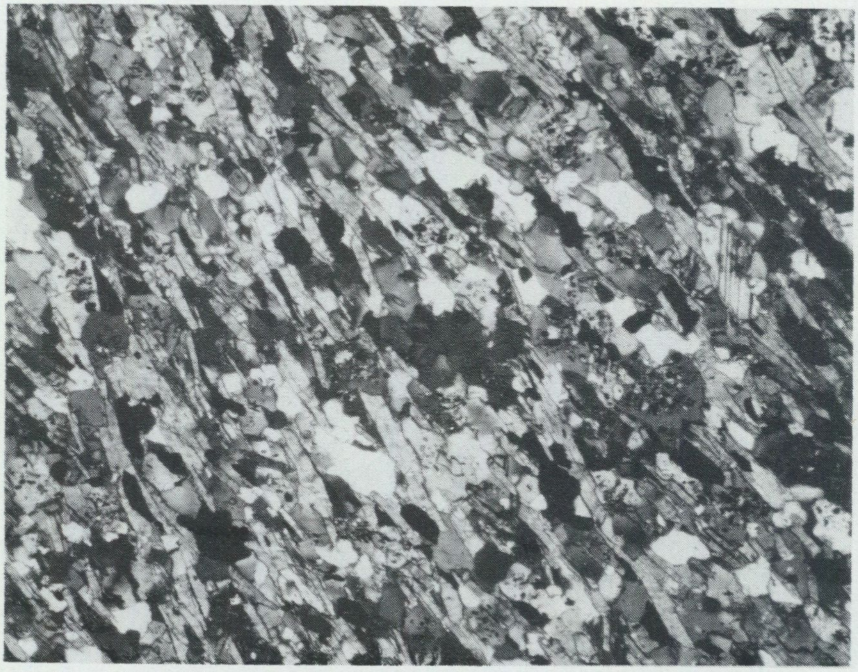


Fig. 27. Mica schist. Albite-quartz (white to grey), biotite (parallel laths with higher relief) and magnetite (black). Teltaja, drill-hole 70901, 47.65 m. Crossed nicols, × 45.

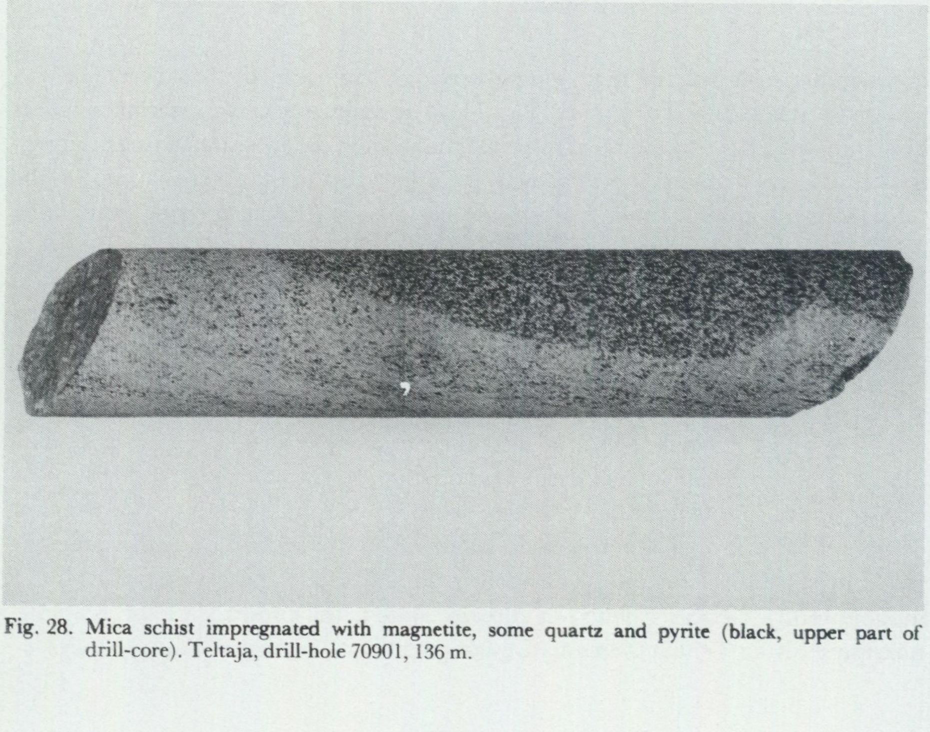


Fig. 28. Mica schist impregnated with magnetite, some quartz and pyrite (black, upper part of drill-core). Teltaja, drill-hole 70901, 136 m.

SATTAVAARA

THE ORE

The iron ore deposit Sattavaara lies east of Sattajärvi on a small hillock and is mainly covered by glacial drift. A small number of outcrops occur (Fig. 2). In 1971 the deposit was investigated by three prospecting trenches with a total length of about 1500 m. It was possible to reach only a restricted amount of bedrock and the current knowledge of the ore and surrounding rocks is therefore spurious.

The Sattavaara ore differs geophysically from the ore in Kevus and Teltaja (Hesselbom 1977). In Sattavaara the magnetic map shows an irregular pattern with rapid variations in the magnetic field, possibly due to a remanent magnetization in different directions. The gravimetric map shows a fairly regular, elliptical anomaly which in the main coincides with the magnetic anomaly. The outlines of the skarn and magnetite zones shown in Fig. 2 are essentially based on the magnetic map.

According to Ambros (1977, 1980) the Sattavaara area has an anticlinal fold structure which plunges towards the south and in which the stratigraphical sequence comprises tuffites, basic schists, iron ore and skarn/graphite schist/tuffite, basic schist/graphite-bearing schist (top). In my opinion there is no means at present of making any closer interpretation of the distribution of the different rock types and fold structures because available data are too scarce. In addition the area seems heavily affected by dislocations; those shown on Fig. 2 are based on geophysical measurements both from ground and air. The NNE and NW dislocations seem most prominent.

Recent investigations made by LKAB Prospektering AB provided many data on the area between the Sattavaara iron and Lake Sattajärvi. A large number of drill-holes revealed an up to 400 m wide horizon of limestone-dolomite. To the south-west, adjacent to mica gneisses rich in biotite, a granite and its pegmatite, there is an up to 100 m wide horizon of magnetite-bearing skarn which has sphalerite mineralization.

In the central part of the deposit there is a skarn-magnetite zone which has a maximum width of 300 m, but generally does not exceed 100 m. The host rock is a chert. The skarn minerals and magnetite occur more or less banded, often as 1–2 cm wide layers. In this zone there are in addition narrow horizons of limestone-dolomite, mostly a few metres wide. The width of the magnetite-rich parts and their iron content are rather incompletely known. Possibly only narrow magnetite-rich layers occur. A 10 m wide magnetite-rich layer in the middle trench contains 33 % Fe. Typical for the skarn-magnetite zone is the presence of manganese bound to the skarn silicates. The content is mostly 1–2 % Mn and occasionally up to 10 % Mn. The skarn-magnetite zone commonly contains pyrrhotite, pyrite and traces of chalcopyrite. Locally there are metre wide sections which contain

0.2–0.3 % Cu, and quite exceptionally up to 1 % Cu. The content of sulphur varies but attains at maximum 10 % S. The content of phosphorus in the skarn-magnetite zone is less than 0.1 % P. The whole zone is characterized by enrichment of barium, mostly exceeding 0.2 % BaO, and there are sections, up to 100 m long, with 1–10 % BaO. Chemical analyses of a metasediment and of different skarns show contents of 1.0–1.7 % BaO (Table 5).

The magnetite and iron sulphides, often associated, form 0.05–0.5 mm long, irregular grains lying as layers or small aggregates in the skarn silicates. The magnetite and the sulphides have simple, mostly straight contacts. The magnetite contains small amounts of ilmenite either as narrow lamellae or as elongated grains. Micro probe analyses show a high content of manganese in the ilmenite (5–11 % MnO, Table 2). The magnetite contains about 0.1 % MnO. The figures show that the ilmenite by comparison with magnetite is preferentially enriched in manganese, which agrees with Gjelsvik (1957), Buddington and Lindsley (1964) and Rumble (1973, 1976). According to Buddington and Lindsley (ibid), temperature is a major factor controlling distribution of manganese between (titaniferous) magnetite and ilmenite, the manganese content in ilmenite being highest (2–4 % MnO) in granites, quartz syenites and some gneisses. Manganese contents in ilmenite as high as found in Sattavaara are, however, rare in the literature. Manganese contents up to 21 % MnO in ilmenite are reported from manganese-bearing associations (olivine-grunerite-garnet-pyroxmangite-kuthnahorite-ilmenite and olivine-grunerite-garnet-magnetite-graphite-ilmenite) in Devonian iron-rich sedimentary rocks in Massachusetts (Huntington 1975, quoted from Rumble 1976).

TABLE 5. Partial chemical analyses of rocks and skarns from Sattavaara. Weight %. Analyst: K. Johansson, Geological Survey of Sweden.

	1	2	3	4
SiO_2	48.5	38.9	62.3	51.9
TiO_2	1.3	1.5	0.92	0.32
Al_2O_3	10.5	10.9	8.2	6.8
Fe_2O_3	30.5	37.5	22.7	10.1
MnO	1.8	5.0	2.6	1.1
CaO	0.8	1.7	0.9	14.5
MgO	1.7	2.0	1.3	9.7
S	0.8	0.6	0.4	< 0.1
BaO	1.2	1.7	1.0	1.4
	96.3	99.2	99.9	95.8

1. Garnet-mica banded tuffite. 3500 N/823 W.
2. Hypersthene skarn with some biotite, quartz, garnet, magnetite and pyrrhotite. 3500 N/934 W.
3. Quartz-biotite skarn with some garnet and hornblende. 3500 N/935 W.
4. Diopside-biotite skarn. 3500 N/1027 W.

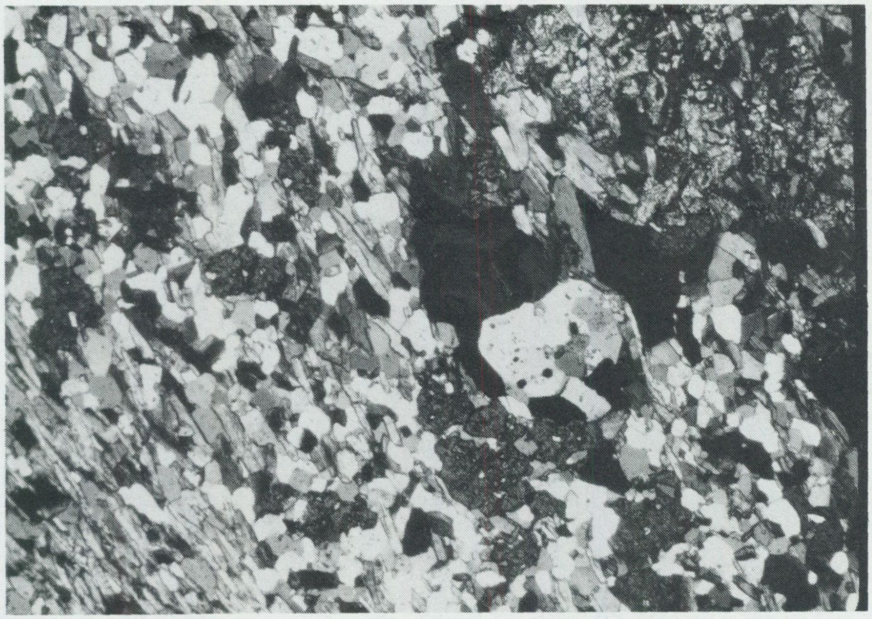


Fig. 29. Skarn-banded chert. Quartz (white to grey), biotite (grey, parallel laths) and some garnet (dark-grey, rounded grains with high relief) dominates. Hypersthene (dark-grey) in the upper, right corner. Black is pyrite with some magnetite. Sattavaara, trench at 3500 N/935 W. Crossed nicols, × 40.

The most common skarn type in the Sattavaara ore is composed of varying amounts of clinopyroxene, biotite, garnet and hornblende. The clinopyroxene is often the dominant component (Fig. 29). This skarn type is rich in iron and contains a relatively high content of manganese (analyses Nos 2 and 3, Table 5). Micro probe analyses confirm the high manganese content in the different silicates and show that these are in parts barium-bearing (Table 6). The clinopyroxene is a colourless or weakly brownish ortho-ferrosilite with 6.6 % MnO. The biotite is dark-brown or green-brown and contains about 0.7 % MnO and 4 % BaO (analysis No. 3, Table 6). The garnet is a reddish almandine-spessartine with about 15 % MnO. The hornblende is greenish and contains around 1 % MnO. Of great genetic interest is the occurrence of a barium-bearing microcline (hyalophane with 8 % BaO) in this type of skarn. The other skarn type is mainly composed of diopside, biotite and small amounts of the above constituents. This skarn type is characterized by a lower content of iron and manganese (analysis No. 4, Table 5). The diopside is a greenish salite with about 2 % MnO. The biotite contains around 1 % MnO and 1 % BaO (analysis No. 2, Table 6).

The skarn at Sattavaara is thus composed of skarn silicates rich in ferrous iron and manganese. Most of the silicates are barium-bearing, the highest contents being found in microcline.

TABLE 6. Chemical composition of skarn minerals from the Sattavaara iron ore. Weight %. Micro probe analyses. Analyst: C. Ålinder, Geological Survey of Sweden.

	1 Hyalophane	2 Biotite	3 Biotite
SiO_2	59.55	36.84	31.58
TiO_2	0.04	2.09	2.56
Al_2O_3	19.79	13.45	12.74
FeO	0.09	18.55	32.92
MnO	0	1.04	0.74
MgO	0	12.93	2.32
CaO	0.02	0.03	0
Na_2O	1.38	0.12	0.08
K_2O	11.18	9.10	7.17
BaO	8.10	0.99	4.24
	100.15	95.14	94.35

Number of ions on the basis of

	(32 O)		(22 O)		(22 O)	
Si	11.46	15.94	5.67	8.00	5.45	8.00
Al	4.48		2.33		2.55	
Al		3.86	0.12	5.85	0.05	5.84
Ti			0.24		0.33	
Fe^{3+}						
Fe^{2+}	0.01		2.39		4.75	
Mn			0.13		0.11	
Mg			2.97		0.60	
Ca			0	1.89		1.90
Na	0.51		0.04		0.03	
K	2.73		1.79		1.58	
Ba	0.61		0.06		0.29	
100 Mg/ (Mg+Fe+Mn)			54.1		11.0	
Mg						
Fe						
Ca						
	Cn	15.8				
	Or	70.9				
	Ab	13.3				

Locality: Analyses Nos 1, 2, 4 and 5; Sattavaara 3500 N/1027 W, sample MA 54/2.
Analyses Nos 3. 6, and 7; Sattavaara 3500 N/934 W, sample MA 35/2.

4 Hornblende		5 Salite		6 Ortho-ferro-silite		7 Almandine-spessartine	
40.47		51.57		47.26		36.74	
0.47		0.02		0.02		0.17	
10.44		0.50		0.17		19.39	
20.28		9.75		40.98		23.22	
1.28		1.90		6.62		14.72	
8.57		12.13		3.87		0.35	
11.06		23.32		0.65		5.18	
2.00		0.35		0.04		0.04	
1.64		0		0		0	
0.10		0.05		0.01		0	
96.31		99.59		99.62		99.81	
(23 O)		(6 O)		(6 O)		(24 O)	
6.38	8.00	1.97	1.99	2.00	2.00	6.03	6.03
1.62		0.02		0			
0.32	5.22					3.76	4.00
0.05		0				0.02	
				1.46	1.98	0.22	
2.67		0.31	2.04	0.24		2.97	6.03
0.17		0.06		0.25		2.05	
2.01		0.69		0.03		0.09	
1.87	2.81	0.95		0		0.91	
0.61		0.03				0.01	
0.33				0			
0		0					
41.4		65.1		12.8		1.7	
30.7		35.4		14.2		2.2	
40.8		15.9		84.0		76.1	
28.5		48.7		1.8		21.7	
						Al 49.5	
						Sp 34.2	
						Gr 9.2	
						An 6.0	
						Py 1.5	

THE WALL ROCK

The skarn-magnetite zone lies in mafic metatuffites-tuffs and metasediments.

In the eastern part of the middle trench there is a banded mica-garnet bearing tuffite in which cm-wide layers of biotite and some garnet alternate with layers of quartz and some feldspar. In the quartz layers there are impregnations and schlieren of magnetite, pyrrhotite and some chalcopyrite. The tuffite, like the skarn, contains some manganese and barium (analysis No. 1, Table 5).

Southwest of the main skarn-ore zone there occur graphite-bearing schists and tuffites. The graphite-bearing schist is a banded rock mainly consisting of diopside with graphite and some sphene. The tuffite is composed of hornblende, subordinate scapolite, diopside and accessory amounts of sphene and calcite. In this rock there are metre-wide layers of magnetite. Further east there is a folded, garnet-biotite banded schist with intercalations of a hornblende-scapolite rock. In the same area there are also fine-grained ”greenstones” consisting of hornblende, biotite and albite. In addition phyllite-like rocks with biotite, tremolite and subordinate amounts of quartz and albite occur.

Even if the above description is incomplete for the different rock types, it is evident that the lithologies are quite different from those in the two other iron ores in the Lannavaara area. The rock association at Sattajärvi is similar to that of the skarn and siliceous iron ores in the Greenstone group in northern Sweden.

THE RELATION BETWEEN THE GREENSTONE AND PORPHYRY GROUPS

According to Ambros (1977, 1980) there is an important hiatus in the Lannavaara area between the Greenstone and Porphyry groups. After deposition of the volcano-sedimentary rocks of the Greenstone group, including the Lannavaara iron ores, the metasedimentary Pahakurkkio group was deposited. It was followed by intrusion of the synkinematic Haparanda suite in connection with regional metamorphism. Later the rocks of the Porphyry group were extruded and at the same time there occurred denudation of the volcanics. At Teltaja the volcanics of the Porphyry group were deposited on the underlying ore, which formed an almost vertical height of about 150 m. In the profile of Teltaja given by Ambros (ibid.) the ore and associated graphite-bearing schist and greenstone form a vertical ridge covered by the volcanics of the Porphyry group.

In my opinion the field relationships do not support a hiatus between the Greenstone and the Porphyry groups. This is based mainly on the fact that the Teltaja ore belongs to the Porphyry group and not to the Greenstone group as postulated by Ambros (ibid.). The ore is not overlain and covered by volcanics of the Porphyry group. It reaches the surface (cf. Fig. 15 and the profile given by Ambros, ibid.), and consequently the volcanics represent a ”normal” wall rock of the ore. The fragment-bearing trachyte (or ”syenite porphyry with conglomerate horizons” according to Ambros, ibid.) is cut by ore veins in the same way as the trachyte, and cannot have formed later than the ore. The volcanic breccias have thus been intruded by the ore, in similarity with the main part of the volcanics.

In summary there seems no reason to postulate a large hiatus between the Greenstone and Porphyry groups at Lannavaara and this accords with the current knowledge of their regional relationships. The two groups are affected by the same phase of deformation and are involved in the same fold pattern. Recent radiometric data indicate a close temporal relationship. A Sm-Nd mineral isochron for a basalt from the Greenstone group at Kiruna gives an age of 1932 Ma, and acid volcanics in the Kiruna–Gällivare area give a zircon age of 1909 Mn (Skiöld and Cliff 1984). Frietsch (1966) previously postulated that the two groups are stratigraphically equal but formed in different environments, the Porphyry group being terrestrial and the Greenstone group waterlaid. On the basis of the petrochemistry it is possible to show that in a modern geotectonic setting the Greenstone group is oceanic and the Porphyry group continental, and that they possibly belong to the same magmatic evolution (Frietsch 1984).

ON THE NATURE AND GENESIS OF THE ORES

The Lannavaara iron ores occur in a tectonically disturbed area where intense faulting obliterates a certain interpretation of the geology. The relationship between the different rock units is thus unclear. It is however evident that the ores and rocks at Kevus and Teltaja belong to one and the same major rock association, different in composition and appearance from the ore and rocks at Sattavaara.

The Sattavaara ore in many respects resembles the siliceous iron ores found in the Greenstone group in other parts of northern Sweden. These ores are made up of cherts in which magnetite and skarn minerals occur in more or less distinct layers. The ores which are poor in iron (mostly below 20 % Fe) have a long persistence along strike but their width is mostly small. Magnetite and skarn minerals are accompanied by small amounts of pyrite and pyrrhotite. The skarn minerals are rich in iron (ferrous) or iron plus magnesium (hornblende, grunerite-cummingtonite, clinoenstatite-hedenbergite and almandite). The content of manganese is mostly low but rises in some deposits to 1–2 %, sited in the silicates. In the Marjarova and Käymäjärvi ores, about 25 km NW of Pajala, the quartzite contains manganese-bearing grunerite, fayalite and hornblende (Geijer 1925, Frietsch 1985). All these features are found in the Sattavaara ore which, however, differs from the other siliceous iron ores in being rich in barium, sited in the silicates.

The siliceous ores of the Greenstone group occur in metasedimentary intercalations in basic volcanics. The association found at Sattavaara of basic tuffite, graphite-bearing schist, phyllite and limestone is relatively typical for the other siliceous iron ores.

In summary the Sattavaara ore resembles the quartz-banded ores in the Greenstone group and like these has a volcano-sedimentary origin, representing an iron-silica-(carbonate)-rich sediment which has attained its present mineralogical composition through later metamorphic processes (Frietsch 1973, 1977).

The association of iron, manganese and barium in the Sattavaara ore is a feature known from other metasedimentary or volcano-sedimentary iron-manganese ores, mainly outside Sweden. In the Potmasburg deposits in South Africa there are iron-manganese ores with barium concentrated in psilomelane and barite in dolomites-shales-quartzites of Early Proterozoic age (Jensen and Bateman 1981). The ores are either formed by residual concentration or by hypogene replacement. The Precambrian manganese ores of India occur in metasediments and the ores represents metamorphosed manganese sediments. They contain ubiquitous barium concentrated in hollandite and psilomelane (Mookherjee 1961, Roy 1980). In Carboniferous metasediments at Tynagh, Ireland, adjacent to the zinc-lead sulphide ore there is a sedimentary iron formation which is high in barium in the distal, manganese-rich part (Russel 1975). In Early Proterozoic acid metavolcanics at Ultevis in northern Sweden there occur manganese-iron ores which are considered to be syngenetic chemical sediments formed in connection with the volcanism (Ödman 1947). The ores contain barium in barite and hollandite. In the Early Proterozoic acid metavolcanics in Central Sweden, there occur manganiferous skarn iron ores with manganese-bearing silicates and iron oxide-manganese oxide ores of the Långban type also with manganese-bearing silicates. Both ore types are of volcano-sedimentary origin (Frietsch 1982). In the manganiferous skarn iron ores, barite is present in the Strömshagsgruvan deposit (Åhman 1973). In the manganese-silicate banded iron ore at Klintgruvan, a barium-bearing feldspar occurs (Geijer and Magnusson 1944). In the Långban type of ore barite is found at Långban, Jakobsberg (Nordmark), Sjögruvan and Harstigen. In Långban, barium in addition occurs in the Ca-Pb arseniates caryinite and hedyphane, in hyalophane, in the Ba-Pb silicate hyalotekite and in the Be-Ba silicate barylite (Magnusson 1930). According to Magnusson (ibid.) the barium content of the Långban ore is, however, so high that it cannot be explained by the presence of these minerals; it is therefore suggested that barium, at least in parts, occurs in carbonate. In the Jakobsberg ore barysilite and celsian have been encountered (Magnusson 1929). In the Sjögruvan ore a Ba-rich feldspar is present (Sundius 1923). The Harstigen ore contains hedyphane (Magnusson 1925). Looking at recent deposits, in metalliferous sediments formed in present day ocean basins there is an accumulation of manganese, iron and in parts also barium as a result of volcanogenic and volcanogenic-sedimentary processes (Varentsov *et al.* 1980, Mitchell and Garson 1981). The formation of the metalliferous sediments is

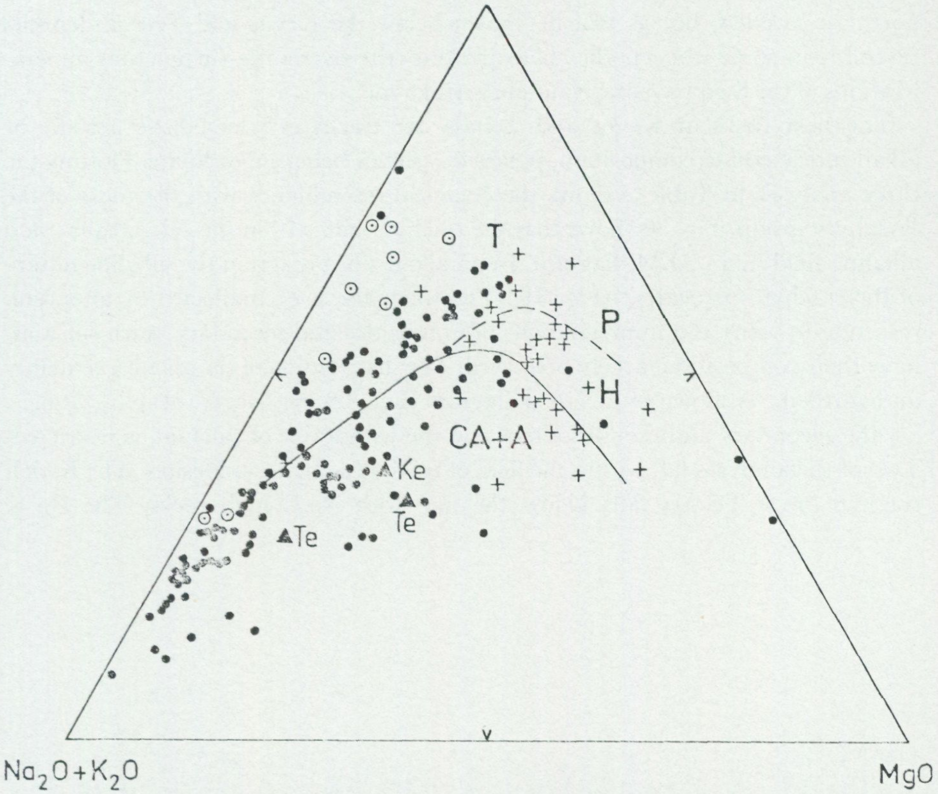


Fig. 30. AFM diagram (weight %). Trachytes from Kevus (Ke) and Teltaja (Te) are denoted by black triangels. For comparison, volcanics of the Greenstone group (crosses) and the Porphyry group (dots, or if sericite-altered, encircled points) in northern Sweden are shown. The continuous line after Irvine and Baragar (1971), determines the tholeiitic (T) and the calc-alkaline + alkaline fields (CA + A); the broken line, after Kuno (1968), determines the fields of the pigeonitic (P) and the hypersthenic (H) rock series.

bound to submarine volcanism along active mid-oceanic ridges, in part related to the activity of hot metal-bearing brines (such as the Red Sea, the Cheleken peninsula in the Caspian Sea, Salton Sea in southern California). In deposition of these sediments barium follows manganese along the ocean ridges (Bonatti *et al.* 1972a, Cann *et al.* 1977, Corliss *et al.* 1978) and in rift areas such as the Red Sea and Afar rift (Bonatti *et al.* 1972b, Puchelt *et al.* 1973).

The above examples show that iron-manganese ores with barium are formed by sedimentary deposition, mostly in connection with volcanic activity that can be either of basic or acid type. The Sattavaara ore represents an example of formation in connection with basic volcanism.

The Kevus and Teltaja deposits represent quite another ore type and a different mode of formation. Counterparts do not exist among the iron ore deposits in northern Sweden, but as will be shown below the Kevus and Teltaja deposits resemble in some respects the chalcopyrite-pyrite-pyrrhotite-(magnetite) mineralizations of the Svappavaara-Nautanen-Aitik type.

The host rocks at Kevus and Teltaja are trachytes whicn have a sodic or alkali-intermediate composition, potassic varieties being subordinate. Plotting the three analyses in Table 2 shows the chemical resemblance with the rocks of the Porphyry group. Fig. 30 shows that the trachytes fall within the calc-alkaline and alkaline field in an AFM-diagram. In an alkali-silica diagram the alkaline nature of the trachytes is evident (Fig. 31). The trachytes, even if affected by alteration resulting in veins and impregnations of iron oxides and secondary skarn silicates, have their composition largely preserved. The distribution of the alkalies is mainly undisturbed. As shown by a Na-Ca diagram (Fig. 32) the "degree of spilitization", i.e. the secondary addition of sodium and the withdraval of calcium, is restricted. Two of the analyses fall within the field of trachytes-dacites-andesites. The K-rich trachyte from Teltaja falls below the line with Na_2O-high rocks. The Na-K

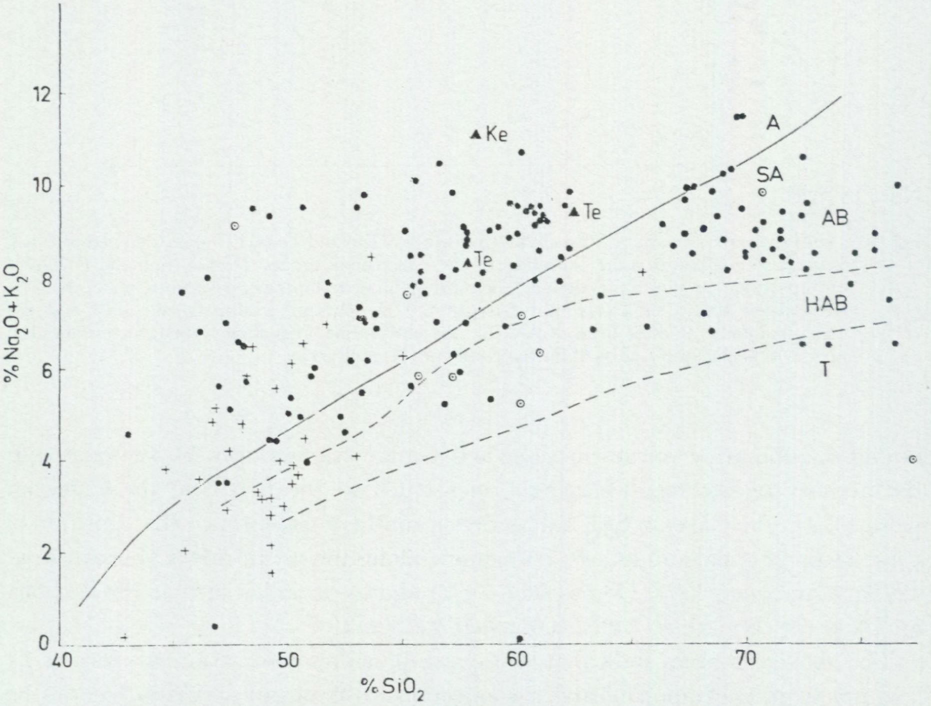


Fig. 31. Alkali-silica diagram (weight %). Trachytes from Kevus (Ke) and Teltaja (Te) are denoted by black triangles. For comparison, the volcanics of the Greenstone group (crosses) and the Porphyry group (dots, or if sericite-altered, encircled points) in northern Sweden are shown. The upper continuous line, after Irvine and Barager (1971), determines the alkaline (A) and the sub-alkaline (SA) fields; the broken line, after Kuno (1968) determines the alkali basalt (AB), the high-alumina basalt (HAB) and the tholeiite (T) fields.

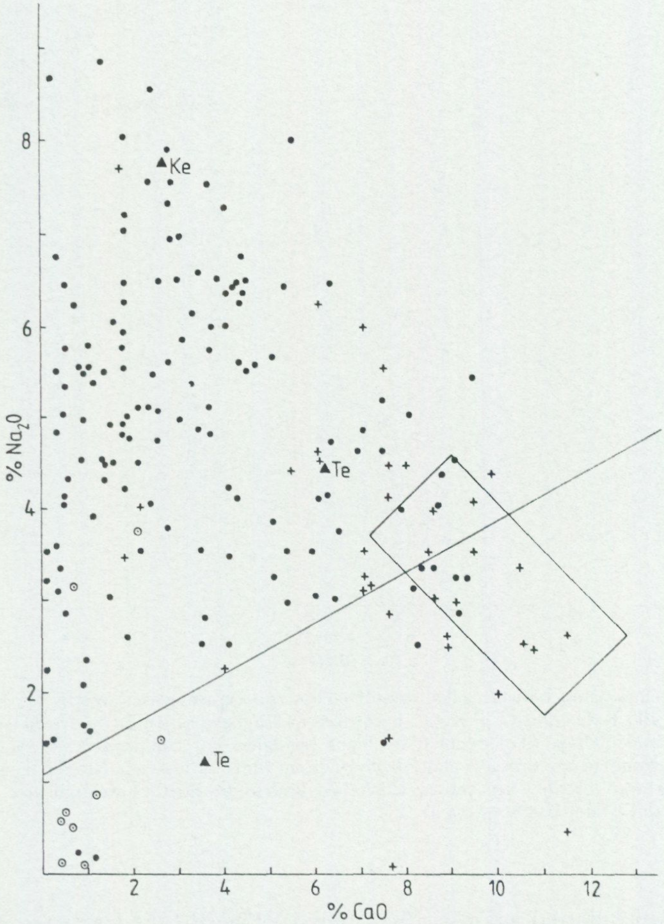


Fig. 32. Na_2O – CaO diagram (weight %). Trachytes from Kevus (Ke) and Teltaja (Te) are denoted by black triangles. For comparison, the volcanics of the Greenstone group (crosses) and of the Porphyry group (dots, or if sericite-altered, encircled points) in northern Sweden are shown. Straight line separates high-Na_2O and low-Na_2O rocks, according to Graham (1976). Box outlines normal, unaltered basalts, according to Štephens (1980).

diagram in Fig. 33 shows moderate changes of alkali composition for the trachytes. The potassic trachyte from Teltaja, however, falls far outside the field of unaltered magmatic rocks. All analyses fall in the upper part of the diagram due to the high content of alkalies.

In all diagrams the similarity to the volcanics of the Porphyry group is apparent. The same relationship is found if other elements are considered. If plotted in a diagram showing the iron content *versus* silica content, the trachytes in Lannavaara resemble the rocks of the Porphyry group, i.e. the iron content decreases with increasing silica content (Fig. 34). In the variation diagram with the Mg/

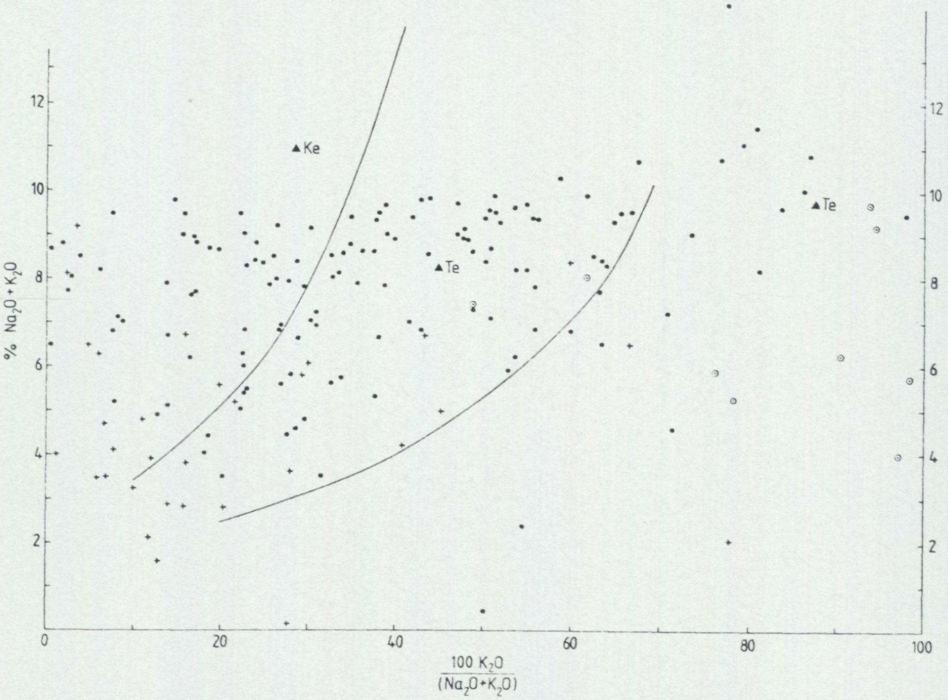


Fig. 33. The relationship between alkalies and potassium, expressed as (weight %) $Na_2O + K_2O$ *versus* 100 K_2O/ ($Na_2O + K_2O$), according to Hughes (1973), in the trachytes from Kevus (Ke) and Teltaja (Te) denoted by black triangles. For comparison, the volcanics of the Greenstone group (crosses) and Porphyry group (dots, or if sericite-altered encircled points), in northern Sweden are shown. The field limited by heavy lines indicates the "igneous spectrum", after Hughes (ibid.).

(Mg+Fe) ratio plotted against silica content (Fig. 35) the trachytes from Kevus and Teltaja fall within the field of the Porphyry group. The Mg/(Mg+Fe) ratio decreases with increasing silica content.

In general the trachytes in Lannavaara thus resemble the rocks of the Porphyry group in mineralogical-chemical composition. However, the high potassium content represents dissimilarity. As pointed out by Frietsch (1984), high potassium contents among the volcanics of the Porphyry group are rare and of restricted extent. The origin of the high potassium content is unclear. It might either be a primary magmatic feature, or a secondary one due to hydrothermal alteration coeval with or directly subsequent to volcanism. As no potassic alteration has been observed at Teltaja it is likely that the high-K trachyte here has a primary origin, even though in the diagram of Fig. 34 this rock falls outside the field of unaltered magmatic rocks, thus favouring metasomatic provenance.

The provenance of the Kevus and Teltaja ores is unclear. The general features indicate that they are epigenetic and formed by magmatic (hydrothermal) proces-

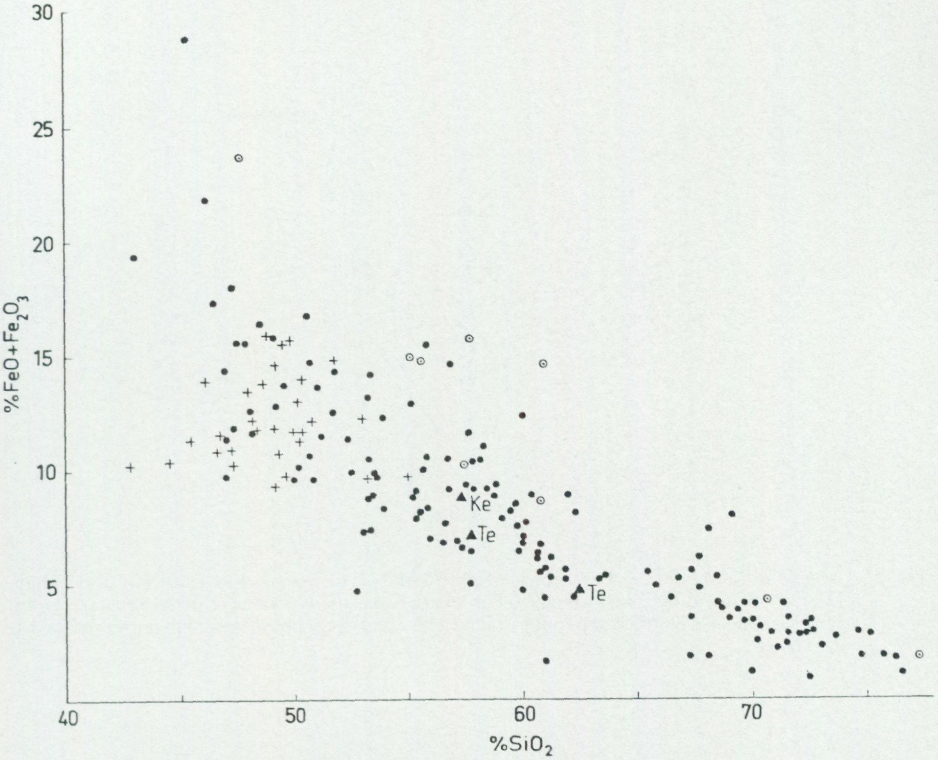


Fig. 34. Iron-silica diagram (weight %). Trachytes from Kevus (Ke) and Teltaja (Te) are denoted by black triangles. For comparison, the volcanics of the Greenstone group (crosses) and the Porphyry group (dots, or if sericite-altered encircled points), in northern Sweden are shown.

ses. Most common among the iron ores of the Porphyry group is the apatite iron (Kiruna) ore type which is made up of magnetite-hematite with mostly high phosphorus content (generally around 1 %) and low sulphur and manganese contents. Tremolite, diopside and calcite are present in small amounts. The ore forms massive bodies or occurs as veinlets forming a network (”ore breccia”). Related as a late phase to the Kiruna iron ore type there are some small, phosphorus-free hematite impregnations of hydrothermal, metasomatic origin. They are accompanied by metasomatic alteration which gave rise to quartz, sericite, chlorite, calcite and small or accessory amounts of baryte, fluorite, allanite, tourmaline and zircon.

The Kevus ore forms massive bodies or veins of magnetite accompanied by skarn silicates and iron sulphides. The ore contains 1–2 % S, less than 0.1 % P and 0.2–0.5 % Mn. The ore occurs at least partly in brecciating veins, resembling the ”ore breccia” in the Kiruna type of ore. In addition there is locally a relatively rich magnetite impregnation in the trachyte. The magnetite is accompanied by

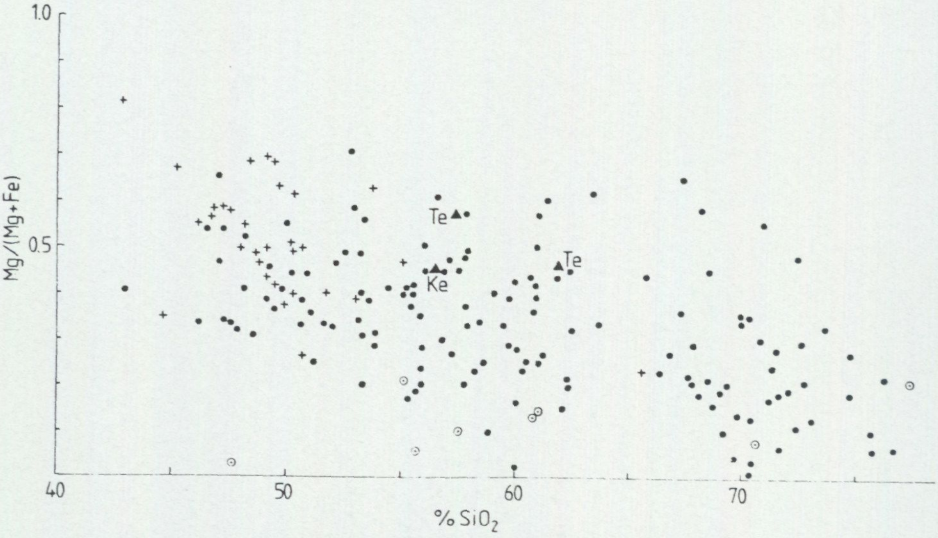


Fig. 35. Atomic ratio Mg/(Mg + Fe) against weight % SiO_2. Trachytes from Kevus (Ke) and Teltaja (Te) are denoted by black triangles. For comparison, the volcanics of the Greenstone group (crosses) and Porphyry group (dots, or if sericite-altered, encircled points) in northern Sweden are shown.

diopside, scapolite, biotite and some calcite. Of genetic interest is the occurrence of tourmaline in relatively large amounts and of analcime in accessory amounts. The Kevus ore veins the wall rock and thus resembles the Kiruna type of ore. The skarn silicates are however of different composition and occur in greater amounts than in the Kiruna ore type. The occurrence of scapolite and tourmaline in the ore-skarn veins suggests a hydrothermal, metasomatic origin. In addition the low apatite content and the omnipresence of pyrite-pyrrhotite is atypical for the Kiruna ore type.

The Teltaja ore consists of magnetite-hematite in a quartzite with small amounts of diopside, tremolite and calcite. The ore forms massive bodies or veins. The content of phosphorus is low, but may rise to 0.3–0.4 % P. The major part of the deposit is poor in sulphur. However, contents up to several per cent are encountered locally. The content of manganese is mostly low (0.1–0.2 % Mn) but rises occasionally to a few per cent. The skarn silicates are diopside, hornblende, biotite and scapolite. Of genetic interest is the fact that the ore veins contain small or accessory amounts of muscovite, barite and tourmaline, and occasionally also analcime and fluorite.

The Teltaja ore is epigenetic and a hydrothermal, metasomatic origin seems probable. The association magnetite-hematite with some apatite indicates an ore of the Kiruna type. However, this is contradicted by the locally high content of iron sulphides. The quartzitic host rock and the presence of muscovite, barite, tourmaline and fluorite in the ore suggest similarity to the late, siliceous hematite ores connected with the Kiruna ore type. The large amount of magnetite and its appearance as massive bodies is, however, not typical for the siliceous ore type.

Ambros (1977, 1980) attached much importance to the manganese content of the Teltaja ore, and stated that two different ore types are present. In his opinion there is a narrow horizon of a manganese-bearing skarn iron ore in the east in a stratigraphically lower position. In the west, in a stratigraphically higher position there is the main magnetite-hematite ore which is rich in silica but manganese-free. In my opinion there is no major differences between the ores. Both are of siliceous type although the eastern horizon is richer in skarn silicates and calcite, the latter mineral in parts forming metre-wide layers. As seen from Fig. 14, the manganese content is mostly similar in the eastern horizon and the western main ore body. The latter has in parts the highest manganese content. It should be pointed out that the manganese content of the Teltaja ore (0.2–0.5 % Mn, cf. p. 20) is roughly similar to the Kevus ore. In both deposits the manganese is probably concentrated in calcite. On the whole the manganese content in these deposits (0.1–0.5 % Mn) is not exceptional by comparison with other iron ores in northern Sweden. The Kiruna ore type mainly contains below 0.1 % Mn, but in some deposits, such as Mertainen, Painirova and Gruvberget, up to 0.2 % Mn are found. At Gruvberget the magnetite ore, rich in calcite, contains 0.2–0.4 % Mn. The skarn iron ore type contains mostly below 0.1 % Mn, but in some deposits, such as Masugnsbyn, Pellivuoma and Vieto, 0.2–0.3 % Mn are found. Notably higher manganese contents, reaching several per cent, occur in the quartz-banded iron ores of the Greenstone group. The manganese is located in the skarn silicates, e.g. in the Marjajärvi, Käymäjärvi and Sattavaara deposits. This clearly shows that the manganese content of the Teltaja ore cannot be used, cf. Ambros (1977, 1980), as a criterion to indicate that the Teltaja ore is a continuation of the Sattavaara ore.

Summarizing the above, it seems probable that the Kevus and Teltaja ores are similar, epigenetic formations intrusive into the trachytic wall rock. The resemblance to the Kiruna ore type is restricted. Teltaja is in some respects similar to the siliceous iron ores that are formed as a late phase in magmatic activity giving the Kiruna type of ore. There is definitely no resemblance between the Kevus-Teltaja ores and the Sattavaara ore.

In the Kevus-Teltaja deposits the ore formation is associated with intense scapolitization and a less prominent tourmalinization. Iron ores formed by scapolitization are not known in northern Sweden. However, formation of sulphides in connection with scapolitization is not unusual in this region, and these mineralizations are often magnetite-bearing. The association pyrite-pyrrhotite-chalcopyrite-magnetite is rather typical. Bornite, chalcocite and molybdenite are occasional constituents. The scapolitized rocks often contain the sulphides in such concentrations that economic deposits are found. Chalcopyrite-bornite-magnetite mineralizations in scapolitized rocks occur at several localities in the Svappavaara–Gällivare region, east-southeast of Kiruna.

At Gruvberget, Svappavaara, the trachytic wall rock of the apatite-bearing iron ore has been metasomatically altered and the secondary mineral association consists of scapolite and varying amounts of tremolite, epidote, quartz, calcite, microcline, zeolites (mainly chabazite), magnetite, chalcopyrite and bornite (Frietsch 1966). In minor amounts there occur biotite, chlorite, diopside, albite-oligoclase, apatite and tourmaline.

East of Gällivare there are several sulphide mineralizations, of which Aitik, Nautanen and Liikavaara Östra are the most important. The mineralizations occur as disseminations or veins in fine-grained schists and gneisses, mostly plagioclase-(microcline)-quartz rocks with varying amounts of biotite and muscovite. The rocks, which according to Geijer (1918) and Zweifel (1976) have a metasedimentary origin, show in parts extensive sericitization, scapolitization and tourmalinization and are rich in skarn bands and veins. Often the veins are accompanied by total replacement of the wall rock. Chalcopyrite, pyrite, pyrrhotite, bornite, chalcocite and magnetite constitute the ore minerals. They occur in connection with skarn zones, mainly with garnet, epidote and amphibole. Bornite and chalcocite occur partly in quartz veins. In addition apatite and zeolites (stilbite and chabazite) belong to the paragenesis. In the Aitik ore, quartz and baryte are the most frequent gangue minerals, others are fluorite, calcite, tourmaline, scapolite and apatite. Chabazite occurs on joints. The major skarn minerals are hornblende and epidote. In the Liikavaara Östra ore, quartz and calcite are the most common gangue minerals, in addition tourmaline and apatite occur whereas baryte and scapolite are missing. In Nautanen the mineralization is characterized by an abundance of magnetite (Geijer 1918). Other minerals are quartz, tourmaline, chalcopyrite and pyrite. Apatite is locally abundant.

The Aitik-Liikavaara Östra-Nautanen mineralizations are thus characterized by occurrence of pyrite, pyrrhotite, chalcopyrite and magnetite in association with scapolite, tourmaline, fluorite, calcite, apatite and hornblende. In Nautanen magnetite is a major constituent.

In the basic metavolcanics forming the host rock of the skarn iron ore Vieto, west of Kiruna, there are scapolite-skarn silicate veins which contain small amounts of pyrrhotite, pyrite, chalcopyrite and magnetite (Eriksson and Frietsch 1979). In addition there are schlieren of hornblende, biotite and tourmaline with small amounts of chalcopyrite, pyrite and magnetite. A third mineralization type is made up of biotite-rich fissure fillings which contain some pennine, hornblende, apatite, pyrite and chalcopyrite.

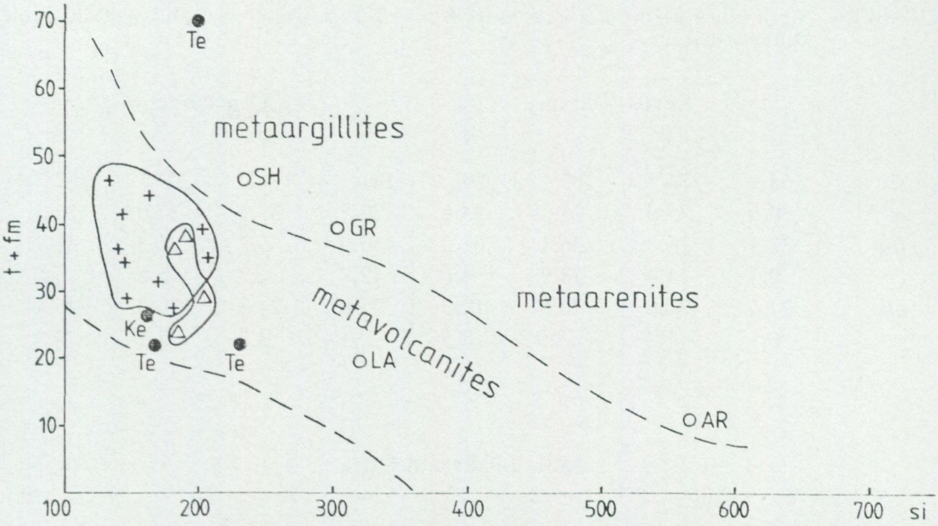


Fig. 36. Diagram showing Niggli values *t + fm versus si*. Black points = trachytes from Kevus (Ke) and Teltaja (Te), triangles = trachytes from Gruvberget, Svappavaara (Frietsch 1966), crosses = host rocks from the Aitik and Liikavaara Östra ores (Zweifel 1976). Circles = average composition of shales (SH), according to Barth (1952), graywackes (GR), lithic arenites (LA) and arkoses (AR), according to Pettijohn *et al.* (1972). The distribution of metaargillites, metaarenites and metavolcanites from Central Sweden is according to Stålhös (1982).

In the mineralizations described above there is a common association of scapolite, hornblende, biotite, tourmaline and apatite. The ore minerals are pyrite, pyrrhotite, chalcopyrite and magnetite. The last of these occurs in significant amounts only in Nautanen. The nature of these mineralizations is obscure. Frietsch (1966) considered the mineralization at Gruvberget, Svappavaara as epigenetic, governed by an adjacent fissure system. According to Zweifel (1976) the Aitik ore is of syn-sedimentary origin but later became mobilized in connection with regional metamorphism. A syngenetic origin for the Vieto mineralization was favoured by Eriksson and Frietsch (1979) mainly due to its stratiform appearance, conformable with the iron ore.

The mineralizations described above and the Kevus and Teltaja ores have much in common as regards the mineralogical composition and associated alteration minerals. However, the Lannavaara deposits differ from these mineralizations in high content of magnetite and the relative poorness in iron sulphides, especially in the Teltaja deposit. The ore formation is associated with scapolitization and tourmalinization. However, in the Aitik ore sericitization is prominent. The similarity in bedrock composition of the Kevus-Teltaja and Gruvberget-Aitik-Liikavaara Östra-Nautanen deposits is striking: there are albite-(microcline)-quartz rocks with varying amounts of silicates such as mica, amphibole and pyroxene. Chemically the rocks resemble one another as shown in Table 7 from

TABLE 7. Niggli values for the host rocks in the Kevus, Teltaja, Gruvberget, Aitik and Liikavaara Östra ore deposits.

	Kevus–Teltaja				Gruvberget			
	1	2	3	4	5	6	7	8
si	165	234	169	200	181	194	203	187
al	30.6	35.0	25.0	23.6	30.5	33.3	37.9	36.3
fm	32.5	26.0	36.1	61.2	30.9	35.7	26.3	31.7
c	9.1	14.4	18.9	4.6	12.8	6.7	5.5	6.6
alk	27.6	24.6	20.0	10.5	25.8	24.3	30.3	25.4
t	−6.1	−4.0	−13.9	8.5	−8.1	2.3	2.1	4.3

	Aitik–Liikavaara Östra									
	9	10	11	12	13	14	15	16	17	18
si	171	149	202	209	142	146	181	134	144	163
al	30	24	34	38	27	27	32	20	23	24
fm	35	40	35	29	41	40	31	53	47	48
c	20	29	12	10	16	15	17	18	17	17
alk	14	7	19	22	16	18	19	9	12	11
t	−4	−12	3	6	−5	−6	−4	−7	−6	−4

1. Trachyte, Kevus from Table 2. 2–3. Trachyte, Teltaja from Table 2. 4. Mica schist, Teltaja from Table 2. 5–8. Trachyte (syenite porphyry), Gruvberget from Frietsch (1966, Table 21). 9–18. Host rocks, Aitik–Liikavaara Östra from Zweifel (1976, Table 16). 9. Biotite gneiss. 10. Skarn-banded rock. 11. Aitik ore zone. 12. Aitik ore (N). 13. E-border zone (Aitik). 14. E-part of antiform. 15. Arenite. 16. Amphibolite. 17. Liikavaara Östra ore zone. 18. Liikavaara Östra ore.

analyses of rocks from Gruvberget, Aitik and Liikavaara Östra. In the opinion of Geijer (1918) and Zweifel (1976) the wall rocks in the Nautanen-Aitik-Liikavaara Östra are metasediments. However, Zweifel (ibid.) expressed some doubt about the sedimentary nature of the rocks: "no obvious sedimentary structures have been observed in the Aitik formation" (p. 17) and "the chemical composition" of the metaarenites "is rather similar to some volcanic rocks" (p. 15). In my opinion it is probable that the Aitik-Liikavaara Östra-Nautanen wall rocks are metavolcanics: in any case their chemical composition does not show resemblance to arenites. The question of a volcanic or sedimentary origin is a common problem in metamorphic feldspar-quartz rocks of an intermediate silica content (55–65 % SiO_2). In this context the relationship between aluminium content and alkali contents can be conclusive. The Niggli t value denotes al — (c+alk) (cf. Burri

1959), and if positive it means excess of aluminium i.e. deficit of alkalies by comparison with aluminium. A positive value (greater than 5) is often present for metasediments in which clay is an important component, and is thus an indicator of sedimentary provenance. The Kevus-Teltaja — Gruvberget and Aitik-Liikavaara Östra wall rocks show *t* values which are mostly negative or near zero, meaning "non-sedimentary" origin. Only the mica schist from Teltaja has $t = 8.5$, showing a slight alumina excess due to the mixture of epiclastic material in the tuffitic rock. If the Niggli values $t + fm$ and *si* are plotted in a diagram (Fig. 36), the rocks from the above mentioned deposits all lie close to one another within the volcanic field. The mica schist from Teltaja also deviates here by falling within the sedimentary field.

The above consideration show that in northern Sweden there are chalcopyrite-iron sulphide-iron deposits which were formed in trachytes by hydrothermal processes rich in volatiles that gave rise to alteration such as scapolitization, tourmalinization and sericitization. The Lannavaara ores represent the iron oxide-rich variety. The source of the ore-forming solutions is obscure, and whether they emanated in connection with the volcanism that produced the wall rock is at present an open question, but a plausible explanation.

ACKNOWLEDGEMENTS

M. Ambros, G. Kautsky, T. Lehto and Th. Lundqvist critically read the manuscript and made valuable improvements. L. Cherns corrected the English. To all these persons I want to express my sincere thanks.

REFERENCES

GFF = Geologiska Föreningens i Stockholm Förhandlingar
SGU = Sveriges geologiska undersökning

ÅHMAN, E., 1973: Vattholmatraktens järnmalms- och kalkstensfyndigheter. — SGU C 685.

AMBROS, M., 1977: Lannavaarafälten. Resultaten av SGU:s undersökning 1967–1971. — Unpubl. report. Berggrundsbyrån, SGU.

— 1980: Beskrivning till berggrundskartorna Lannavaara NV, NO, SV, SO och Karesuando SV, SO. — SGU Af 25–30.

ANNERSTEN, H., 1969: Magnetites from a sulphide bearing iron ore formation in Sweden. — Mineralium Deposita 4, 234–240.

ARNOLD, R. G., 1962: Equilibrium relations between pyrrhotite and pyrite from 325°C to 743°C. — Econ. Geol. 57, 72–90.

BARTH, T. F. W., 1952: Theoretical petrology. — J. Wiley & Sons, New York.

BONATTI, E., FISHER, D. E., JOENSUU, O., RYDELL, H. S., and BEYTH, M., 1972a: Iron-manganese-barium deposit from the Northern Afar rift (Ethiopia). — Econ. Geol. 67, 717–730.

BONATTI, E., HONNOREZ, J., JOENSUU, O., and RYDELL, H., 1972b: Submarine iron deposits from the Mediterranean Sea. *In* D. J. Stanley (ed.): The Mediterranean Sea. — Hutchinson & Ross, Stroudsburg. Pp. 701–710.

BUDDINGTON, A. F., and LINDSLEY, D. H., 1964: Iron-titanium oxide minerals and synthetic equivalents. — J. Petrol. 5, 310–357.

BURRI, C., 1959: Petrochemische Berechnungsmetoden auf equivalenter Grundlage. — Birkhäuser Verlag, Basel.

CANN, J. R., WINTER, C. K., and PRITCHARD, R. G., 1977: A hydrothermal deposit from the floor of the Gulf of Aden. — Min. Mag. 41, 193–199.

CORLISS, J. B., LYLE, M., DYMOND, J., and CRANE, K., 1978: The geochemistry of hydrothermal mounds near the Galapagos rift. Earth Plan. — Sci. Let. 40, 12–24.

DESBOROUGH, G. A., and CARPENTER, R. H., 1965: Phase relations of pyrrhotite. — Econ. Geol. 60, 1431–1450.

ERIKSSON, B., and FRIETSCH, R., 1979: Vieto järnmalmsfyndighet. — Unpubl. report, Berggrundsbyrån, SGU, 1–35.

FRIETSCH, R., 1966: Berggrund och malmer i Svappavaarafältet, norra Sverige. — SGU C 604.

— 1973: Precambrian iron ores of sedimentary origin in Sweden. Genesis of Precambrian iron and manganese deposits. — Proc. Kiev Symposium 1970. UNESCO, Paris. Earth Sciences 9, 77–83.

— 1977: The iron ore deposits in Sweden. *In* A. Zitzman. (ed.): The iron ore deposits of Europe and adjacent areas. Explanatory notes to the international map of the iron ore deposits of Europe. – Hannover, Bundesanstalt für Geowiss. und Rohstoffe, v. 1, 478–485.

— 1982: A model for the formation of the non-apatitic iron ores, manganese ores and sulphide ores of Central Sweden. — SGU C 795.

— 1984: Petrochemistry of the iron ore-bearing metavolcanics in Norrbotten county, northern Sweden.— SGU C 802.

— 1985: Formation of Mg-bearing magnetite and serpentine in skarn iron ores of northern Sweden. — GFF 106, 219–230.

GEIJER, P., 1918: Nautanenområdet. — SGU C 283.

— 1925: Eulysitic iron ores in northern Sweden. — SGU C 324.

— 1931: Berggrunden inom malmtrakten Kiruna–Gällivare–Pajala. — SGU C 366.

GEIJER, P., and MAGNUSSON, N. H., 1944: De mellansvenska järnmalmernas geologi. — SGU Ca 35.

GJELSVIK, T., 1957: Geochemical and mineralogical investigations of titaniferous iron ores, west coast of Norway. — Econ. Geol. 52, 482–498.

GRAHAM, C. M., 1976: Petrochemistry and tectonic significance of Dalradian metabasaltic rocks of the SW. Scottish Highlands. — J. Geol. Soc. 132, 61–84.

HESSELBOM, Å., 1977: Geofysisk tolkning. — Unpubl. report, SGU.

HÖGBOM, B., 1924: Rapport över Lannavaarafältet. — Riksarkivet.

HUGHES, C. J., 1973: Spilites, keratophyres, and the igneous spectrum. — Geol. Mag. 109, 513–527.

IRVINE, T. N., and BARAGAR, W. R. A., 1971: A guide tcal classification of the common volcanic rocks. — Canad. J. Earth Sci. 8, 523–548.

JENSEN, M. L., and BATEMAN, A. M., 1981: Economic mineral deposits. Third edition. — J. Wiley & Sons. New York.

KUNO, H., 1968: Differentiation of basalt magmas. *In* H. H. Hess and A. Poldervaart (eds.): Basalts. — Interscience Publishers. New York. Pp. 623–688.

MAGNUSSON, N. H., 1925: Persbergs malmtrakt. Beskrivning över mineralfyndigheter 2. — Kungl. Kommerskollegium, Stockholm.

— 1929: Nordmarks malmtrakt. — SGU Ca 13.

— 1930: Långbans malmtrakt. — SGU Ca 23.

MITCHELL, A. H. G., and GARSON, M. S., 1981: Mineral deposits and global tectonic settings. — Academic Press, London.

MOOKHERJEE, A., 1961: Distribution of minor elements in the gonditic manganese ore and its geochemical significance. — Econ. Geol. 56, 723–729.

ÖDMAN, O. H., 1947: Manganese mineralization in the Ultevis district, Jokkmokk, North Sweden. — SGU C 487.

PETTIJOHN, F. J., POTTER, P. E., and SIEVER, R., 1972: Sand and sandstone. — Springer-Verlag, Berlin.

PUCHELT, H., SCHOCK, H. H., and SCHROLL, E., 1973: Rezente marine Eisenerze auf Santorin, Griechenland. I. Geochemie, Entstehung, Mineralogie. — Geol. Rundschau 62, 786–803.

ROY, S., 1980: Manganese deposits of India. *In* I. M. Varentsov and G. Y. Grasselly (eds): Geology and geochemistry of manganese. Vol. II. Manganese deposits on continents. — Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Pp. 237–264.

RUMBLE, D., III, 1973: Fe-Ti oxide minerals from regionally metamorphosed quartzites of western New Hampshire. — Contr. Mineral. and Petrol. 42, 181–195.

— 1976: Oxide minerals in metamorphic rocks. *In* D. Rumble, III (ed.): Oxide minerals. — Reviews in Mineralogy 3, Mineralogical Society of America. Pp. R1–R24.

RUSSELL, M. J. 1975: Lithogeochemical environment of the Tynagh base-metal deposit, Ireland, and its bearing on ore deposition. — Trans. Inst. Mining Metal 84, B128–B133.

SKIÖLD, T., and CLIFF, R. A., 1984: Sm-Nd and U-Pb dating of Early Proterozoic mafic-felsic volcanism in northernmost Sweden. — Precambrian Res. 26, 1–13.

STÅLHÖS, G., 1982: Beskrivning till berggrundskartan Nynäshamn NO/SO. — SGU Af 138.

STEPHENS, M. B., 1980: Spilitization, element release and formation of massive sulphides in the Stekenjokk volcanites, central Swedish Caledonides. — Norges Geologiska Undersøkelse 360, 159–193.

SUNDIUS, N., 1923: Grythyttefältets geologi. — SGU C 312.

VARENTSOV, I. M., DIKOV, Yu. P., and BAKOVA, N. V., 1980: On the study of Fe-Mn ore formation in recent basins: Experiments on the synthesis of Mn, Fe, Ni, Co hydroxide phases on iron hydroxides (μ-Fe00H). *In* I. M. Varentsov, and Gy. Grassely (eds): Geology and geochemistry of manganese. — Schweizerbart'sche Verlagsbuchhandlung, Stuttgart. Vol. 3, pp. 91–104.

ZWEIFEL, H., 1976: Aitik – geological documentation of a disseminated copper deposit. — SGU C 720.

PRISKLASS E

Distribution
Liber Distribution
162 89 STOCKHOLM
Tel. 08-739 91 30

ISBN 91-7158-314-9
ISSN 0082-0024

Schmidts Boktryckeri AB
Helsingborg 1985