The Kallak stratiform-stratabound magnetite iron ore deposit, Norrbotten County, Sweden

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Cover photo: Outcrop of iron ore with layers of quartz trachyte, Kallak.
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SAMMANFATTNING

Järnmalmsfyndigheten Kallak ligger i den nordvästra delen av den Fennoskandiska skölden, i Norrbottens län, Sverige. Värdbergarten till Kallaks järnmalm är främst en omvandlad granatförande kvartsstrakyt. Dess värdberg bildades för 1 873 ± 11 miljoner år sedan under den svekokarelska orogenesen. Intermediära och basiska metavulkaniska bergarter finns också i järnmalmens absoluta närhet. Bildningen av järnmalm vid Kallak tolkades tidigare som antingen en kvartsbandad vulkanisk sedimentavlagring eller en chert-förande bandad järnmalm (BIF). Observationer och data i den aktuella studien visar att Kallaks järnmalm bildades i en stratiform-stratabound vulkanogen miljö, möjligen i samband med sub-aeriela processer. Jämfört med den klassiska apatitjärnmalmen vid Kiruna, finns det ingen likhet med avseende på bergartskemisk sammansättning, förutom de varianter som har lågt innehåll av apatit. Även de är i allmänhet rikare på spårelement jämfört med den provtagna delen av järnmalmen vid Kallak. Geofysiska data, både mark- och luftburna mätningar, används för att visualisera omfattningen av Kallak-, Parkijaure-, Åkosjegge- och Akkihaure-järnmineraliseringar, liksom den storskaliga fördelningen av bergarter för området Kallak-Parkijaure-Akkihaure. Högupplösta foton och hyperspektral avbildning av borrkärnor används för att dra slutsatsen att bandningen som ses i Kallakmalmen består av felsiska vulkaniska bergarter och inte av kvarts eller chert (hornsten).

ABSTRACT

The Kallak iron ore deposit is located in the north-western part of the Fennoscandian Shield, in the Norrbotten County, Sweden. The host rock of the Kallak iron ore deposit is mainly a metamorphosed garnet-bearing quartz trachyte. Its host rock formed at 1873±11 Ma during the Svecokarelian orogeny. Intermediate and basic metavolcanic rocks are also present in the vicinity of the iron ore. The Kallak iron ore deposit was earlier interpreted as either a quartz-banded volcanic sedimentary deposit or a chert-bearing banded iron formation. Observations and data in the present study show that the Kallak iron ore deposit formed in a stratiform-stratabound volcanogenic setting, possibly during subaerial processes. Compared to the classical Kiruna-type apatite iron ore, there is no close lithogeochemical compositional connection but for those varieties that show low content of apatite, and even those are generally enriched compared with the sampled Kallak iron ore. Geophysical data, both ground and airborne measurements, are used to visualize the extent of the Kallak, Parkijaure, Åkosjegge, and Akkihaure iron deposits, as well as the larger scale distribution of rocks for the area Kallak-Parkijaure-Akkihaure. High-resolution photos and hyperspectral imaging of drill cores are used to infer that the banding seen in the Kallak ore consists of felsic volcanic rocks and not of quartz or chert.

Keywords: Kallak, Magnetite iron ore, Stratiform, Quartz trachyte host rock, Magmatic Fe oxide ore, Jokkmokk iron ores

INTRODUCTION

The Norrbotten County, Sweden is a key area for future exploration and mining in Europe. A north–south to north-north-east–south-south-west trending zone of iron mineralisations, hosted by supracrustal rocks occur in an area west of Jokkmokkk and south of Kiruna (fig. 1). Data from recent mapping in the area by the Geological Survey of Sweden (SGU) are here further used to present a description of some of the deposits. These data include geophysical data, litho-geochemistry, petrographical studies, and hyperspectral imaging of some drill cores. The deposits at Kallak, Parkijaure, Akkihaure, and Åkosjegge are relatively well investigated and considered to be potential ore deposits whereas Pakko, Maivesvare, and Tjårovaratj are regarded as possible ore targets (Johansson 1980). Kallak, Parkijaure, Akkihaure, and Åkosjegge are interpreted to occur associated with volcanic host rocks, whereas the Åkosjegge deposit occurs in gneissic skarn rocks and possible metasedimentary rock components as well. The Kallak iron ore deposit was recently suggested to be either a quartz-banded iron ore (Frietsch 1997) or a chert-bearing banded iron formation (Martinsson *et al*. 2016).

No modern description of the presented occurrences is at hand and this paper will add to the knowledge of different types of iron-oxide deposits that are present in the northern part of Sweden.

GEOLOGICAL SETTING

The study area is located in the north-western part of the Fennoscandian Shield, in the Norrbotten County, Sweden (fig. 1). The Precambrian crystalline bedrock is to a large extent covered by Quaternary deposits and any two-dimensional geological model of it is depending on geophysical data. The Svecokarelian orogeny (2.0–1.8 Ga) in the area shows a convergent tectonic setting, during which volcanic and sedimentary rocks were formed and intruded by several generations of intrusive rocks (fig. 1 and 2). Regional deformation, including folding and shearing, occurred mostly under low to intermediate pressure and variable temperature conditions, where metamorphism reached greenschist to upper amphibolite facies (e.g. Claeson & Antal Lundin 2019a, b). The Kallak iron ore deposit is hosted by a quartz trachyte that formed around 1.87 Ga ago during a continental arc-setting stage of the Svecokarelian orogeny. The classical Kiruna iron ores are located some 130 km to the north-north-east and the Malmberget iron ores some 80 km to the north-east of the Kallak iron ore deposit (fig. 1 and 2), possibly roughly in the same lithological unit and within reported age differences of c. 10 Ma for their host rocks (Westhues *et al*. 2016, Claeson *et al*. 2018, Sarlus *et al*. 2020).

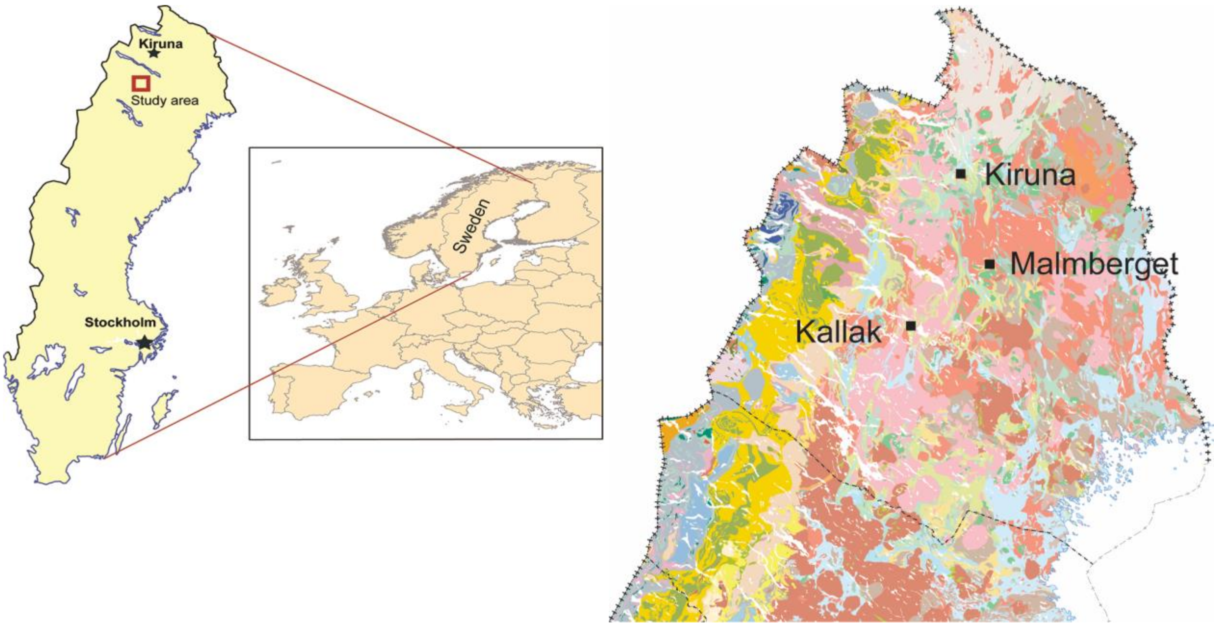


Figure 1. Location of the study area left and right bedrock map showing location of the Kallak iron ore and rock units of northern Sweden. Legend see https://apps.sgu.se/kartvisare/kartvisare-berg-50-250-tusen.html.

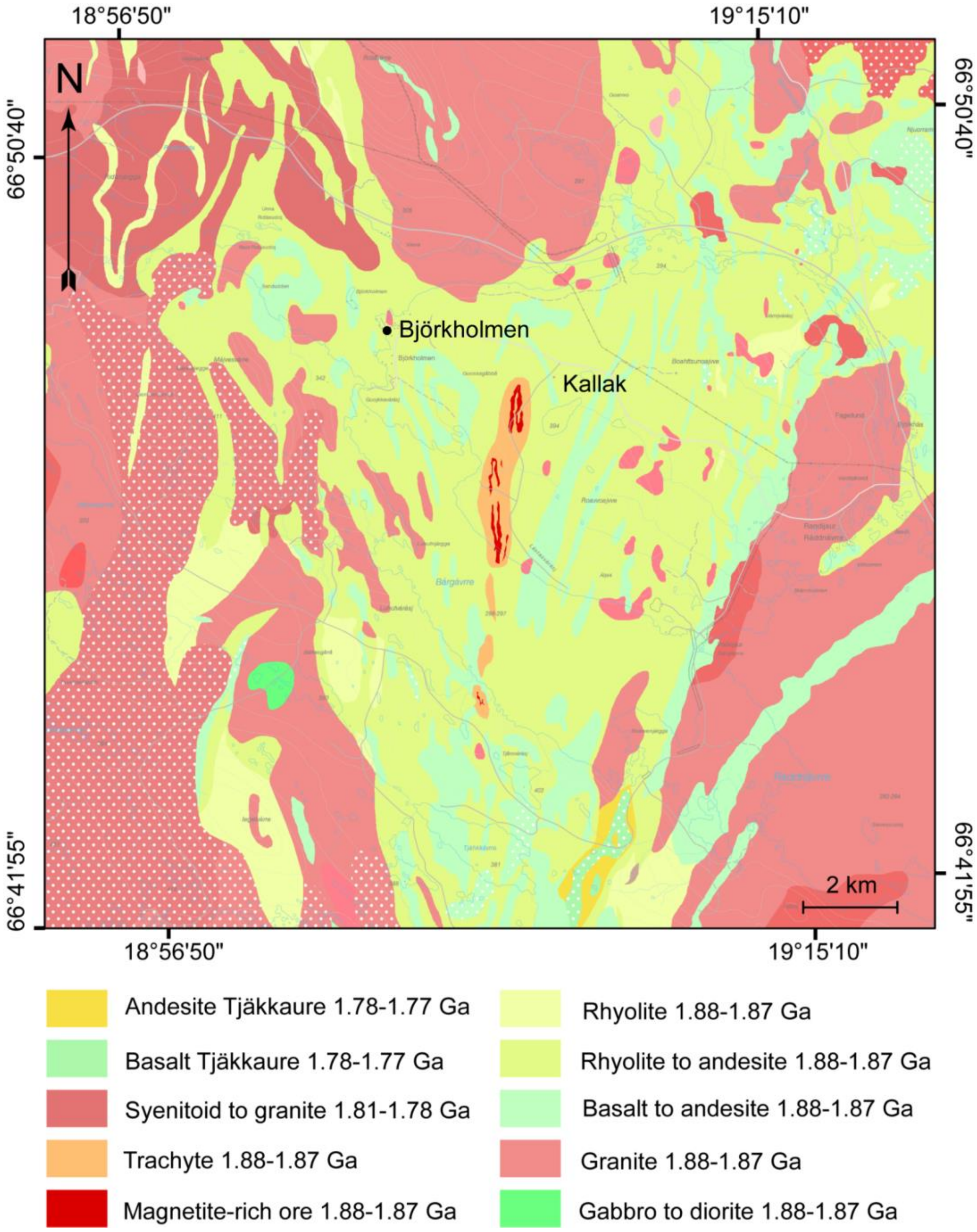


Figure 2. Bedrock map showing location of the Kallak iron ore and rock units in the study area.

GEOPHYSICAL DATA OVER THE KALLAK AND ADJACENT IRON ORE DEPOSITS

Comprehensive ground measurements of the magnetic field, electromagnetic field (slingram), and closely spaced gravity measurements of the deposit are from older exploration campaigns performed between 1968 and 1970. The measurement distance between points is between 10–20 and 40–80 m, the line spacing is between 20 and 80 m (locally up to 150 m). The investigated area is 18 by c. 5 km (fig. 3).

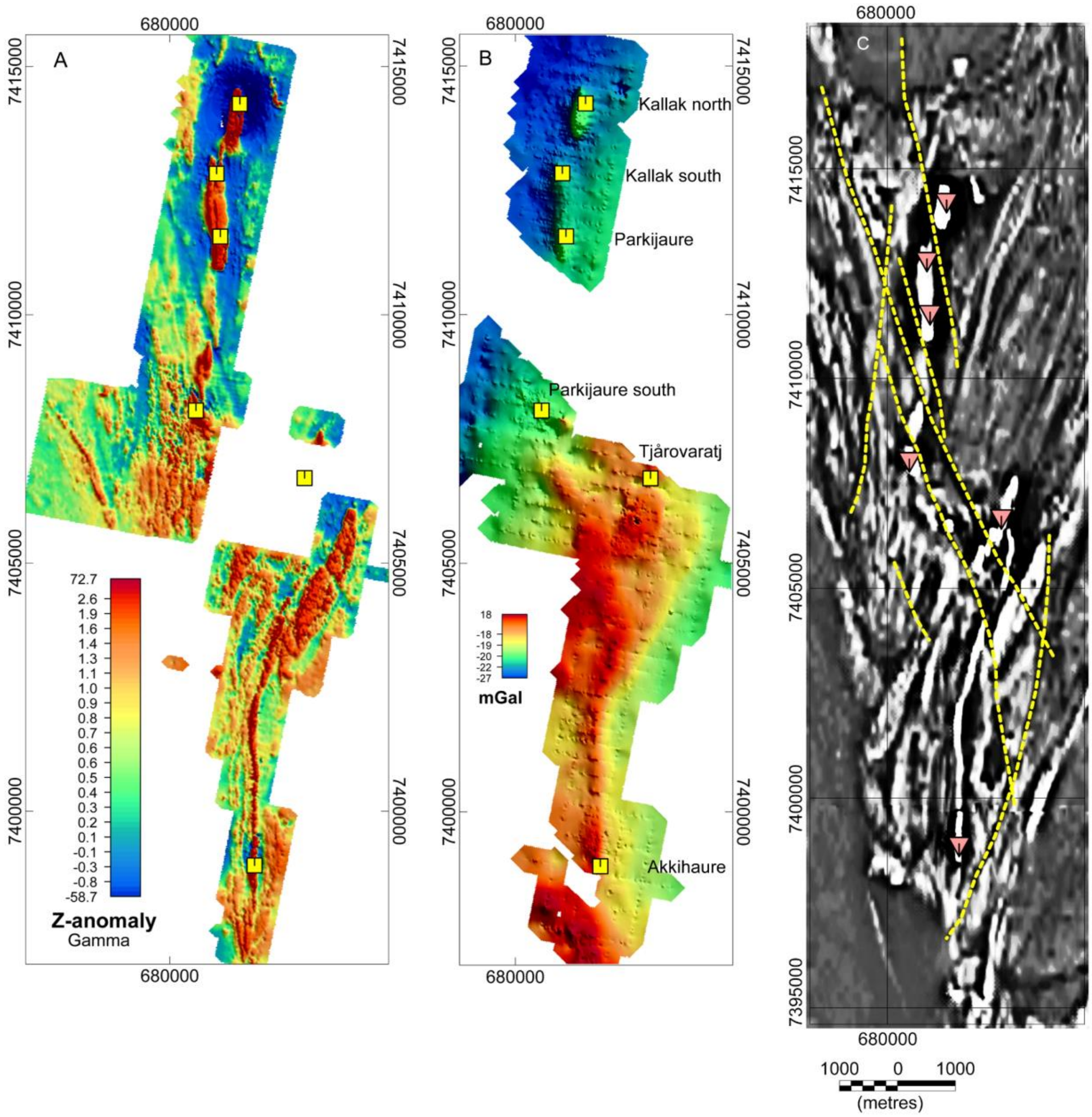


Figure 3. Geophysical data over the Kallak, Parkijaure, Tjårovaratj, and Akkihaure. The iron oxide mineralisations (ore) are shown as yellow squares in A and B. **A.** Magnetic anomaly map, vertical component. **B.** Terrain corrected Bouguer anomaly map, with names of the deposits. **C.** Aeromagnetic data (vertical derivative) indicate that the ore bodies are structurally separated and displaced by deformation zones (in yellow) in north-south and north-north-west direction Grid in SWEREF99TM.

The by far strongest magnetic anomaly of the study area occurs about 3.5 km south-east of Björkholmen where the iron ore deposit "Kallak North" occurs (fig. 3). The field strength of the ore, measured from an aircraft at 60 m altitude, is 18,500 nT higher than the average of the magnetic total field in the area at about 52,300 nT. Ground measurements show a field strength greater than 120,000 nT, thus more than a doubling of the average magnetic total field strength. The magnetic data indicate that the ore bodies at Kallak are structurally separated by deformation zones trending north south and north-north-west, where they have become displaced along the deformation zones (fig. 3). Furthermore, the magnetic data are interpreted to show that the string of iron mineralisations and ore deposits from Kallak to Akkihaure are stratiform and formed in more or less the same host rocks at the same time (fig. 3).

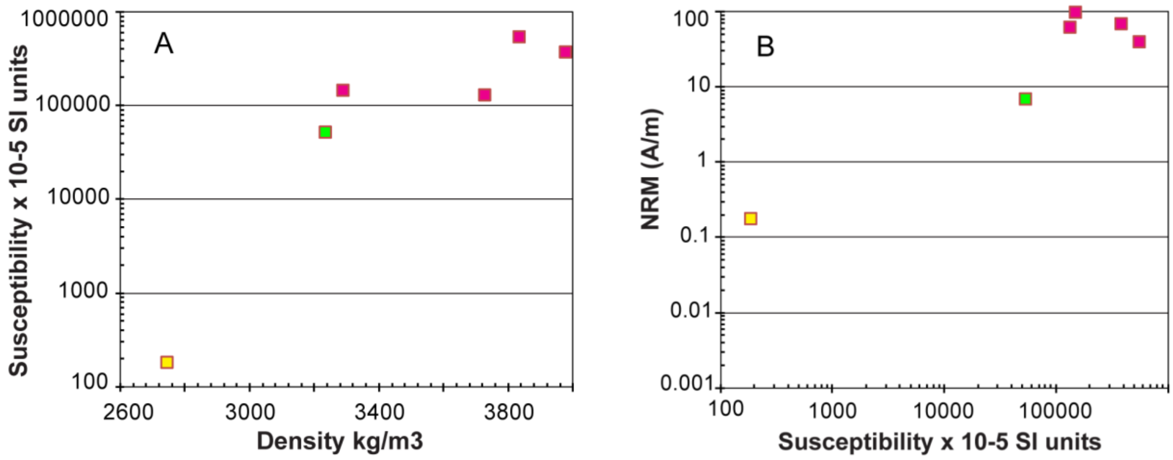


Figure 4. Petrophysical properties of iron-oxide ore (red square), mineralised quartz trachyte (green square), and quartz trachyte (yellow square). **A.** Density vs. magnetic susceptibility and **B.** magnetic susceptibility vs. natural remanent magnetisation.

The petrophysical properties of the iron oxide ore is obviously different from those of the quartz trachyte; in addition to much higher susceptibility it shows significantly higher density as well as higher natural remanent magnetization (fig. 4). Magnetic susceptibility measured on outcrops and in trenches is variable, for quartz trachyte: 0.0007 to 0.01 at outcrops, and from 0.046 to 0.12 SI-units, in the trenches. Susceptibility for the magnetite-rich mineralisation and iron ore parts varies from 0.34 to 0.99 SI-units and often above 1 (overflow for the instrument).

KALLAK AND PARKIJAURE IRON ORE DEPOSITS

A larger area with iron mineralisations at Kallak-Björkholmen and Parkijaure is known since the 1940's when SGU documented the outcrops, and extensive work, e.g. core drilling, was performed (Eriksson BRAP83801). Ground geophysical surveys using magnetometry and gravity measurements were carried out during the years 1947 (at Kallak North) and 1968–1970. Mineral resource estimate calculations were presented 1980, where the combined estimate of iron ore for Kallak-Björkholmen and Parkijaure was c. 149 Mt using gravity data and c. 123 Mt using magnetic data. With a correction for a possible 30% hematite content in both Kallak occurrences, the estimate is c. 161 Mt (Johansson 1980). Since 2013 the Kallak area is a designated national interest. Exploration has recently (2010–2014) been completed with core drilling in the northern and southern part by Jokkmokk Iron Mines AB - Beowolf Mining plc. The company estimated in November 2014 that the "Kallak deposit", i.e., resources of both Kallak North and South together, contains more than 150 Mt of ore at 26.2 to 27.5% Fe, and that Kallak North is open to the north and at depth (http://beowulfmining.com/projects/sweden/kallak/). The issue of mining the deposit has not yet been resolved and is pending early 2020.

In connection with our fieldwork in the area during 2014, the trenches and blasted test pits made by Jokkmokk Iron Mines AB at Kallak were visited, documented, and sampled (fig. 5A, B). Three trenches with several test pits in each, had been completed in roughly east-west direction, and their sizes were from north to south c. 10 × 60 m, c. 8 × 75 m, and c. 10 × 125 m, respectively. The distances between the trenches were from the northern to the central c. 200 m and a further c. 80 m to the southern trench. During a field excursion organized by the SGU in 2015, the company had restored and covered all trenches meticulously as requested by the permit, with pine seedlings already in place and a total lack of iron-ore boulders on the surface to study.

Figure 5. A. Northern prospecting trench and test pits at Kallak. **B.** Southern prospecting trench and test pits at Kallak. **C.** Outcrop in trench of iron mineralisation at Kallak with bands of quartz trachyte. Centimetre scale in the images. **D.** Close-up of banding of millimetre- and centimetre width, which is made up of magnetite-rich and quartz trachyte bands, respectively. **E.** Close-up of the sampled quartz trachyte volcanic rock from the northern prospecting trench at Kallak. **F.** Hand specimen showing fine lamination in iron ore from Kallak, cut and wetted surface.

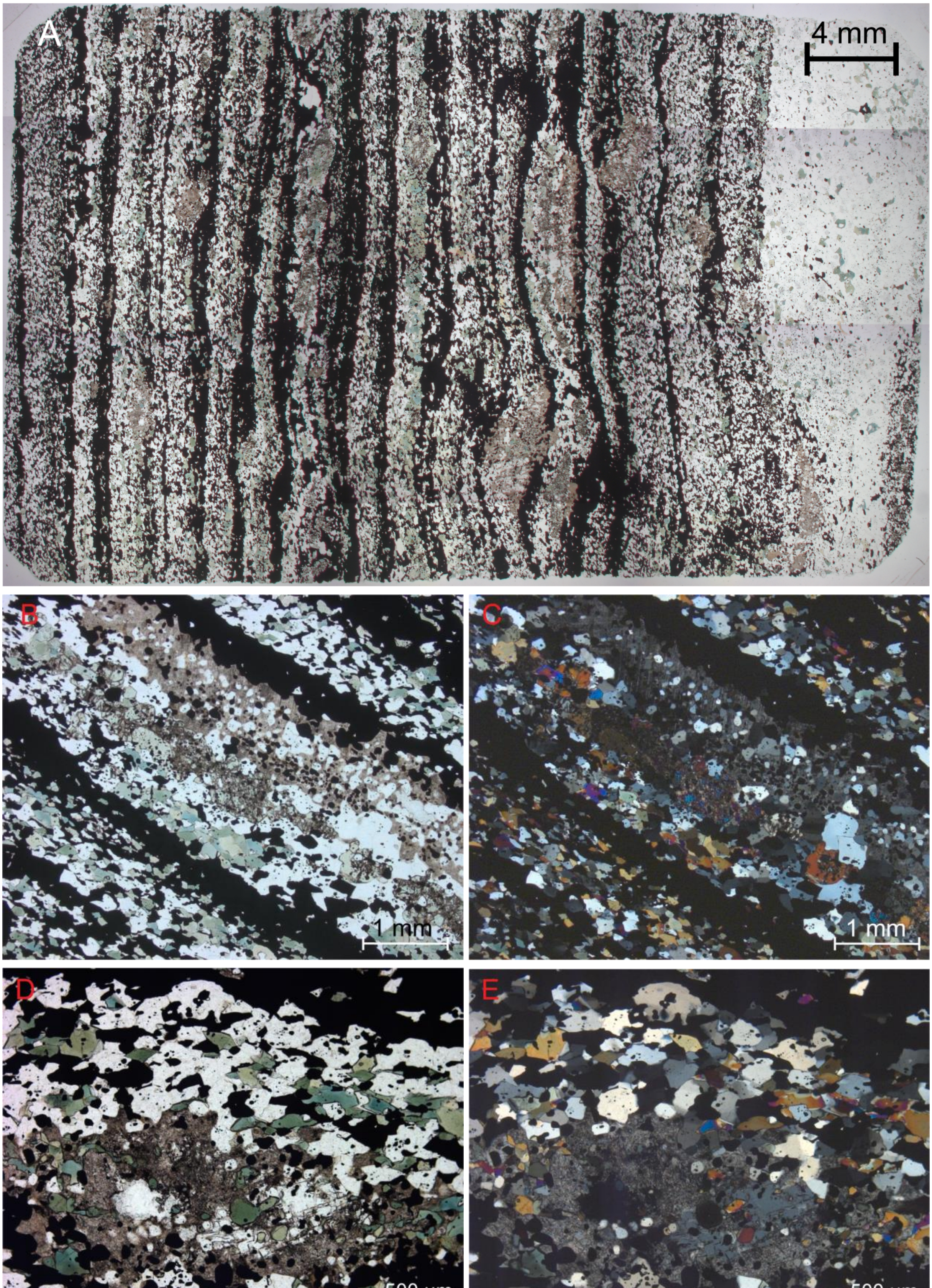
The most magnetite-rich bedrock at Kallak shows foliation and lineation, contain fragments of both felsic and mafic volcanic rocks, and displays conformable banding to the surrounding acid volcanic rock (fig. 5C, D). Structures like foliation were not actually measured because of the very high magnetite content in the bedrock. A consistent lineation plunges to the south, in the central trench foliation dips steeply to the west and in the southern trench foliation is sub-vertical to vertical. The iron mineralisation is laminated, which is clearly visible in hand specimen (fig. 5F).

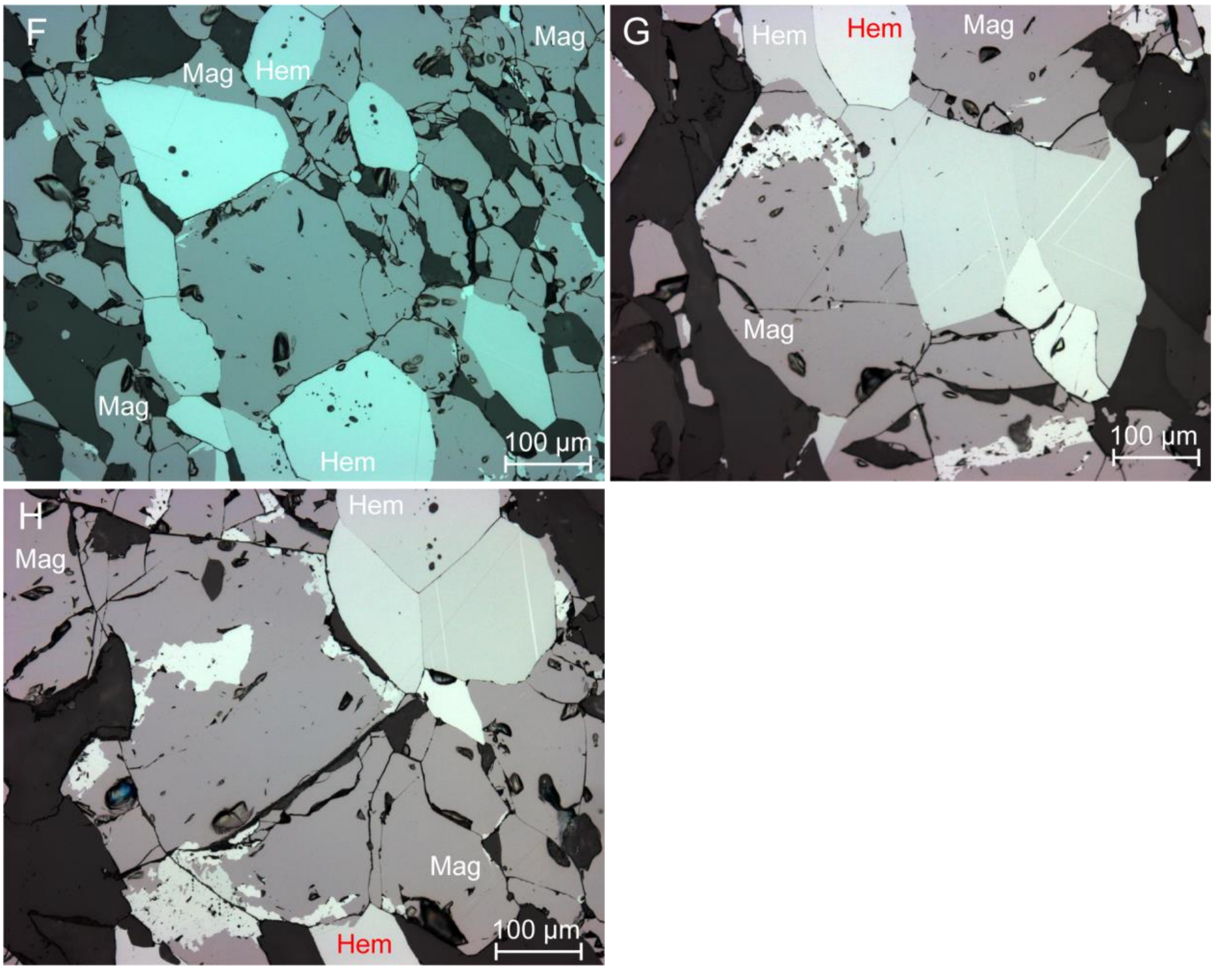
The acid volcanic rock occurring in the pits and trenches is a garnet-bearing quartz trachyte with open or rusty amygdales (fig. 5E). Smaller amounts of skarn consisting of amphibole, garnet, epidote, pink to orange calcite, and greenish apatite occur in both the quartz trachyte and the iron mineralisation. Garnet-epidote skarn and minor amounts of hematite is reported in several of the borehole protocols from the 1940's. Both the iron ore and the quartz trachyte were intruded by dykes of massive, grey to greyish red granite to pegmatite that post-date the high-grade metamorphism. An age determination of the quartz trachyte shows that there is a heterogeneous set of zircon, with the oldest being Archaean at c. 2700 Ma and that the formation age of the quartz trachyte is 1873±11 Ma (Claeson *et al.* 2018). The age of the host quartz trachyte of the Kallak iron ore, overlaps with that of the ore body at Kiirunavaara, which was recently determined to 1877±4 and 1874±7 Ma (Westhues *et al.* 2016) and that of the Malmberget iron ore at 1885 ± 6 Ma and 1881 ± 6 Ma (Sarlus *et al.* 2020).

Petrography of the Kallak iron ore and quartz trachyte host

A microscope study of the iron mineralisation shows a laminated pattern defined by the presence of alternating lamina of opaque minerals and of mostly both felsic and mafic silicates (fig. 6A). Point counting of a thin section of the iron ore, resulted in the mineral distribution of quartz 22%, plagioclase 3.5%, pyroxene 0.7%, amphibole 14% and magnetite 60%. Some parts, looking like micro enclaves, consisting for the most part of altered plagioclase and clinopyroxene are present within the laminated iron ore, (fig. 6B–E). Micro enclaves of different dimensions and compositions are also clearly visible in hand specimen and at outcrops, (fig. 5F). Twin lamellae in hematite are seen in some grains but not all (fig. 6F–H). The twin lamellae are of varying width, irregularly distributed, and never seen passing through adjacent grains of hematite (fig. 6F–H). Therefore, the twinning is regarded as due to growth and not deformation. The annealed texture of recrystallised hematite with 120° dihedral angles may either be due to slow cooling from depositional/magmatic conditions or slow heating during metamorphism (Craig & Vaughan 1994). Martite, where hematite has replaced magnetite due to oxidation, is seen at borders, fractures, and within magnetite grains (fig. 6F–H).

▶ **Figure 6. A.** A fine laminated appearance is defined by the distribution of the opaque minerals, plane-polarized light. Possible micro enclaves consisting of remnant clinopyroxene and plagioclase, recrystallised amphibole and secondary calcite, **B.** plane polarised light and **C.** crossed nicols. Close-up of possible micro enclave, **D.** plane polarised light and **E.** crossed nicols. In reflected light magnetite, hematite, and martite are easily recognised. **F.** Martitization of almost whole magnetite crystal seen just above centre of image. **G.** Twin lamellae in hematite. **H.** Annealed texture of recrystallised hematite with 120° dihedral angles and one crystal showing twinning. Martite, where hematite has replaced magnetite due to oxidation, is seen at borders, fractures, and within magnetite grains (**F–H**).

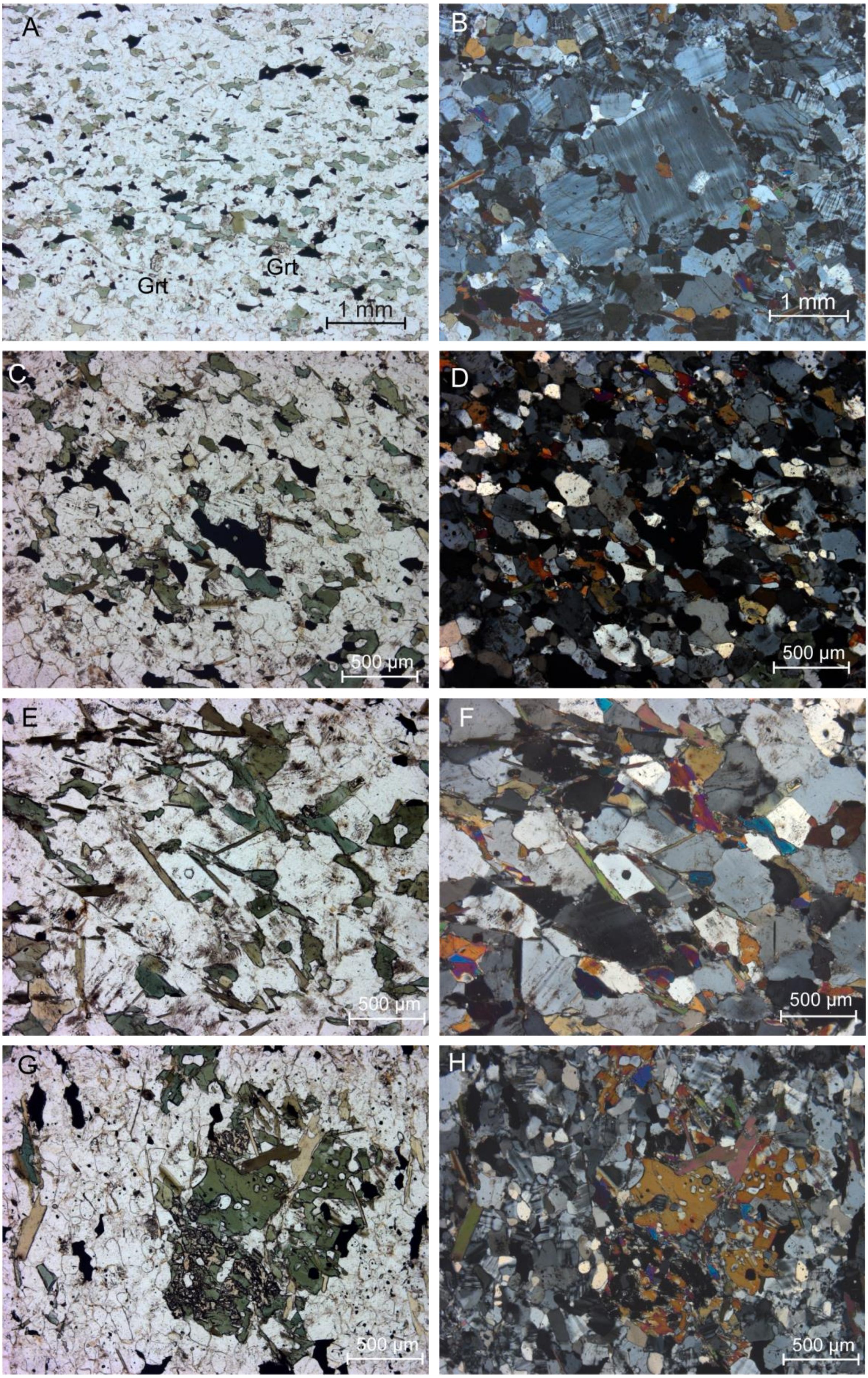

A
4 mm
B
1 mm
C
1 mm
D
500 µm
E
500 µm



Small garnets, less than 0.25 mm in size but readily observed in thin section, are present in the quartz trachyte (fig. 7A). Potassium feldspar occurs as rare phenocrysts in the quartz trachyte and are not severely altered (fig. 7B). Inclusions of early formed mafic minerals, e.g. amphibole and magnetite, are present within these phenocrysts along with plagioclase. Amphibole and biotite are ubiquitous throughout the quartz trachyte (fig. 7). There is a general preferred orientation along the banding but in some portions, the mafic minerals may be oriented in any direction measured along their long axis (fig. 7) Larger aggregates of amphibole are seen with garnet (fig. 7H).

Pervasive alteration is reported from other iron ore deposits of different affinities in the Norrbotten County, usually as Na, K, Cl, or Ca metasomatism (e.g. Frietsch 1974; Parák 1975; Frietsch *et al.* 1997; Smith *et al.* 2007; Westhues *et al.* 2016). However, although our samples do show evidence of high-grade metamorphism, alteration is mostly that of recrystallization, growth of metamorphic minerals and not so much metasomatism of the above-mentioned kinds.

▶ **Figure 7. A.** Up to 250 µm large garnet crystals in quartz trachyte, plane polarised light. **B.** Phenocrysts of potassium feldspar in quartz trachyte, inclusions of amphibole, plagioclase, and magnetite, crossed nicols. Amphibole and biotite are ubiquitous throughout the quartz trachyte, **C.** plane polarised light and **D.** crossed nicols. There is a general preferred orientation along the banding but in some portions, the mafic minerals may be oriented in any direction measured along their long axis, **E.** plane polarised light and **F.** crossed nicols. Larger aggregate of amphibole with garnet, **G.** plane polarised light and **H.** crossed nicols.


A
Grt
Grt
1 mm
B
1 mm
C
500 µm
D
500 µm
E
500 µm
F
500 µm
G
500 µm
H
500 µm

Whole-rock geochemistry of the Kallak iron ore and quartz trachyte host

One sample each of the iron ore and the quartz trachyte from the trenches were analysed for whole-rock lithogeochemistry, using the analysis packages CCP-PKG01, ME-MS41, and PGM-ICP23 of ALS Chemex.

It must be crystal clear that the limited sampling of ore and host rock along with the very limited area of the prospecting trenches, means that there might be parts of the iron ore that contain higher abundance of apatite and that different host rocks might also occur at the Kallak iron ore deposit.

The iron ore and the quartz trachyte have similar REE patterns, but the iron ore sample shows significantly lower levels of REE (fig. 8A, Table 1). The same applies to the multi-element diagram, which shows similar trends for the two samples but where the iron mineralisation has significantly lower levels of the plotted elements than the quartz trachyte (fig. 8B). This is evidence that the banding is made of quartz trachyte and iron ore, because if it would have been quartz or chert instead none of the above patterns would look the same, and the difference is for the most part an effect of dilution by the magnetite. The pronounced negative Sr anomaly of the iron ore compared with the quartz trachyte is most probably due to similar apatite content in both rocks. The negative Zr anomaly of the iron ore sample is not seen in the quartz trachyte indicating very low content in the magnetite of the iron ore or that the thin bands of quartz trachyte differ in Zr content compared with the host rock proper. The very low content of apatite in our sample of the iron ore explain the low REE levels compared to the iron ores of the Norrbotten region that are characterized as apatite-bearing iron ore (e.g. Westhues *et al.* 2016; Martinsson *et al.* 2016 and references therein). Furthermore, the data show that apatite, monazite, allanite, or xenotime may not be present in the sampled Kallak iron ore but for very minor amounts (Table 1). The sample of the magnetite iron ore shows low contents of TiO_2, MnO, and P_2O_5. The low concentrations of V (19 ppm), S (0.09%), Cu (2.3 ppm), Th (1.12 ppm), Nb (1.9 ppm), and Zr (19 ppm) are different from those of Kiruna-type apatite iron ore; possibly they resemble those varieties of Kiruna-type that show low contents of apatite, although even those are generally enriched in these elements compared to the Kallak iron ore sample (cf. Martinsson *et al.* 2016). Furthermore, the lithogeochemical data of the ore show no resemblance of skarn iron ore, BIF, or epigenetic Cu-Au Fe oxide deposits of the region (e.g. Martinsson *et al.* 2016). The iron ore and the host rock have low contents of C suggesting no major carbonate component (Table 1). The quartz trachyte that was sampled at the trench for lithogeochemical analysis shows a high content of barium at 2350 ppm, possibly indicating that volcanic-hydrothermal processes have been active (fig. 5E, Table 1).

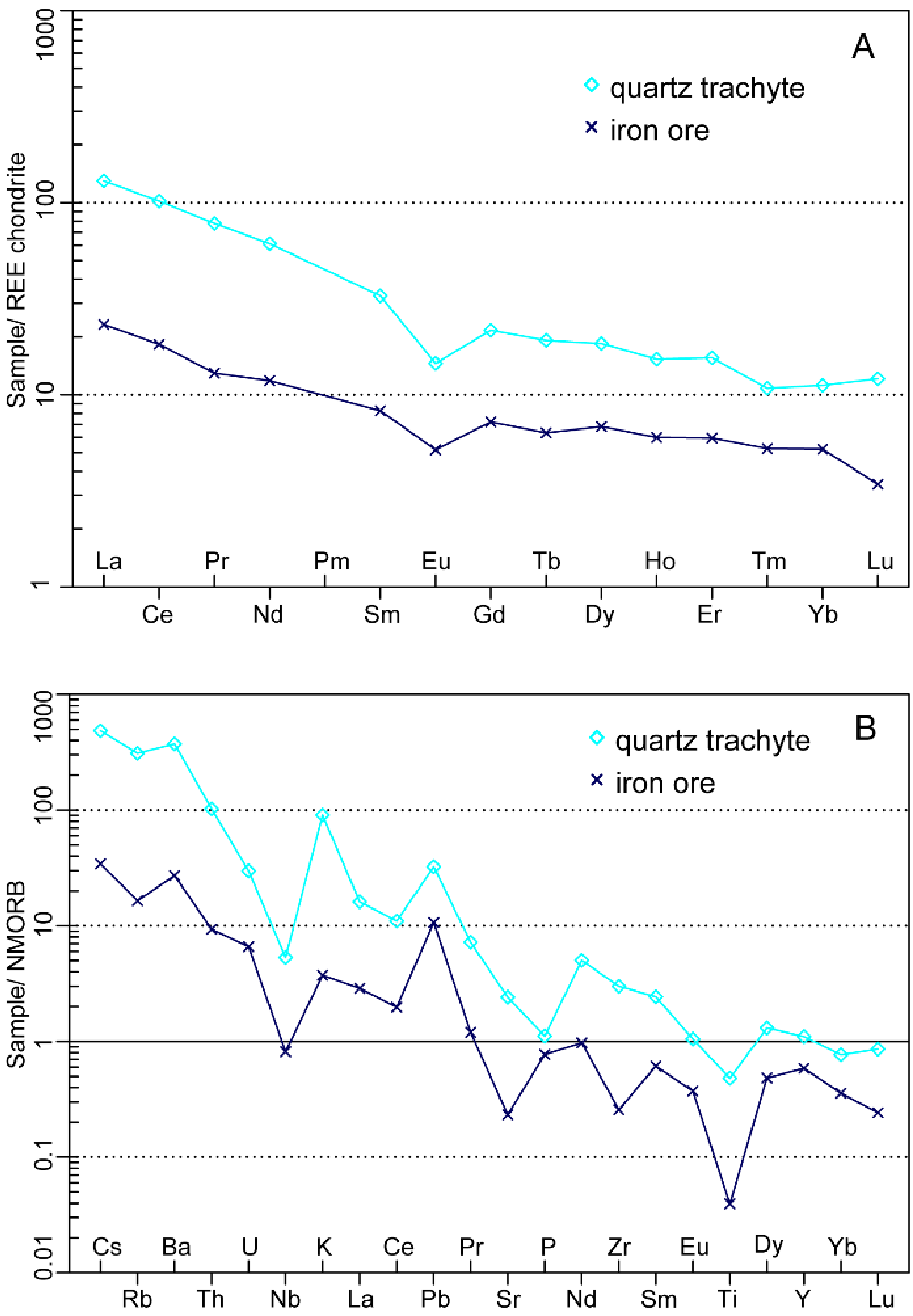


Figure 8. A. REE-diagram with data from lithogeochemical analyses of the host rock quartz trachyte and the iron ore at Kallak. Normalizing values for chondrite from Boynton (1984). **B.** Multi-element diagram, rocks and symbols as in A. Normalizing values for N-MORB from Sun & McDonough (1989).

Table 1. Whole-rock geochemistry of the Kallak iron ore and quartz trachyte host rock. Oxides, C, and S in %, elements in ppm.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	LOI	Total
Iron Ore	34.3	1.24	62.3	1.67	2.26	0.23	0.27	0.05	0.33	0.09	-1	101.77
Quartz trachyte	63.1	13.7	7.47	2.33	2.46	2.79	6.55	0.61	0.44	0.13	0.48	100.36
	C	**Ba**	**Ce**	**Cr**	**Cs**	**Dy**	**Er**	**Eu**	**Ga**	**Gd**	**Hf**	**Ho**
Iron Ore	0.02	171	14.8	10	0.24	2.2	1.25	0.38	2.7	1.87	0.6	0.43
Quartz trachyte	0.01	2350	82.4	120	3.4	5.95	3.27	1.07	18.5	5.61	6.2	1.1
	La	**Lu**	**Nb**	**Nd**	**Pr**	**Rb**	**Sm**	**Sr**	**Ta**	**Tb**	**Th**	**Tm**
Iron Ore	7.2	0.11	1.9	7.1	1.58	9.2	1.61	20.9	0.1	0.3	1.12	0.17
Quartz trachyte	40.3	0.39	12.4	36.7	9.51	174	6.39	217	1	0.91	12.3	0.35
	U	**V**	**Y**	**Yb**	**Zr**	**Bi**	**Hg**	**Sb**	**Se**	**Te**	**Ag**	**As**
Iron Ore	0.31	19	16.4	1.09	19	0.15	0.005	1.4	0.2	0.01	0.01	38.3
Quartz trachyte	1.4	124	30.8	2.34	222	0.08	0.005	0.78	0.2	0.01	0.02	6
	B	**Be**	**Cd**	**Co**	**Cu**	**Ge**	**In**	**Li**	**Mo**	**Ni**	**Pb**	**Tl**
Iron Ore	10	0.42	0.02	11.7	2.3	0.52	0.011	7.9	0.13	3.4	3.2	0.0005
Quartz trachyte	9	0.13	0.01	8.4	8	0.09	0.015	13.8	0.23	15.9	9.7	0.0005
	S	**Sc**	**Sn**	**Tl**	**W**	**Zn**	**Au**	**Pt**	**Pd**			
Iron Ore	0.09	0.3	0.2	0.02	0.41	38	0.0005	0.0025	0.0005			
Quartz trachyte	0.03	2.9	1.1	0.13	0.18	49	0.0005	0.0025	0.001			

Drill core scanning at SGU of samples from the Kallak iron deposit

The new SGU database with optical and infrared drill core imagery serve as a compliment to the physical drill cores that are stored in Malå, Sweden. The data can be used by exploration companies as well as researchers and will contribute to a sustainable use of Sweden's mineral resources. The results are freely available at https://apps.sgu.se/kartvisare/kartvisare-borrkarnor.html through the SGU map viewer "Drill Cores" and the data can be ordered from the SGU customer service for a minor fee. The data is licensed under Creative Commons Attribution 2.5 Generic (CC BY 2.5).

Six drill cores from the Kallak deposit, produced during the 1940's by SGU, have been photographed and scanned. Here we only present those from a single box representing drill core BJH48003, and where some iron ore occurs to visualize what the rocks look like (fig. 9). The rocks seen here represent a depth of c. 96 to 114 m and are similar to those in the trenches and test pits (fig. 5C, D). The same core box is also shown with the hyperspectral imaging setting of false colour composite, long-wave infrared using an OWL scanner, PH7600–11900 LWIR, and PW7600–11900 LWIR (fig. 10). Unfortunately, the technique is non-diagnostic for oxides like magnetite. However, quartz is readily diagnosed, and no quartz-banded parts have been identified in the hyperspectral images of the drill cores, whereas relatively infrequent fractures filled with quartz are present. The alternating thin and wide bands in the iron ore parts are felsic volcanic rocks according to the high-resolution photos and the hyperspectral images (fig. 9 and 10). This is in very good agreement with what the logger designated as "leptite" in the borehole protocol, an obsolete term used for metamorphic acid volcanic rocks.

Figure 9. High-resolution photo of core box BJH48003-6 from the Kallak iron ore deposit, depth c. 96 to 114 m.

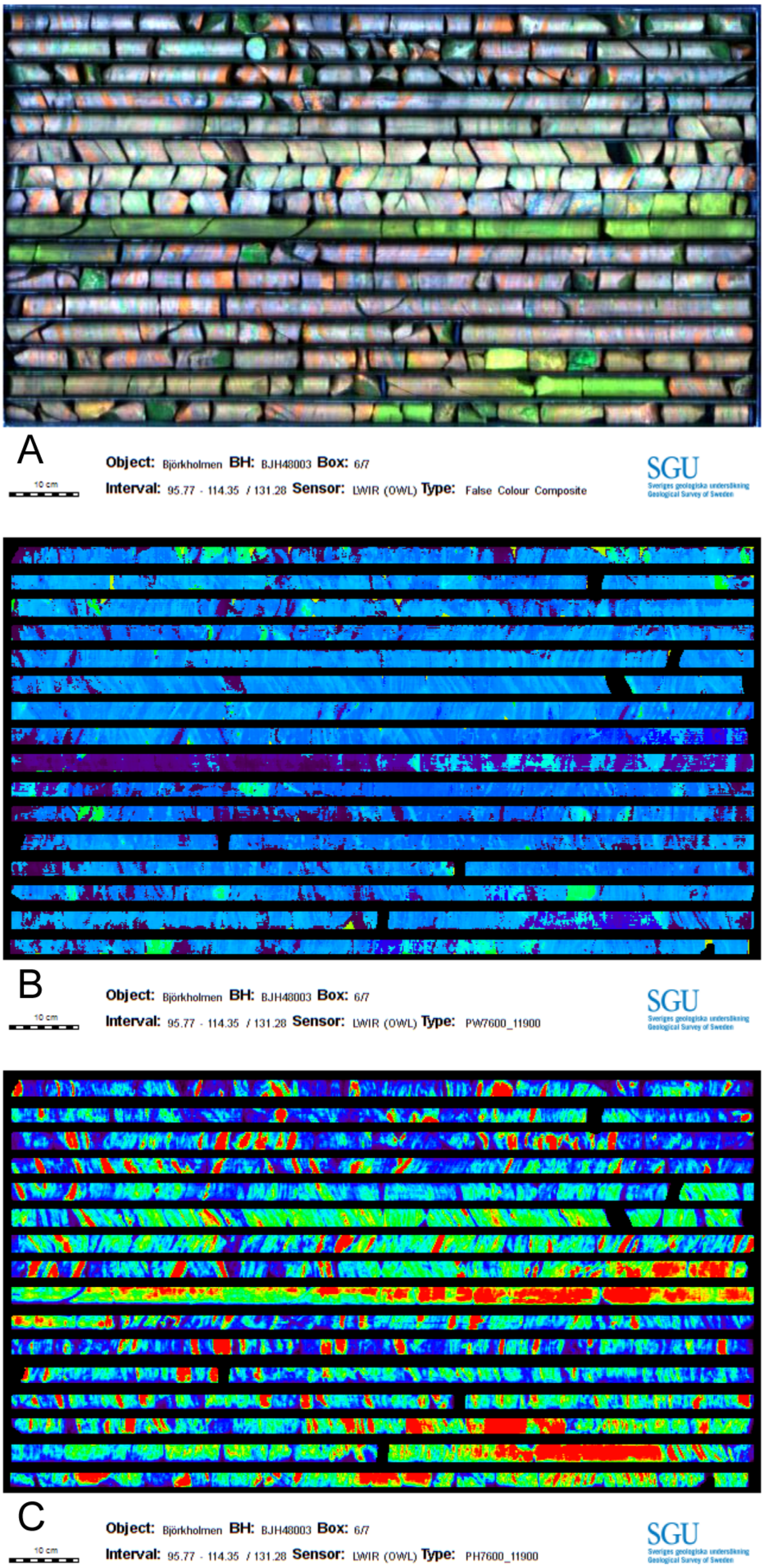


Figure 10. Hyperspectral imaging of core box BJH48003-6 from the Kallak iron ore deposit, depth c. 96 to 114 m. **A.** False colour composite, long-wave infrared using an OWL scanner, **B.** PH7600–11900 LWIR, and **C.** PW7600–11900 LWIR.

AKKIHAURE IRON ORE DEPOSIT

The magnetite mineralisation causing a positive magnetic anomaly at Akkihaure is mainly located below lake Akkihaure, and no outcrops have been discovered (southernmost yellow symbol in fig. 3). Geophysical surveys during the 1960's by SGU including magnetometry and gravity measurements located it (Frietsch 1997). One drill core (SGU borehole No. 72704) was drilled during 1972 but has yet not been photographed or scanned. The ore-bearing zone strikes north–south and forms a steeply plunging, isoclinal fold that is open to the north. A magnetic profile measurement was made to determine the width and dip of the magnetic body. The highest value in the profile was 77,100 nT. At a nearby location, the proton magnetometer could not register a value, probably due to the magnetic field being stronger than the upper detection level (Hellström & Berggren 2014). According to the borehole protocol, the magnetite-rich rock is hosted by an amphibole-biotite-feldspar gneiss, but a more recent report denoted the rock as a strongly altered dacite (Hellström & Berggren 2014). On the ground surface, the ore-bearing area is about 650 m long and 50–60 m wide, where the largest mineralised zone is up to 30 m wide and situated in the western limb of the fold. Estimates based on data from gravity- and magnetic measurements indicate an iron ore tonnage of 12 to 13 Mt (Johansson 1980). A lithogeochemical analysis of a portion of the core from the iron ore shows: 48.4% Fe, 0.01% P, 0.01% Ti, < 0.01% Mn and 13 ppm V (section 178.35 to 178.62 m, Hellström & Berggren 2014).

ÅKOSJEGGE IRON ORE DEPOSIT

Åkosjegge is located c. 23 km north-east of Kallak. Airborne geophysical measurements were carried out in the Norrbotten County within an iron inventory program performed between 1963 and 1973. Some new discoveries were then made, among them the so-called Jokkmokk ores and Åkosjegge (Frietsch 1997). Ground geophysical surveys using magnetometry and gravity measurements were performed during the years 1969–1970 in an area of c. 4 km^2 (Johansson 1980). The magnetic field was measured using 40 and 80 m line distances and with 10 and 20 m point distances, densest where the magnetic field was strongest as indicated by the airborne measurements (fig. 11). The gravitational field was measured using 40 m point distance and 160 m line distance (fig. 11). A calculation of the iron ore deposit potential from geophysical data suggests an approximate tonnage of 75 Mt, using a steep dipping, slab-formed ore body with a depth of 200 m and density of 3500 kg/m^3 (Johansson 1980). The ground measurements show that the south-western part of the magnetic anomaly is weaker than the north-eastern, the difference being c. 10,000 gamma. Correspondingly, the gravity field is c. 1.5 mGal weaker in the south-western part. Frietsch (1997) states that the ore zone is about 1.5 km long and 500 m wide, with an iron content of c. 30% Fe.

Two cores (SGU boreholes 72601 and 72602) were drilled during 1972 and geophysical borehole-logging, including the use of borehole magnetometer, was conducted. The borehole protocols show an iron mineralisation with parts of skarn, and the rocks are described as grey to green skarn-bearing gneisses. A very small percentage of the two, c. 200 m deep boreholes were classified as magnetite iron ore during logging. Where magnetite occurs in the cores an iron content in the range of 10–24% was reported. The question is whether the drillings encountered the mineralisation indicated by the geophysical ground measurement data (fig. 11). Both drill cores made by the SGU during the 1970's have been photographed and scanned by SGU. Core box 5 from drill core Åkosjegge 72602 is shown to visualize the rocks (fig. 12). The closest outcrops, c. 600 m and 800 m, respectively, away from the indicated iron ore body, have hydrothermally altered and veined, amphibole- and magnetite-rich basaltoid to andesitoid metavolcanic rocks (Claeson & Antal Lundin 2019a). The rocks in the photos of the core boxes resemble the hydrothermally altered and veined amphibole- and magnetite-rich basaltoid to andesitoid volcanic rocks at the outcrops. Studying the scanned images of the drill cores and reading the borehole protocol lead us to conclude that this iron ore deposit is hosted by a different rock than the Kallak deposit and that the protoliths of the host skarn-bearing gneisses primarily are basaltoid to andesitoid volcanic rocks.

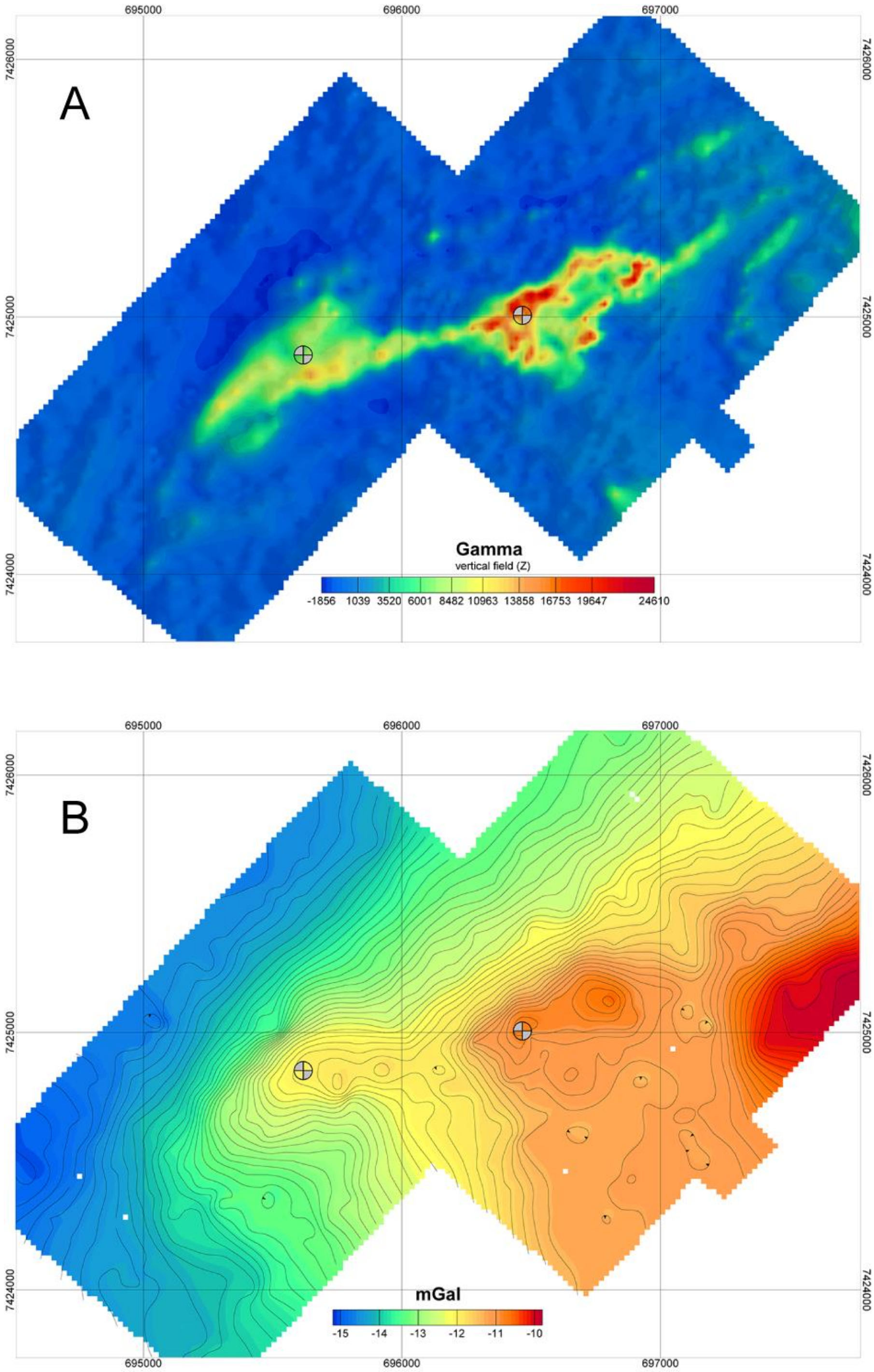
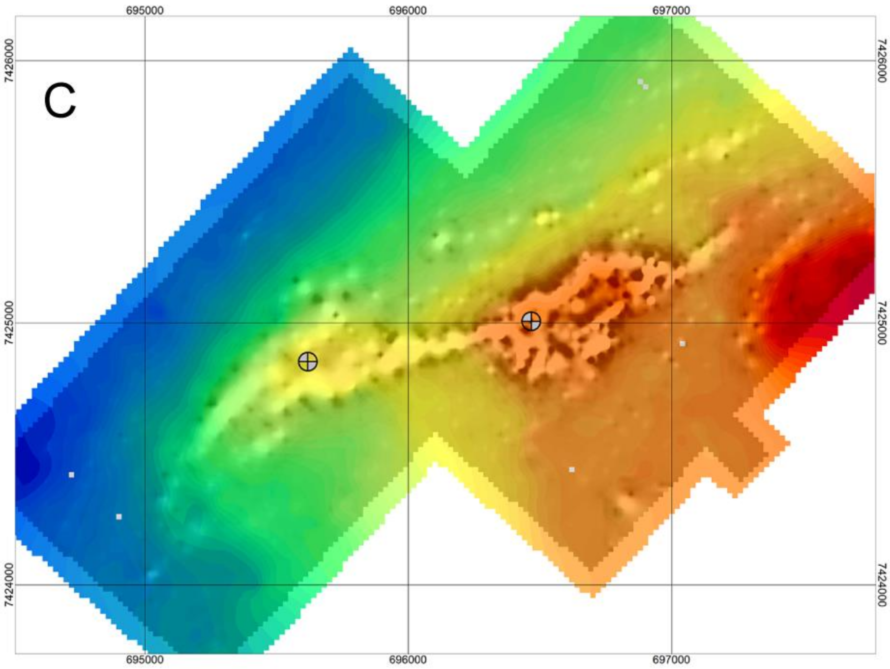


Figure 11. Geophysical results from the ground measurements at Åkosjegge, location of boreholes visualised as circles. **A.** Magnetic anomalies, vertical field. **B.** Gravity field. **C.** (next page) Combined magnetic- and gravity field. Vertical derivative magnetic field shown in grey shades beneath and gravity field on top in colour. Grid in SWEREF99TM.



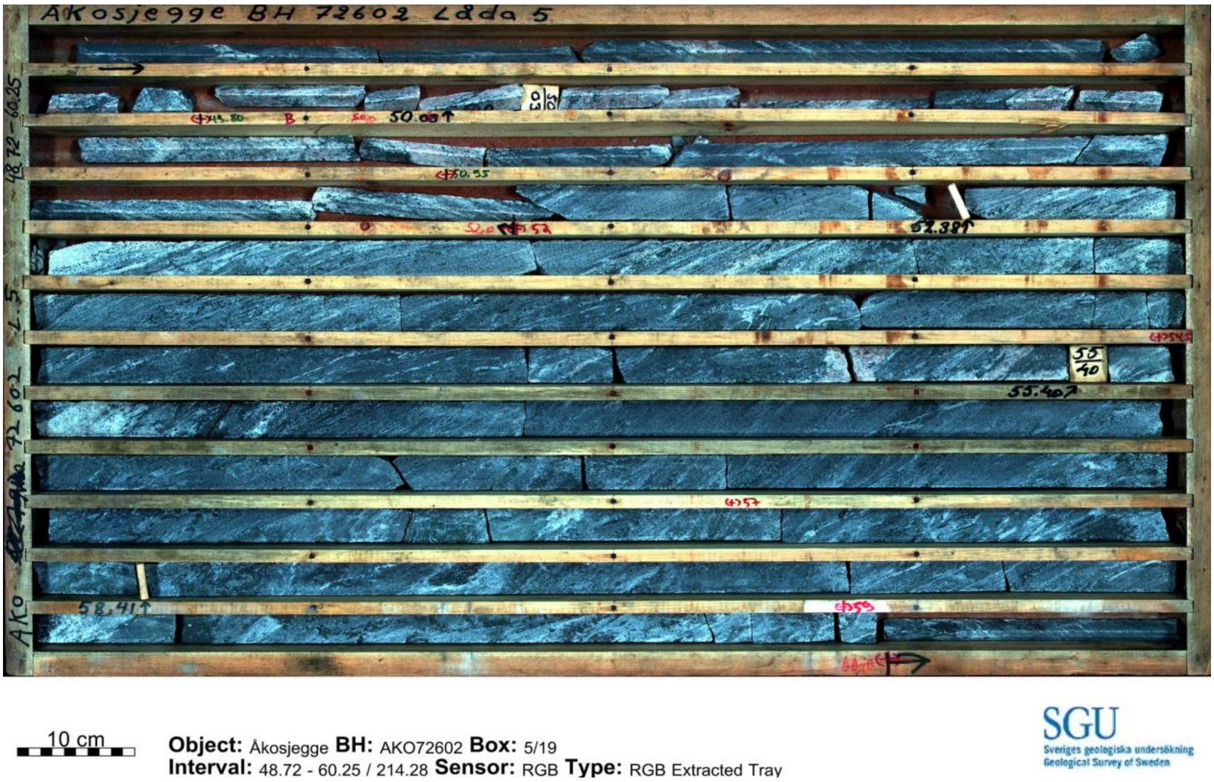


Figure 12. High-resolution photo of core box BH72602-5 from the Åkosjegge iron ore deposit, depth c. 49 to 60 m.

DISCUSSION

Several competing ideas of how Kiruna-type apatite iron oxide deposits may form exist and a consensus is far from attained in each case. Today the most endorsed models for the Kiruna-type apatite iron ore deposits are a magmatic origin (e.g. Jonsson *et al.* 2013; Nyström *et al.* 2016), a magmatic-hydrothermal origin (e.g. Dare *et al.* 2015), or a combination of the two (e.g. Knipping *et al.* 2015a, b). Other studies invoke the possible influence from hydrothermal systems originating from intrusions in the vicinity of an iron ore (e.g. Westhues *et al.* 2017). Recent research suggests possible transportation of metals on vapour bubbles in magmas (e.g. Mungall *et al.* 2015) and that the temperature at which iron-phosphorus ore liquids might exist is lower than earlier thought (Zhang *et al.* 2011) and thus expand the possibility of an extrusive origin.

A volcanic and possibly subaerial origin for the Kallak iron ore is advocated in this paper. The interpretation of the results from the investigations is that the iron ore was deposited in a volcanogenic environment, rather than in a sedimentary environment with a previously proposed relationship to quartz-banded iron ores, (e.g. Frietsch 1963, 1997). During the recent mapping project by SGU (Claeson & Antal Lundin 2019b), the quartz-banding that Frietsch (1963, 1997) mentions, was neither observed in outcrops nor in recently drilled cores available to us. Neither is quartz bands ever mentioned in the drill protocols from the 1940's and 50's, whereas banding related to the appearance of the ore or the volcanic rocks is frequently noted (Eriksson BRAP83801). The obsolete term "leptite" is used in the drill protocols for severely altered volcanic rocks, and sometimes the logger refers to magnetite ore banded with leptite or leptite with magnetite-rich banding. Recently, Martinsson *et al.* (2016) postulated that the Kallak deposit is a banded iron formation (BIF), but nothing in the data that have been presented here or our interpretation of the ore genesis even suggests that the ore remotely resembles a classic banded iron formation. There are no occurrences of chert present in any outcrops, trenches, pits, or drill cores. Ödman (1957) stated: "Of the ore material's origin can nothing with certainty be spoken. The ore environment is volcanic – the leptite in the area are interpreted as tuffitic rocks – and it seems likely that iron was precipitated from the volcanic thermal water". Frietsch (1997) related the ores in the study area to "In the intermediate-felsic volcanic rocks of the c. 1.9 Ga old Porphyry Group in the region west and north-west of Jokkmokk and south-west of Malmberget, there are quartz banded iron ores of volcanogenic origin". The felsic components of bands and laminae found within the iron ore, clearly visible in thin section (fig. 6A), consists of quartz trachyte rather than quartz-rich sediments or chert. This feature is also observed in parts of the rock surface exposed by the exploration trenches (fig. 5C, D, F). It is also clearly seen in the photographed and scanned drill cores (fig. 9 and 10). These observations suggest that the ore genesis should be interpreted as syngenetic or diplogenetic along with the volcanic host rocks (cf. Lovering 1963; Claeson & Antal Lundin 2019b).

Work on younger iron deposits, at e.g. El Laco in Chile (age Plio-Pleistocene, e.g. Nyström *et al.* 2016), Cerro de Mercado in Mexico (30 Ma old, Lyons 1988), and Zhibo in China (320 Ma old, Zhu *et al.* 2009, Zhang *et al.* 2012), documented rocks that show none, minor or much less metamorphic overprinting and deformation than those at the Kallak deposit. These younger deposits are interpreted to be syngenetic, where e.g. vesicular iron ore, subaerial lava flows and ash deposits made up of mostly magnetite and martite occur. Earlier work on El Laco which is considered an enigmatic deposit, have invoked a volcanic genesis with liquid immiscibility (e.g. Nyström & Henríquez 1994; Naslund *et al.* 2002), magmatic-hydrothermal replacement (e.g. Sillitoe & Burrows 2002), hydrothermal precipitation IOCG-style (e.g. Barton 2014; Dare *et al.* 2015), and a combination of igneous and magmatic-hydrothermal processes (Knipping *et al.* 2015a, b) to explain, e.g. the vesiculated "magnetite lava flows" at the El Laco. The recent findings of magnetite spherules in parts of pyroclastic iron ore at El Laco is yet another finding suggesting that an extrusive volcanic petrogenesis for iron ore is conceivable (Nyström *et al.* 2016).

The iron ore at Cerro de Mercado, Durango, Mexico shows alteration associated with the iron deposit but not in the above laying subaerial volcanic rocks (Lyons 1988). The conclusion is that the iron deposit itself consists of rocks produced by a variety of subaerial volcanic processes: eruption of iron magma flows, iron oxide ignimbrite, ashes of magnetite-hematite, and subvolcanic intrusive rocks of iron magma (Lyons 1988). The tectonic setting of the Cerro de Mercado is a continental arc setting (e.g. Camprubí 2013).

The Zhibo syngenetic volcanogenic iron deposit in China is ascribed to have formed during a late Palaeozoic subduction process (Zhang *et al.* 2012). Recent research on the Fe_2O_3–P_2O_5 system shows significantly lower liquidus temperatures than early work from the 1930's suggests and the presence of liquids below 1000 °C (Zhang *et al.* 2011 and references therein). With an effective flux like H_2O, which is comparatively abundant in arc magmas, even lower liquidus temperatures might be possible. Furthermore, the probable high content of H_2O in arc magmas may facilitate formation of vapour bubbles that are suggested to be capable of transporting metals and sulphur even into the atmosphere (e.g. Mungall *et al.* 2015).

The iron deposit at Kallak is situated in highly deformed rocks and overprinted by metamorphism, where it is hard to envisage any primary features with accuracy. Nevertheless, the fine-laminated and banded occurrence of magnetite and volcanic rock seen at several locations and in drill-cores suggest a syngenetic volcanic process, if not even subaerial in character (fig. 5, 6, 9). The ancient tectonic setting should have been that of the modern equivalents mentioned above, i.e. subduction-related magmatism in a continental arc, since that is what is advocated for the volcanic rocks that surround the deposit (Claeson & Antal Lundin 2019b).

CONCLUSIONS

The Kallak iron ore deposit is stratiform-stratabound and formed in a volcanogenic setting, possibly due to subaerial processes. It is coeval with Kiruna-type apatite iron deposits of northern Sweden. The quartz trachyte host rock is similar to several other acid to intermediate volcanic host rocks of iron ore deposits in the region. This contrasts with earlier interpretations that had the deposit described as a quartz-banded sedimentary/volcanic ore or a chert-bearing banded iron formation. The study has implications for the distribution of stratiform-stratabound volcanogenic iron ore deposits within the Svecokarelian units of northern Sweden.

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