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PETROPHYSICAL AND ROCK MAGNETIC STUDIES TO AID AU EXPLORATION – CASE STUDIES FROM THE HÄME BELT, SOUTHERN FINLAND

by

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Petrophysical, rock magnetic and anisotropy of magnetic susceptibility (AMS) measurements have been carried out on a porphyry type Cu-Au deposit in Kedonojankulma, on an orogenic gold deposit in Uunimäki and on the exploration target of Mäyrä in the Palaeoproterozoic Häme belt of Southern Finland. The mineralizations occur in strongly altered and sheared zones. The main aim of the laboratory studies has been to identify and characterize ore-related alteration processes that are reflected in the physical properties of rocks. The studies have focused on magnetic properties and the identification of magnetic minerals using rock magnetic tests. Magnetic mineralogy was verified by SEM studies.

In the Kedonojankulma quartz-plagioclase porphyrite occurrence, the induced and remanent magnetizations are slightly higher in the altered auriferous shear zone than in the less altered host rock. In the altered zone, the only magnetic mineral is monoclinic pyrrhotite with a high Curie temperature, while in the host rock the main magnetic mineral is ilmenite with minor magnetite.

In the Uunimäki gabbroic occurrence, the highest magnetization values correlate with strong IP anomalies, the magnetization being carried by monoclinic pyrrhotite with a high Curie temperature. In the more weakly magnetized rocks, the magnetization predominantly resides in ilmenite. In the strongest IP anomaly area, which is also regarded as the most gold bearing, the remanent magnetization also has strong intensity, and a Svecofennian age remanence could be isolated. The result thus suggests that provided that gold and pyrrhotite are contemporaneous at the site, the gold is post-tectonic.

Based on AMS data, the magnetic foliation planes follow the general foliation structures in both formations, although the degree of anisotropy varies considerably.

In the Mäyrä occurrence, the magnetization of the shear zone has decreased due to hydrothermal alteration. The surrounding gabbros, whether coarse-grained dark gabbro or fine-grained lighter coloured gabbro, contain magnetite as the main magnetic mineral, while the shear zone also contains pyrrhotite in addition to magnetite.

Keywords (GeoRef Thesaurus, AGI): paleomagnetism, magnetic properties, magnetic susceptibility, magnetization, petrophysics, magnetic minerals, gold ores, mineral exploration, Häme Belt, Proterozoic, Paleoproterozoic, Finland

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INTRODUCTION

Petrophysical laboratory measurements of mineralized and barren rock samples have been carried out at several locations in the Palaeoproterozoic Häme belt of southern Finland (Fig. 1). The study areas were selected utilizing airborne geophysical data. Most systematic and detailed sampling was carried out across hydrothermal alteration zones in the porphyry type Cu-Au deposit in Kedonojankulma, in the orogenic Au deposit of Uunimäki and the exploration target of Mäyrä, the results of which are described in this paper.

The main aim of the study was to identify and characterize alteration processes that are reflected in the physical properties and especially in the magnetic properties of the rocks during the mineralization processes. Circulation of hydrothermal fluids and consequent fluid–rock interaction can significantly modify the physical properties of ore-bearing deposits. These processes typically also produce compositional and textural changes in ferromagnetic minerals, which can be studied and quantified by using magnetic methods. Therefore, in addition to basic petrophysical properties (density, magnetic susceptibility and remanence), rock magnetic tests were carried out to identify the magnetic minerals and their grain sizes, which also have relevance to the stability of remanence.

Palaeomagnetic studies were conducted for some of the study objects to delineate the timing for the alteration process. AMS (anisotropy of magnetic susceptibility) studies were carried out to characterize the fabrics of the occurrences. As the known ore bodies are related to alteration zones and because detailed petrophysical investigations at the outcrop scale can delineate differences between ore and host rocks, the studied petrophysical properties have relevance to exploration.

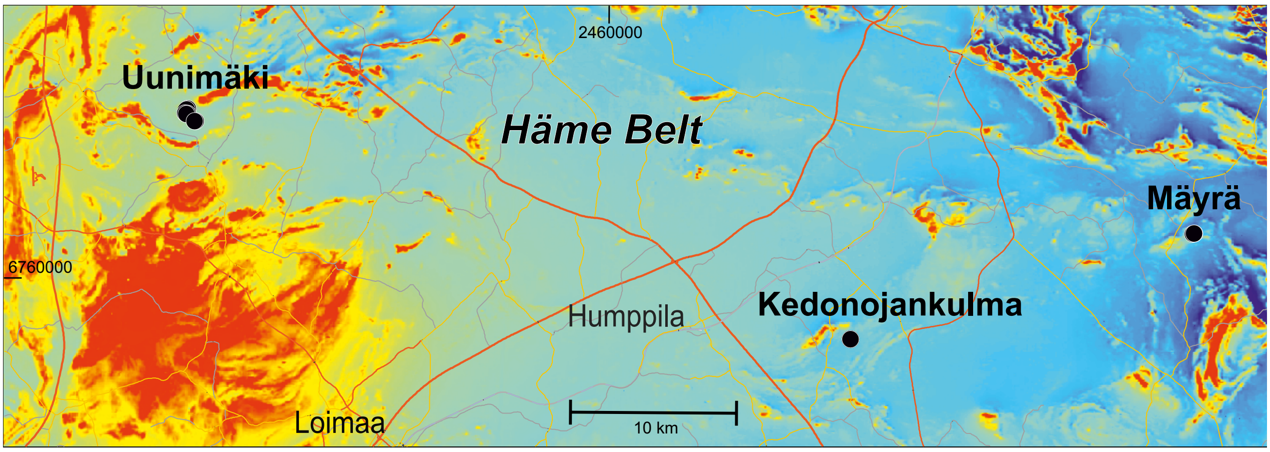

Fig. 1. Aeromagnetic map of the Häme belt showing the study areas. The studied sites are indicated by black circles and comprise Mäyrä (sites 1–3), Kedonojankulma (sites 4–10) and Uunimäki (sites 16–25).

GEOLOGICAL BACKGROUND

The bedrock of southern Finland was formed during the Svecofennian orogeny at 1.9–1.8 Ga, involving several collisional and metamorphic stages that produced different types of ore formations. The studied formations occur in the Häme belt, where the age of magmatic activity is in general 1.88 Ga (Saalmann et al. 2009), and the last active orogenic evolution took place at ca. 1.79 Ga (Lahtinen et al. 2005). The ore formations can be either syngenetic or later than the earliest deformation, but in any case their formation precedes the youngest brittle deformation at 1.79 Ga (see Eilu et al. 2012 for references).

The main study objects comprised the Kedonojankulma porphyry type Cu-Au deposit hosted by the subvolcanic quartz-plagioclase porphyritic phase of a tonalitic intrusion (Tiainen et al. 2012) and the Uunimäki orogenic gold deposit hosted by shear zones in a metamorphosed gabbro (Grönholm and Kärkkäinen 2013). In addition, a potentially Au mineralized and strongly altered shear zone and host gabbroic rocks in the Mäyrä target were investigated.

The Kedonojankulma study area (Fig. 2) is located in the western part of the Svecofennian volcanic-intrusive Häme belt (Fig. 1). The Cu-Au occurrence is mainly located in a porphyritic tonalitic intrusion and partly in the surrounding volcanic host rocks (Tiainen et al. 2012, 2013). The granitoids surrounding the Kedonojakulma occurrence represent volcanic arc type granitoids. The size of the occurrence is about 1.5 x 0.5 km. The highest Cu-Au contents occur in a strongly altered and sheared quartz-plagioclase porphyritic phase of the tonalitic intrusion, in the Rusakkokallio outcrop (Fig. 2), where the quartz-plagioclase porphyry is cut by a network of thin quartz veins. The main ore mineral is chalcopyrite and the main magnetic mineral is pyrrhotite (Tiainen et al. 2012).

The Uunimäki gold prospect of the age of ca. 1.88 Ga in the Häme belt (Fig. 1) is hosted by shear and fault zones within a heterogeneous gabbro intrusion that is metamorphosed but only weakly deformed outside the shear zones (Grönholm and Kärkkäinen 2013). The gabbro is typically fine or medium grained. One gabbro type contains uralite phenocrysts (as remnants of igneous clinopyroxene) within fine-grained groundmass and one type is equigranular. A network of thin cross-cutting quartz veins occurs at some outcrops. Typical ore minerals include locally abundant pyrrhotite, and minor chalcopyrite, arsenopyrite and ilmenite. The Au-critical area correlates with a distinct IP anomaly that was used as the basis of petrophysical sampling. In the gravimetric maps, the geochemically gold potential NW–SE-trending zones appear to be related to gravity minima (Vuori et al. 2007). Gold-critical major shear and fault zones are also recognized in aeromagnetic maps as diffuse non-magnetic and locally gently curving lineaments.

The Mäyrä target in Hämeenlinna has not been extensively studied, but it is important as it is located in a notable till geochemical anomaly area observed in recent mapping by GTK in the Häme belt (Fig. 1) (Huhta 2013, 2014). The main rock types are a coarse-grained gabbro and a more fine-grained gabbro, the latter possibly being an inclusion in the coarse-grained rock. Both gabbro types are cut by a shear zone that might be related to hydrothermal alteration associated with the geochemical Au anomaly in the region. The main sulphide minerals are pyrrhotite and arsenopyrite.

SAMPLING, INSTRUMENTS AND METHODS

Samples were taken with a portable Pomeroy minidrill and oriented with the sun and a magnetic compass. The diameter of samples was 2.5 cm and the length ca. 6 cm. In addition to oriented core samples, oriented and un-oriented hand samples were taken from some sites for petrophysical measurements.

At Kedonojankulma (Fig. 2), samples were taken from five sites (sites 4–8). Sites 4–6 in Rusakkokallio are located close to each other in an outcrop area of about 50 x 10 m. They comprised the subvolcanic quartz-plagioclase porphyritic phase of the tonalitic intrusion that hosts the Cu-Au occurrence (Tiainen et al. 2012). At site 4, five samples were taken from the least altered quartz-plagioclase-porphyry. At site 5, five samples were taken from the more altered quartz-plagioclase-porphyry and at site 6 (close to site 5), seven samples were taken across a profile of an altered rusty shear zone. Sites 7 and 8 are located about 200 m apart from each other in Passi (Fig. 2). At site 7, the rock type is tonalite with sporadic epidote inclusions. Four core samples were taken from unaltered tonalite (samples 7a, Fig. 3) and three from epidotized and sheared inclusions in the tonalite (samples 7b, Fig. 3). At site 8, a contact between tonalite and quartz-plagioclase-porphyry is clearly visible. Three oriented hand samples were taken from the tonalite (samples 8a, Fig. 3) and three samples from the quartz-plagioclase-porphyry (samples 8b, Fig. 3).

Sampling of gabbro at Uunimäki (Fig. 14) was planned by utilizing the IP anomaly map in order to constrain the physical properties of rocks of the lowest and highest anomaly, the latter one suggested to be related to the Au occurrence. A profile across the IP anomaly, comprising 8 sites, was sampled. In addition, two sites with a weaker IP anomaly outside the profile were sampled. Approximately 5 oriented core samples were taken at each site. In addition, petrophysical measurements were carried out on three borehole cores (M211109R314, M211109R315 and M211109R316) that were also geochemically analysed (Labtium Oy) in the course of ore potential investigations.

The exploration target Mäyrä comprises gabbroic rocks and was sampled at three sites (sites 1–3). At site one, nine oriented samples were taken across a profile over a shear zone. The width of the profile was 10 m and the most altered central part of the shear zone is about 10 cm broad (samples 1.3.–1.4). The main rock type is black coarse-grained gabbro (samples 1.1, 1.2, 1.7, 1.8 and 1.9), but the other side of the most altered zone is bordered by a band where the gabbro has a lighter colour and is more fine grained (samples 1.5 and 1.6). Corresponding to site one, coarse-grained gabbro and lighter fine-grained gabbro were sampled at two other sites (sites 2 and 3, respectively) outside the profile.

In the laboratory, samples were processed into standard cylinders (height 2.5 cm, diameter 2.1 cm). The principal petrophysical parameters measured before the palaeomagnetic and AMS measurements were magnetic susceptibility (applied field intensity of 130 A/m), electrical conductivity and density. Remanent magnetization was measured with a 2G-RF SQUID magnetometer. Alternating field and thermal demagnetizations, coupled with SQUID measurements, were applied to some of the samples. Anisotropy of magnetic susceptibility (AMS) was measured with an Agico KLY-3 kappabridge (applied field intensity of 300 A/m). Determinations of magnetic mineralogy comprised thermomagnetic analyses in an Ar atmosphere with a KLY-3/CS-3 device. Three component IRM measurements, so-called Lowrie tests (Lowrie 1990), were carried out with a Molspin pulse magnetizer, coupled with thermal demagnetizations and measurements with SQUID or GTK-built spinner magnetometers. In the Lowrie test, the sample is subjected to three different high magnetic fields (1.5 T, 0.4 T and 0.12 T) along the z-, y- and x-axes of the sample, respectively. The sample is subsequently heated to increasing temperatures (typically up to 680°C). The measurements give information on the magnetic minerals, their grain sizes and magnetic domain states (see Mertanen and Karell, 2009, 2011 for a detailed description of the method). Three Lowrie test measurements were carried out at the Solid Earth Geophysics Laboratory of the University of Helsinki (by Dr Johanna Salminen), where the thermal demagnetizations could be performed in an Ar atmosphere and the remanence measurements were carried out with a 2G-DC SQUID magnetometer.

RESULTS AND DISCUSSION

Mean petrophysical properties of all three study areas are presented in Table 1.

Kedonojankulma

Sites 4–6, Rusakkokallio

Figure 2 illustrates the locations of the sampling sites on an aeromagnetic map, which evidences the very low magnetization of the Kedonojankulma deposit. Sites 4–6 are from the Rusakkokallio quartz-plagioclase porphyry, with the highest Cu and Au contents, and sites 7–8 from the Passi area, where the outcrops are tonalite and plagioclase-quartz porphyry with low Cu and Fe. Figure 3a presents the susceptibility – density plot, and Figure 3b the susceptibility – Q-value plot of the Kedonojankulma samples. The Q-value is the relationship between the remanent magnetization and the induced magnetization, and reflects the dominance of remanence if the value is over 1.

The quartz-plagioclase porphyries at the Rusakkokallio site are typically weakly magnetized (Figs 3a and 3b). At the Rusakkokallio site 4, with the least altered quartz-plagioclase-porphyry, the magnetic susceptibilities and remanence intensities are generally lower compared to the more altered rocks of the auriferous shear zone of sites 5 and 6. In the shear zone, the overall susceptibilities and remanence intensities and, consequently, the Q-values are slightly increased due to increased amounts of pyrrhotite. The Q-values are highest within the shear zone, indicating the dominance of remanent magnetization over induced magnetization. The altered rocks (sites 5 and 6) show

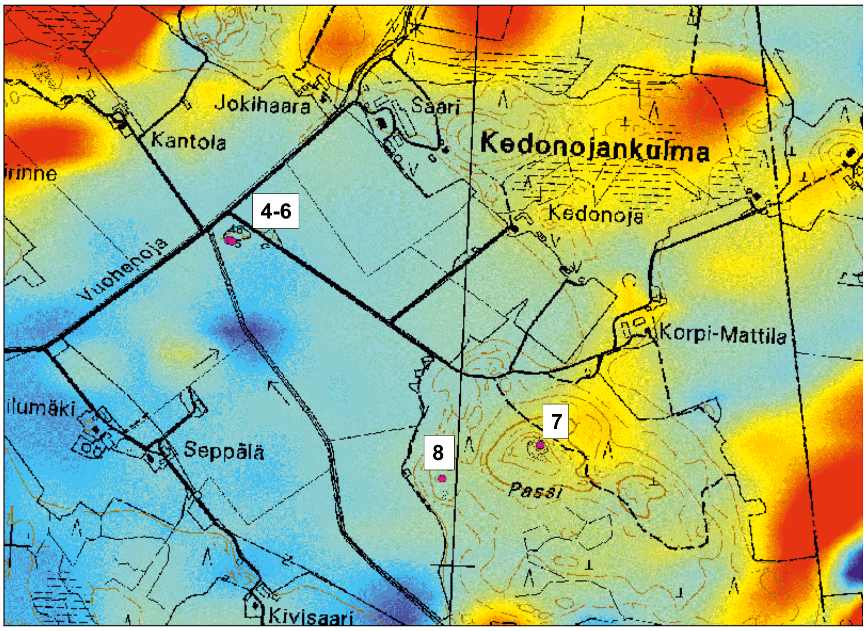

Fig. 2. Sampling sites in Kedonojankulma shown on an aeromagnetic map. Sites 4–6 are in Rusakkokallio and sites 7 and 8 in Passi. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

Table 1. Mean petrophysical properties of the studied rocks

Site	Rock type	Comment	x	y	n	Density	Suscept.	Reman.	Q
						kg/m^3	$x\ 10^{-6}$	mA/m	
Kedonojankulma									
4	Q-plg-porph.	Least alt.	6761604	3311775	6	2655	154.0	1.0	0.17
5	Q-plg-porph.		6761606	3311781	6	2679	321.5	63.9	3.23
6	Q-plg-porph.	Shear zone	6761602	3311785	9	2676	214.0	41.8	3.93
7A	Tonalite		6761142	3312482	5	2735	571.0	3.7	0.13
7B	Tonalite	Epidote	6761142	3312482	3	2801	5526.7	46.3	0.22
8A	Q-plg-porph.		6761066	3312260	16	2660	695.1	19.5	1.85
8B	Tonalite		6761066	3312260	8	2742	1910.1	45.6	0.35
Uunimäki									
16	Granodiorite		6774778	3273855	14	2775	395.1	3.6	0.23
17	Gabbro		6774732	3273788	13	2904	775.5	105.6	2.92
18	Gabbro		6774680	3273773	11	3006	845.6	5.1	0.15
19	Gabbro		6774650	3273758	12	3082	1050.8	3.9	0.03
20	Gabbro		6774603	3273758	14	3007	887.6	21.2	0.03
21	Gabbro		6774532	3273696	11	2899	632.5	0.5	0.03
22	Uralite porph.		6774510	3273832	12	3022	975.6	689.4	14.73
23	Gabbro		6774489	3273772	14	2955	740.9	0.9	0.03
24	Gabbro		6774074	3274308	13	3012	759.3	2.8	0.09
25	Gabbro		6774080	3274233	12	3002	823.5	0.9	0.03
Mäyrä									
1	Gabbro	Coarse gr.	6767616	3331387	10	3002	4056.8	260.4	1.39
1	Gabbro	Shear zone	6767616	3331387	3	2963	769.3	0.9	0.03
1	Gabbro	Fine gr.	6767616	3331387	4	2938	1278.0	26.0	0.48
2	Gabbro	Coarse gr.	6767640	3331467	10	2999	7567.2	1496.3	5.84
3	Gabbro	Fine gr.	6767638	3331456	11	2902	1035.2	19.3	0.45

Note. *Site gives the site number, Q-plg-porph. is quartz-plagioclase porphyry, x,y are the coordinates of the site, n is the number of specimens. Suscept. is the magnetic susceptibility, Reman. is the remanence, Q is the Königsberger ratio (the ratio of the remanent magnetization to the induced magnetization). In Kedonojankulma, the sites in Passi are divided according to the visible occurrence of epidotic inclusions at site 7B and according to rock type at site 8.*

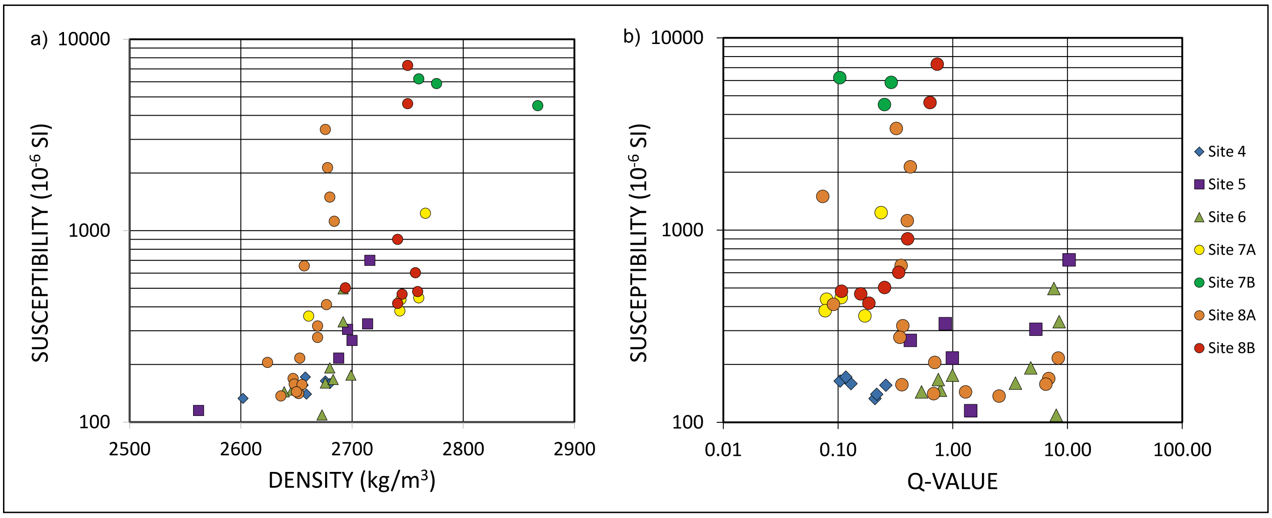

Fig. 3.a) Susceptibility – Density plot, b) Susceptibility – Q-value plot of the Kedonojankulma samples.

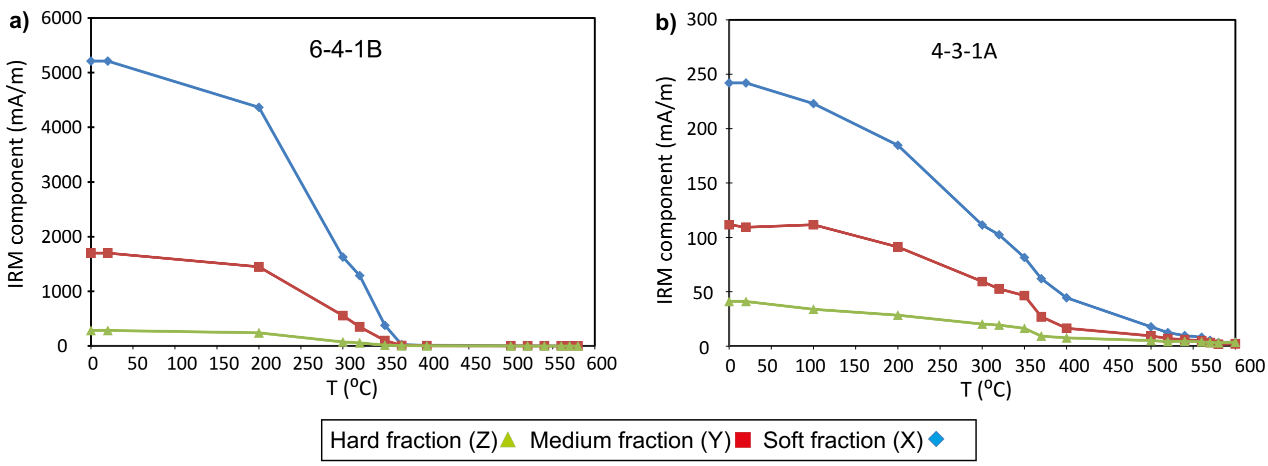

Fig. 4. Three-axis isothermal magnetization (Lowrie test) of sample 6-4-1B from the Rusakkokallio shear zone. Magnetizations were produced along three orthogonal directions: the Z component in magnetizing field 1.5 T, the Y component in field 0.4 T and the X component in field 0.12 T. a) Only pyrrhotite, with an exceptionally high Curie temperature of 350 °C, occurs, b) Lowrie test of sample 4-3-1A from the least altered plagioclase-quartz porphyry at the Rusakkokallio site. Both pyrrhotite and magnetite with unblocking temperatures of about 560 °C occur.

considerable internal variation in magnetic properties, which reflects the varying content of magnetic material in the rock. On the whole, the magnetic properties at Rusakkokallio have somewhat increased due to alteration. Densities are not markedly affected by the alteration, as both the unaltered and most altered rocks have the same approximate densities of ca. 2670 kg/m³.

At the Rusakkokallio sites, the typical magnetic mineral is monoclinic pyrrhotite with an exceptionally high Curie temperature of ca. 370 °C (Fig. 4a, specimen 6-4-1B). The typical Curie temperature of ferrimagnetic monoclinic pyrrhotite is 320 °C, and a disordered lattice structure or impurities in the lattice were therefore considered as the source of high temperatures. According to SEM studies, however, the pyrrhotite does not contain impurities, but the composition at Rusakkokallio is typical for monoclinic pyrrhotite.

The explanation for the observed Curie temperature remains unresolved. Lowrie test measurements, including thermal demagnetizations in an argon atmosphere at the University of Helsinki, also give high Curie temperatures. As shown below (see the results for the Uunimäki deposit), the high Curie temperature of pyrrhotite seems to be a common phenomenon in the studied formations. The sheared rocks of site 6 do not contain other magnetic minerals than pyrrhotite. In addition, chalcopyrite and ilmenite are observed optically in SEM images (Fig. 5), but they do not contribute to the magnetization properties of the rock. In the unsheared rock of site 4, pyrrhotite also has a high Curie temperature of 370 °C. In these rocks, pyrrhotite occurs together with small amounts of magnetite (Fig. 4b, specimen 4-3-1A) or more probably ilmenite (see discussion on Uunimäki). The results thus suggest that shearing was accompanied by reducing fluid flow that produced pyrrhotite at the expense of magnetite/ilmenite. The gold and/or copper were probably formed in the same process.

At sites 4–6, electrical conductivities were in general very low, except for few samples from sites 5 and 6, where the conductivity was increased due to an excess of pyrrhotite. This result is in agreement with ground IP surveys, which have revealed an increased IP anomaly in the sheared area in Rusakkokallio (Tiainen et al. 2012).

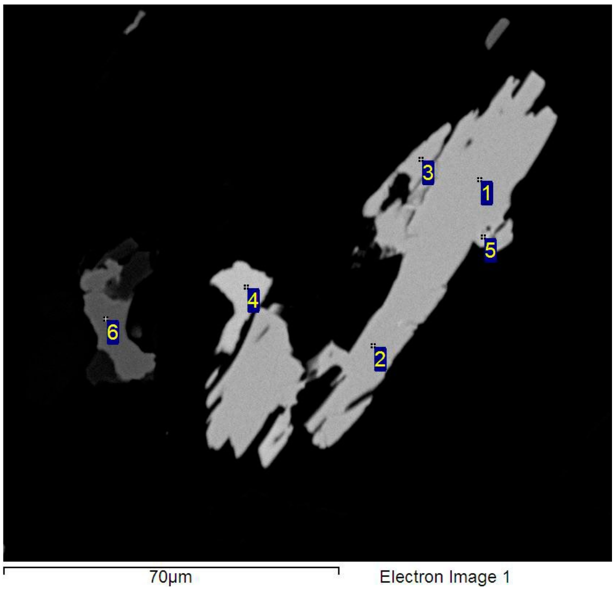

Fig. 5. SEM image of sample 6-1-1A from the shear zone in Kedonojankulma. 1-3 = pyrrhotite, 4 = chalcopyrite, 6 = ilmenite.

For palaeomagnetic studies, some of the samples were demagnetized in order to obtain the characteristic remanent magnetization component that could give information on the relative age of the shearing and mineralizing fluid event. However, the directions of remanence were found to be scattered at each site, and palaeomagnetic data could not therefore give further information on the timing of mineralization. The scatter of directions may indicate that the fluid flow was followed by or was contemporaneous with shearing, which randomized and destroyed the original remanence directions.

Sites 7–8, Passi

At Passi (Fig. 2), some of the plagioclase-quartz porphyries have similar magnetic properties to those at sites 5 and 6 of the sheared Rusakkokallio plagioclase-quartz porphyries; the low susceptibility and higher Q-value (over 1, Site 8A, Table 1) also indicate the dominance of pyrrhotite in these rocks. In some of the samples, the susceptibilities are significantly higher due to magnetite, which occurs together with only small amounts of pyrrhotite (Table 1). For example, sample 8-1-2A (Fig. 6a) has a high susceptibility value of 1500 x 10^{-6} SI compared with the mean value (695 x 10^{-6} SI) of the site (site 8A, Table 1). The magnetic mineralogy of these samples from Passi (Fig. 6a) resembles the unsheared plagioclase-quartz porphyry samples of the Rusakkokallio site 4 (Fig. 4b, site 4, Table 1), although the susceptibility values (site 8A, Table 1) are higher due to a higher amount of magnetite. The pyrrhotite has a similarly high Curie temperature of ca. 370 °C as at the Rusakkokallio sites. The magnetite-bearing tonalite (Fig. 6b) carries the highest susceptibility values (sites 7A, 7B and 8B, Table 1), consistent with aeromagnetic data. In the epidotized inclusions, the magnetization values and densities are the highest, which can also affect the aeromagnetic anomaly pattern. In two specimens of one tonalite hand sample, the magnetization values are significantly high, which reflects the unhomogeneity of the rock.

According to AMS data (Fig. 7) the magnetic foliations at Rusakkokallio strike almost vertically along the general NE–SW trend of shearing, and magnetic lineations plunge moderately to the SW. The Rusakkokallio samples have slightly lower anisotropy degrees (6–10%) than the samples from Passi (11–13%). In particular, the least altered samples from Rusakkokallio (sites 4–5) are characterized by low anisotropy degrees accompanied by low magnetic susceptibilities. At Passi, the magnetic foliations dip steeply to the SE and the magnetic lineations plunge moderately to the S-SE. The shapes of AMS ellipsoids are predominantly oblate.

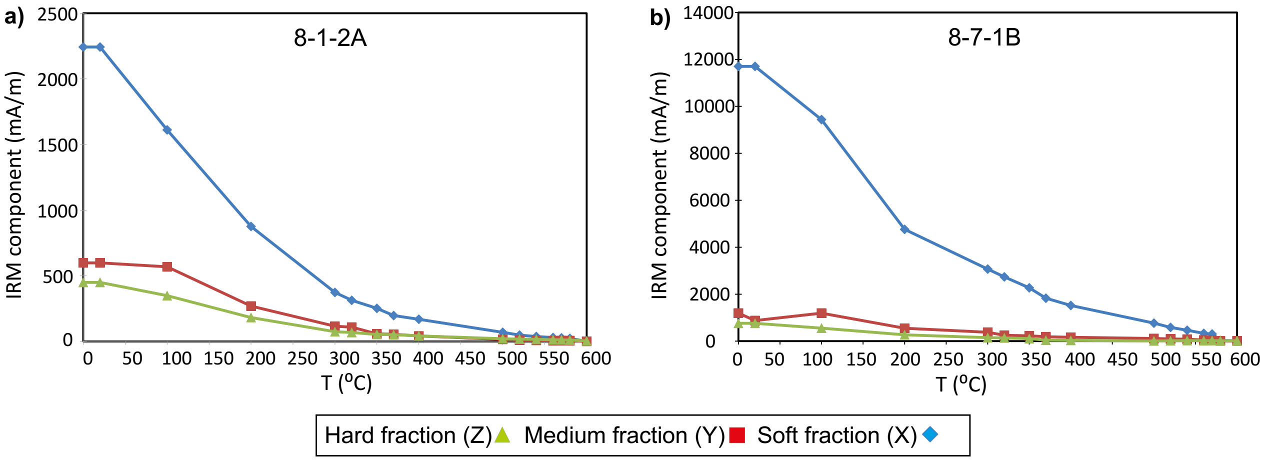

Fig. 6.a) Lowrie test of sample 8-1-2A from the plagioclase-quartz porphyry at the Passi site. Both pyrrhotite and magnetite occur. For explanations, see Fig. 4a, b) Lowrie test of sample 8-7-1B of tonalite at the Rusakkokallio site. The main ferromagnetic mineral is coarse-grained magnetite, shown as a dominance of the low coercivity x-phase.

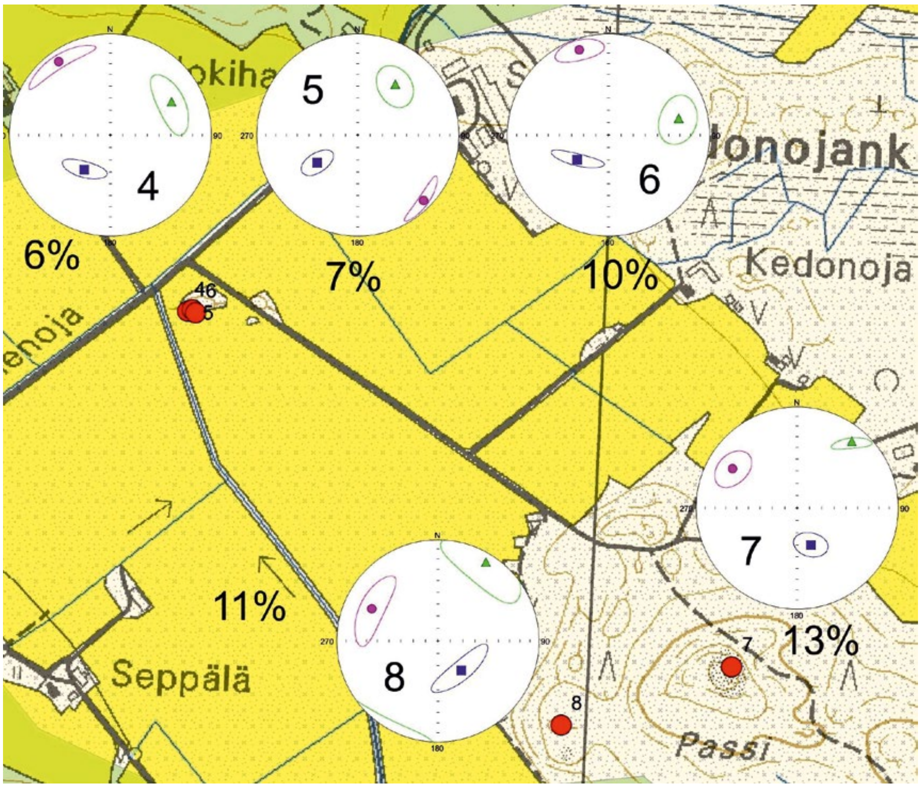

Fig. 7. AMS data from Kedonojankulma. The anisotropy degree (P') is shown as percentages for each site (numbers 4–8). The mean AMS directions of the principal axes k1 (blue square), k2 (green triangle) and k3 (red circle) are shown with their α95 confidence ellipses. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

Uunimäki

The Uunimäki gabbro is characteristically weakly magnetized (Fig. 8). On the aeromagnetic map the deposit is within a NW–SE trending structure, where the total magnetization is only slightly higher compared with the surrounding granodiorite. The highest magnetization values and conductivities correlate with a strong IP anomaly (Fig. 14).

Sampling was carried out by utilizing the IP anomaly so that samples were taken outside the highest IP anomaly (sites 16, 21 and 23–25, Fig. 14) and within the highest anomaly area (sites 17–20 and 22). The susceptibility – density plot is presented in Figure 9a and the susceptibility – Q-value plot in Figure 9b.

Figure 9a presents a linear correlation between susceptibility and density, which mostly reflects the amount of magnetic minerals in the rocks. The susceptibilities are in general very low, below 1000 x 10^{-6} (SI), and for most samples the densities vary between ca. 2850 and 3050 kg/m^3. In general, susceptibilities below 1000 x 10^{-6} (SI) suggest that the samples do not contain significant amounts of ferromagnetic minerals. Exceptionally low values are seen in samples from site 16 of the surrounding granodiorite. Higher density and susceptibility values come from inside the high IP anomaly area due to increased amounts of pyrrhotite, as discussed below. Sites 17, 19 and 22 show the widest variation in magnetic properties and density, which probably reflects both the original compositional differences and the variation in the degree of alteration.

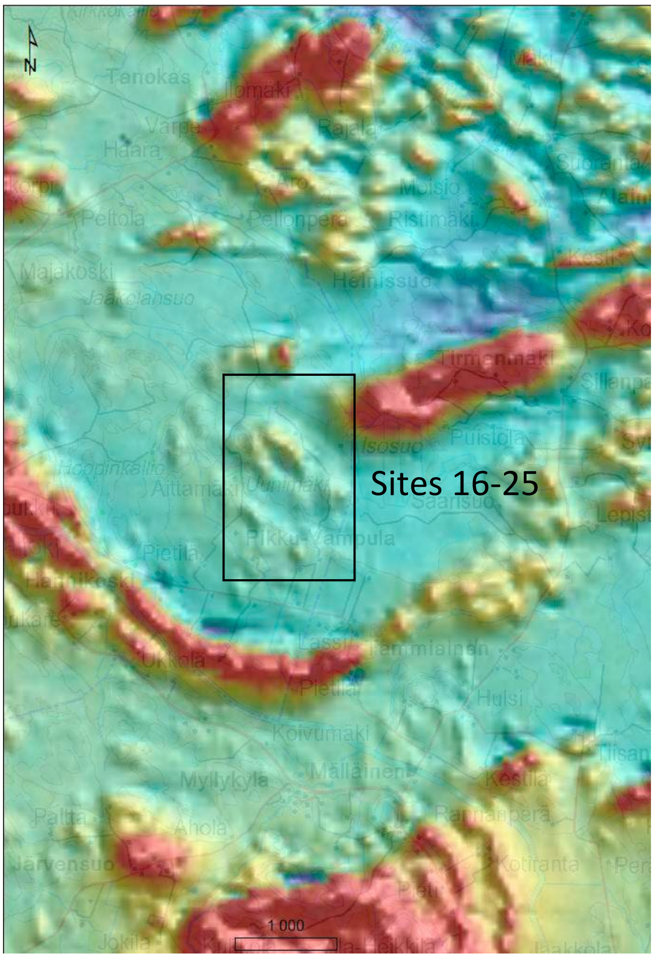

Fig. 8. An aeromagnetic map with the square showing the sampling area in Uunimäki. Detailed sampling sites are indicated in Fig. 14. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

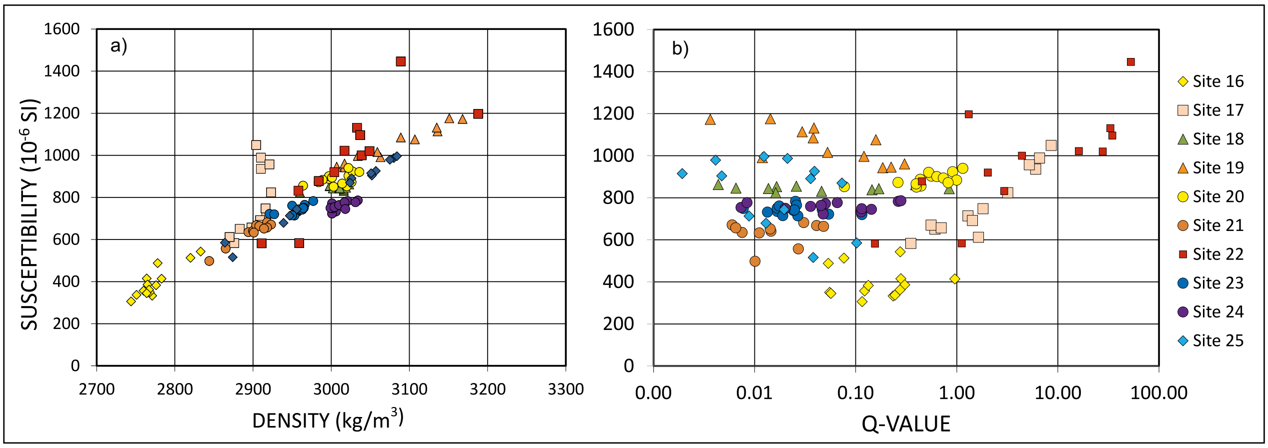

Fig. 9. Petrophysical properties of the Uunimäki deposit. a) Susceptibility – Density plot, b) Susceptibility – Q-value plot.

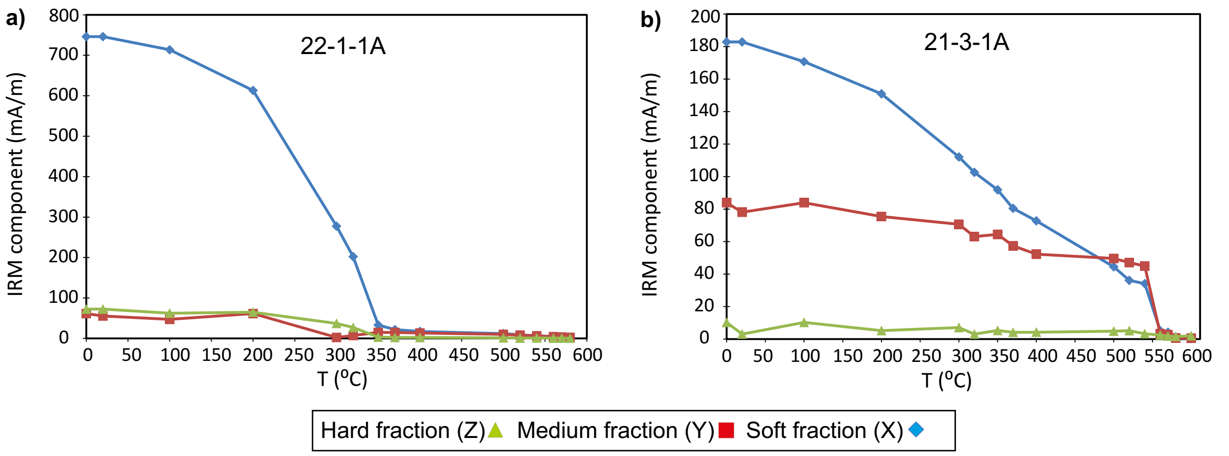

Fig. 10. Lowrie test of samples from the Uunimäki deposit. a) Sample 22-1-1 is from the highest IP anomaly and shows only coarse-grained pyrrhotite as the ferromagnetic mineral. b) Sample 21-3-1 is outside the highest IP anomaly and shows magnetite as the main ferromagnetic mineral. As discussed in the text, the magnetite may have been formed during laboratory heating.

The susceptibility – Q-value plot (Fig. 9b) illustrates that the intensities of remanent magnetization are typically below 1, indicating the dominance of induced magnetization over remanence. Only at sites 17 and 22 do the remanences dominate and show Q-values higher than 1. Site 22 is a fine-grained uralite porphyrite and has the highest magnetization values, in accordance with the highest magnetic (Fig. 8) and IP anomalies (Fig. 14).

According to Lowrie tests, the rocks with the highest IP anomaly carry monoclinic subordinate pyrrhotite with exceptionally high Curie temperatures of ca. 350–370 °C (Fig. 10a). The same high Curie temperatures were obtained from sites 17–18, 20 and 22. However, two samples from site 22 were studied with thermomagnetic curves (susceptibility versus temperature), and they show pure monoclinic pyrrhotite with a typical Curie temperature of 320 °C (Fig. 11). Likewise, according to SEM analyses of samples from sites 17 and 22 (Fig. 12), the observed pyrrhotite has a typical composition without impurities. These samples have corresponding high Q-values and susceptibilities (Fig. 9b), and both show high Curie temperatures for pyrrhotite.

Rochette et al. (1990) described an almost similar situation with an unexceptionally high unblocking temperature of 350 °C for monoclinic pyrrhotite in the Lower Jurassic schists. The origin of the high temperature was not resolved, but one explanation could be in the ordering of iron vacancies in the lattice of pyrrhotite. Zegers et al. (2003) also found high unblocking temperatures of up to 380 °C, and they suggested, based on studies by Graham et al. (1987), that small amounts of oxygen occur in the crystal lattice of pyrrhotite. As the origin of the high Curie temperature of pyrrhotite

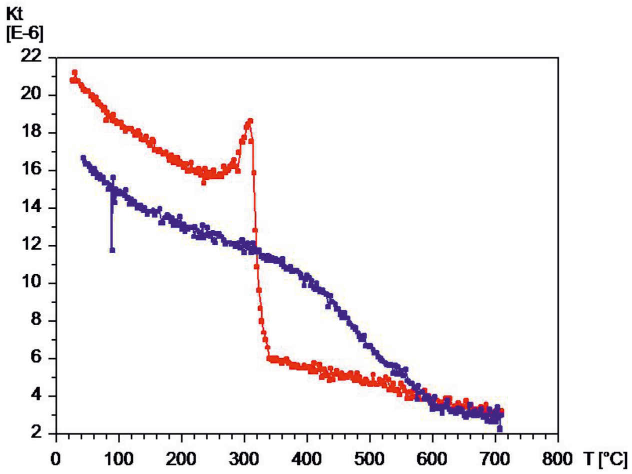

Fig. 11. Thermomagnetic curves showing magnetic susceptibility (μSI) vs. temperature (°C) for sample 22-4-1B from site 22. The red line denotes heating and the blue line is a cooling curve. The vertical axis is in arbitrary units, as the susceptibility is not corrected for actual sample volume. The heating curve shows a typical Curie temperature of 320 °C for pyrrhotite.

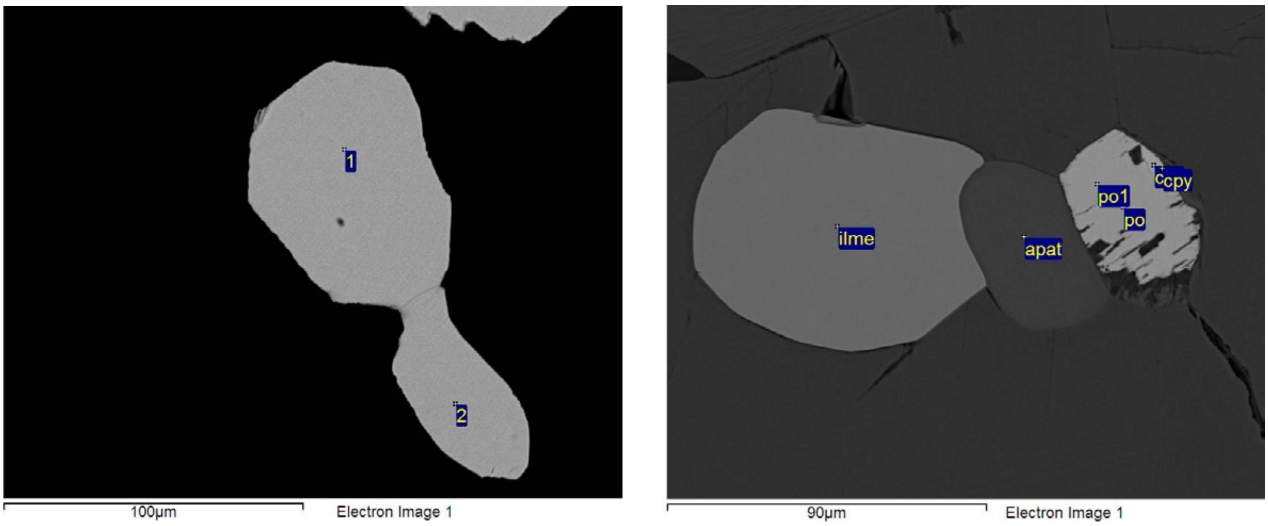

Fig. 12. SEM images from the Uunimäki deposit. a) uralite porphyritic gabbro from site 22 (sample 22-4-1B) showing solid grains of pyrrhotite (numbers 1 and 2), b) SEM image of gabbro from site 17 showing a large ilmenite grain in addition to apatite (apat) and intergrown pyrrhotite (po) and chalcopyrite (cpy).

in Uunimäki, and as shown before also in Kedonojankulma, was not resolved along this study, it should be studied more thoroughly in the future, as it may have some relevance to the occurrence of ore mineralogy. According to SEM studies, the sites of the highest IP anomaly also contain some ilmenite and chalcopyrite (Fig. 12).

The lowest magnetization values were found among weak IP anomalies (sites 16, 21 and 23–25, Fig. 14). According to Lowrie tests, these samples carry magnetite with an unblocking temperature of 560 °C (Fig. 10b, sample 23-2-1R). However, SEM studies indicate that the Fe oxide mineral is ilmenite (Fig. 12b, sample 17-1-1A). The occurrence of ilmenite instead of magnetite is supported by low susceptibilities (Fig. 9) and thermomagnetic curves that do not show Curie temperatures of magnetite. The Curie temperatures of magnetite in the Lowrie tests may be explained by laboratory heating, when mafic Fe-bearing silicate minerals or pyrrhotite have altered to magnetite. Therefore, this test is not suitable for these samples as such. It can be observed, however, that Curie temperatures of magnetite come only from the low IP anomaly areas whereas, the high IP anomaly area shows only pyrrhotite in the Lowrie and the thermomagnetic tests. In the weakly magnetic rock around the high IP anomaly, very small amounts of pure monoclinic pyrrhotite with a typical Curie temperature of 320 °C (Fig. 10b) were also revealed, in addition to ilmenite. Some of the samples also showed a very weak drop in intensity at 350–370 °C.

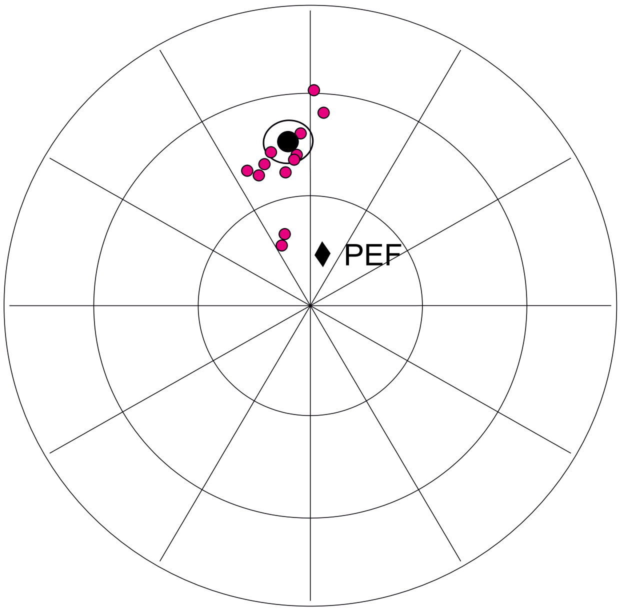

Fig. 13. Natural Remanent Magnetization (NRM) directions of samples from site 22, before AF demagnetization. The black circle with its α95 confidence circle shows the mean remanence direction after AF demagnetization of the samples. PEF shows the Present Earth's Field direction of the site.

The overall rock magnetic results from the Uunimäki gabbro thus indicate that the main ferromagnetic mineral in the unaltered rock outside the IP anomaly is ilmenite, with only a minor occurrence of pyrrhotite with the typical Curie temperature of 320 °C. In the highly altered rock with a high IP anomaly, pyrrhotite with a high Curie temperature of 350–370 °C is the dominant magnetic mineral. Whatever the reason for the high Curie temperatures, it is evident that the magnetic minerals within the high and low IP anomaly areas show clearly different behaviour. Provided that in the high IP area the gold mineralization and the dominating pyrrhotite are related and formed in the same process (Grönholm and Kärkkäinen 2013), it is possible that the high Curie temperature can be used to delineate the occurrence of gold.

Remanent magnetization directions were measured from each sample of the Uunimäki deposit. Due to deformation, the directions are typically highly scattered and no constant characteristic directions were obtained from the different sites. However, site 22 forms an exception. At this site, a consistent remanence direction was isolated, and it clearly deviates from the present direction of the Earth's magnetic field (PEF, Fig. 13). Figure 13 illustrates the remanence directions of all samples from the site before demagnetization. After alternating field demagnetization, a characteristic remanence direction was obtained from six specimens. The mean direction (declination = 352.1°, inclination = 43.9°, α95 = 6.3°, k = 115.6, n = 6 specimens) with its α95 confidence circle is presented in Figure 13. It was used to calculate a virtual geomagnetic pole (VGP) (Plat = 54.3 N, Plong = 215.1 E, dp = 4.9°, dm = 7.8°) for the site. The pole corresponds well to the poles obtained previously from late Svecofennian formations in the Fennoscandian shield (e.g. Mertanen and Pesonen 2012). The age of the magnetization is about 1800 Ma. The result is in accordance with proper isotope age datings that suggest a late Svecofennian age of 1.82–1.79 Ga for the gold mineralizing event in the Häme belt (Saalmann et al. 2009).

Provided that the remanent magnetization of site 22 is primary, formed during original cooling of the magma, the preservation of an original Svecofennian remanence direction indicates that either the site has been preserved from later tectonic processes, or that at this site a younger Svecofennian age magmatic pulse, post-dating deformation, has taken place. The rock type at site 22 is uralite porphyritic gabbro, and the site also shows the highest magnetization and conductivity values (Figs 9 and 14), and as described above, the ferromagnetic mineral at this site is pyrrhotite (Fig. 11). According to SEM studies, the pyrrhotite at this site (Fig. 12a) seems to be more solid compared to the sample from site 17, where pyrrhotite mostly occurs with chalcopyrite and is more broken (Fig. 12b). Therefore, the reason for the observation that only site 22 shows stable remanence directions while the other sites show scattered directions is the different magnetic mineralogy and texture.

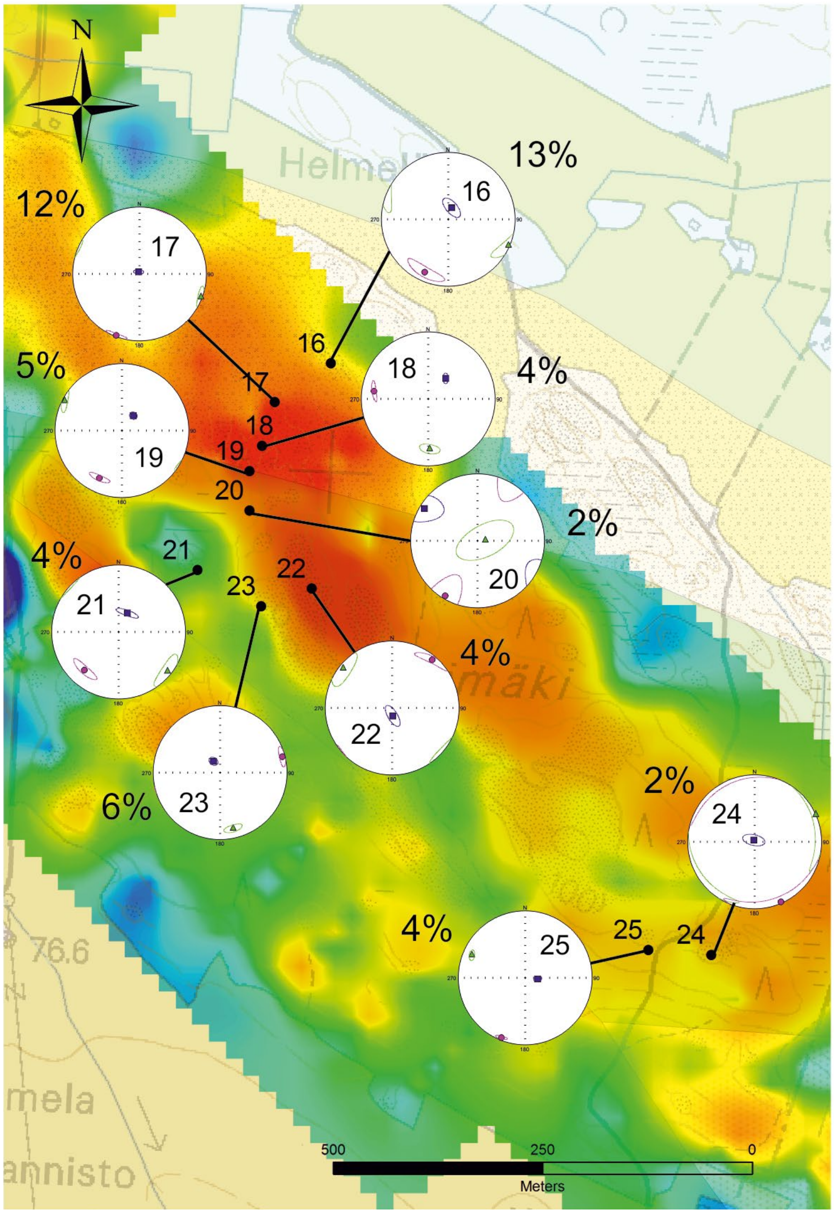

Fig. 14. IP anomaly map of the Uunimäki deposit. Sampling sites (16–25) are indicated as small black dots. The anisotropy degree (P') of magnetic susceptibility is shown as percentages for each site, and the principal axes k1 (blue square), k2 (green triangle) and k3 (red circle) are presented with their α95 confidence ellipses. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

Table 1 presents the exceptionally high remanence and Q-values for site 22, which also explains the occurrence of stable remanence directions. The overall result may thus indicate that the rock with dominant pyrrhotite was formed from a separate mineralizing fluid flow event that, based on the preservation of a typical Svecofennian age remanence direction, must post-date the tectonic events of the region. Consequently, provided that pyrrhotite and the gold mineralization were formed in a simultaneous process (Grönholm and Kärkkäinen 2013), the palaeomagnetic age for pyrrhotite and gold is at maximum 1.8 Ga.

AMS directional data within Uunimäki are characterized by NW–SE striking, almost vertically dipping magnetic foliations and predominantly vertically plunging magnetic lineations (Fig. 14). The anisotropy degree is generally low, from 2–5%, but in the northern part the anisotropy degree increases up to 13%. The shapes of the AMS ellipsoids are both oblate and prolate.

In order to correlate the geochemical and petrophysical properties of the Uunimäki gabbro, three drill cores were studied (M211109R314, M211109R315 and M211109R316). Some of the rocks were defined as gabbro and others as uralite

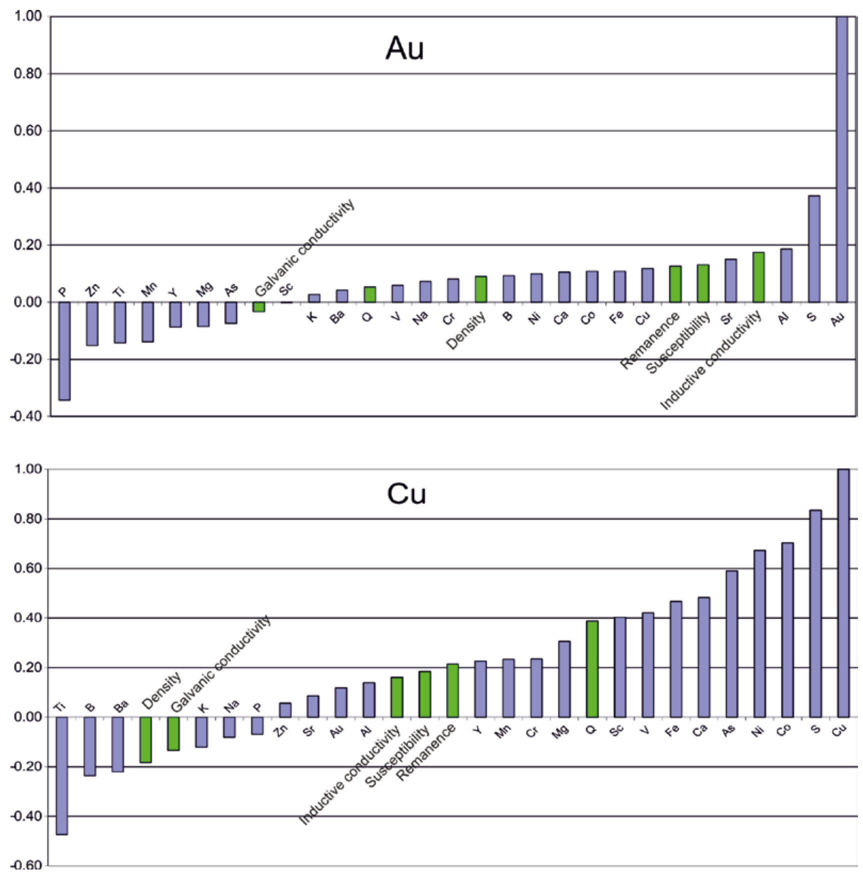

Fig. 15. Correlation of geochemical and petrophysical properties of the Uunimäki deposit. The data were obtained from three drill cores, M211109R314, M211109R315 and M211109R316.

porphyritic gabbro. The lengths of the drill cores were 65.05, 81.05 and 90.40 m. In total, 75 samples were analysed for petrophysical studies and 55 samples for geochemical studies. Petrophysical and geochemical samples were not exactly the same, but the samples were taken as close to each other as possible.

Geochemical correlations indicate that the occurrence of gold is only weakly correlated with other heavy metals (Fig. 15). From the petrophysical parameters, gold is best correlated with inductive conductivity, consistent with the occurrence of pyrrhotite. Because pyrrhotite mostly occurs as disseminated grains, it is not shown in galvanic conductivity. In the Au-bearing zones, pyrrhotite also occurs as thin veins, but because they are mostly perpendicular to the core, they are not invariably caught in the petrophysical samples.

Copper correlates with heavy metals. From the petrophysical properties it is best correlated with Q-value, as it is connected to pyrrhotite (and nickel). Copper has a negative correlation with Ti and density. Titanium is connected to magnetite, which is not related to pyrrhotite.

One reason for the weak correlation between the petrophysical parameters and geochemistry is partly because the petrophysical and chemical analyses were not conducted on the same samples.

Mäyrä

The Mäyrä target (Fig. 16) is within a prominent regional geochemical Au anomaly, but the source of gold in this area has not yet been studied. Petrophysical sampling was carried out across a shear zone that might be part of a mineralized zone (site 1, Fig. 17). The main aim was to examine how the alteration in the zone has affected the petrophysical properties. The other aim was to compare the petrophysical properties of two mafic intrusive rock types in the outcrops: one a dark coarse-grained gabbro (site 2) and the other a lighter coloured fine-grained gabbro (site 3). The sampling scheme is described under the section Methods and sampling.

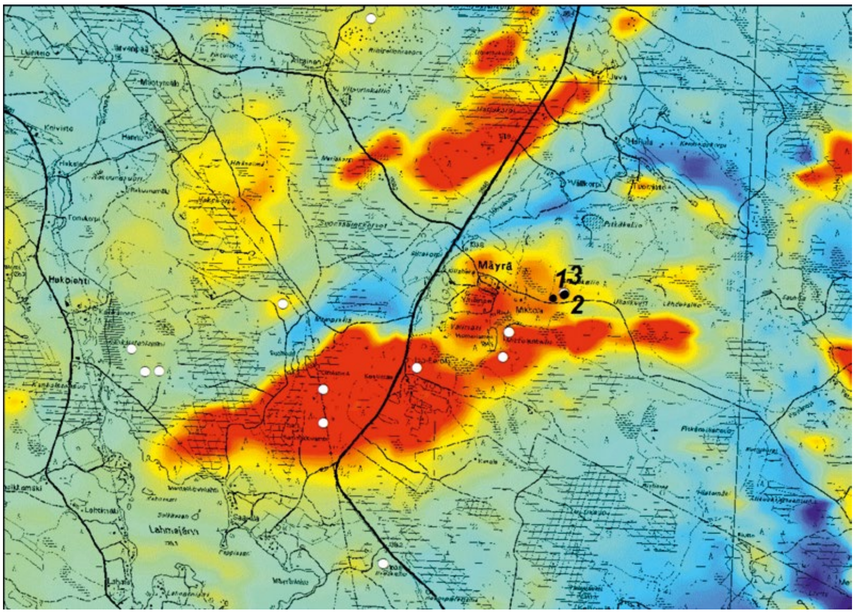

Fig. 16. Aeromagnetic anomaly map of the Mäyrä occurrence. Numbers 1–3 show the sampling sites of this study, while white dots are study locations not reported here. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

Table 1 presents the mean petrophysical values for each site at the Mayrä target. The highest susceptibilities and remanences occur in the coarse grained gabbro not affected by shearing (site 1 and site 2, Fig. 18a, Table 1). In these samples, the susceptibilities have large variation ranging between 2 000–14 000 (x10^{-6} SI) and the remanences generally range between 100 and 800 mA/m. One sample has an exceptionally high remanence of about 5300 mA/m, which raises the mean value (Mäyrä, site 2, Table 1). All Q-values of the coarse grained dark gabbro of site 2 and of samples from unsheared coarse gabbro of site 1 are above 1 (Fig. 18b, Table 1). In the fine-grained gabbro of sites 1 and 3 (Table 1), the susceptibilities are lower and Q-values are below 1. In the centre of the shear zone of site 1, both the susceptibility and Q-values are the lowest (Table 1). The result indicates that due to hydrothermal alteration in the shear zone, most magnetic minerals have vanished. Densities are clearly lowered at the shear zone corresponding to densities of the fine-grained light-coloured gabbro (Fig. 18b).

According to Lowrie tests, the main magnetic mineral in the coarse-grained dark gabbro (Fig. 19a) and in the fine-grained lighter coloured gabbro is magnetite, with some amounts of pyrrhotite, while in the shear zone it is only pyrrhotite (Fig. 19b). High Q-values above 1 in the coarse-grained gabbro indicate magnetite of a small grain size accompanied by pyrrhotite. The coarse-grained black

Fig. 17. Site 1 of the Mäyrä deposit showing the samples taken across a hydrothermally altered shear zone. Orientation device is placed on one of the cores.

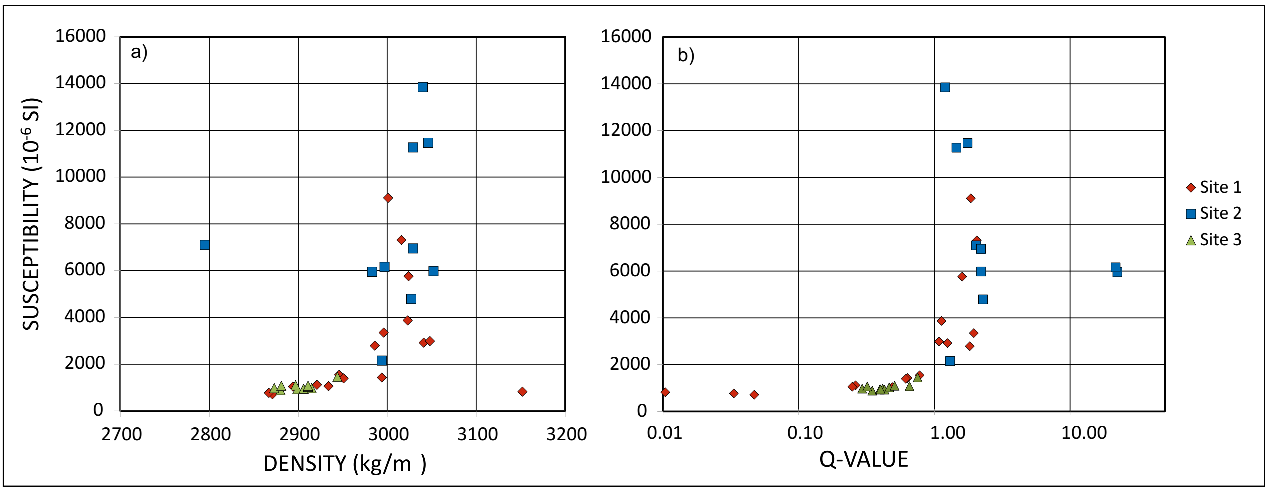

Fig. 18. Petrophysical properties of the Mäyrä gabbro a) Susceptibility – Density, b) Susceptibility – Q-value. Samples of site 1 were taken from the hydrothermally altered shear zone where the lowest values come from the shear zone and the highest values from the coarse-grained gabbro. Site 2 represents the coarse-grained gabbro and site 3 the fine-grained gabbro.

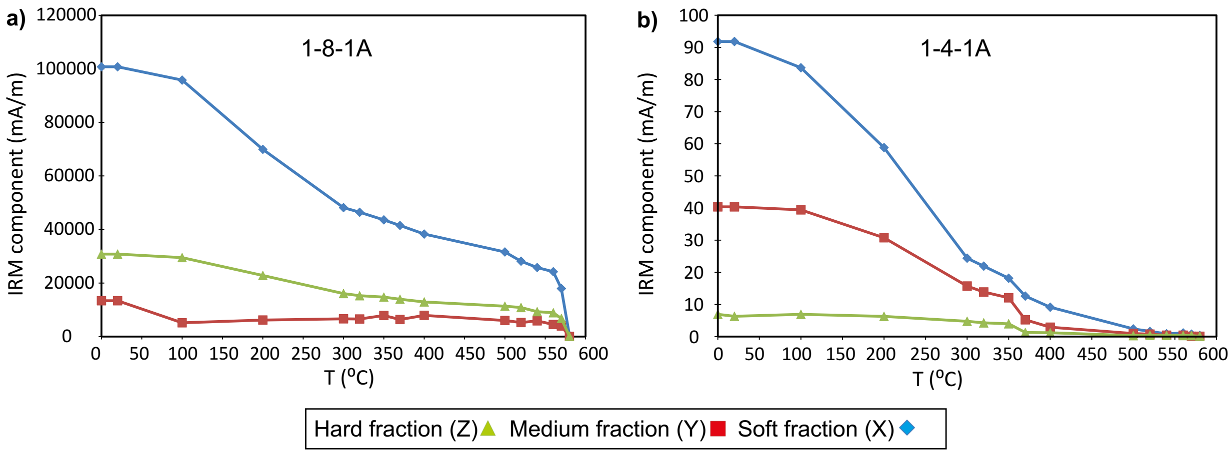

Fig. 19. a) Lowrie test of sample 1-8-1A from the coarse-grained dark gabbro shows magnetite as the main magnetic mineral, b) sample 1-4-1A from the shear zone shows pyrrhotite with a Curie temperature of ca. 370 °C in addition to magnetite (550 °C).

gabbro shows electrical conductivity, but the lighter coloured gabbro does not. Likewise, the shear zone is not clearly conductive, probably due to only small amounts of pyrrhotite.

Comparison of magnetic minerals of the coarse-grained and fine-grained gabbros shows that both contain magnetite (Fig. 20), although their magnetization behaviours and magnetization intensities are clearly different. The Curie temperature of magnetite in both samples is about 580 °C. The long tail above 600 °C in sample 1-8-1B is probably due to hematite.

Directions of remanent magnetization are generally scattered without a consistent direction in the samples. However, a certain trend can be observed in the remanence directions of the shear zone. In the middle of the shear zone (sample 1-4), a NW-pointing direction with intermediate inclination is isolated. Such a direction is typically seen in formations of Svecofennian age (see Fig. 13 from the Uunimäki site 22). The samples further away from the central shear zone carry either a NE- or SW-pointing low inclination remanence direction. It is interpreted that in the centre of the shear zone, the remanence has been locked after deformation and later than the remanence in the surrounding gabbros, which have been involved within the deformation and lost their original Svecofennian remanence direction. Therefore, it seems that as in Uunimäki, the hydrothermal event in Mäyrä is also post-tectonic. However, because these results are only based on a few samples, the interpretation is so far only speculative.

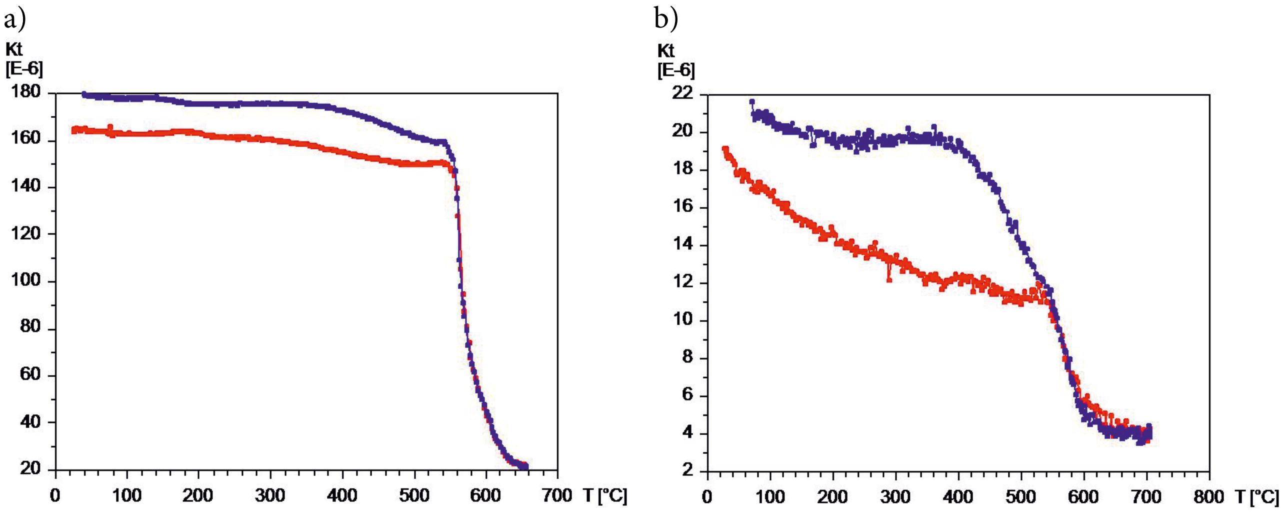

Fig. 20. Thermomagnetic curves showing the variation in susceptibility with heating (red curve) and subsequent cooling (blue curve). a) Sample 1-8-1B is from the coarse grained gabbro and b) sample 3-4-1A is from the fine-grained gabbro and shows some alteration during laboratory heating.

CONCLUSIONS

The study areas were selected by utilizing airborne geophysical data in order to delineate the source of anomalies. Detailed investigations on petrophysical and rock magnetic properties of the prospect occurrences can be used to aid in exploration by verifying the differences in the physical properties of the ore and host rock. Investigations at the outcrop scale have shown that in the porphyry type Cu-Au deposit of Kedonojankulma and in the orogenic Au deposit of Uunimäki, the magnetic properties have increased in the auriferous shear zones due to alteration of Fe-oxide to pyrrhotite. On the other hand, in the gabbroic Au-target of Mäyrä, the magnetizations have decreased due to hydrothermal alteration.

In the quartz-plagioclase porphyry of the Rusakkokallio site of the Kedonojankulma occurrence, the induced and remanent magnetizations are slightly higher in the altered auriferous shear zone than in the less altered host rock. In the altered zone, the only magnetic mineral is monoclinic pyrrhotite with an exceptionally high Curie temperature of ca. 370 °C, while in the host rocks the main magnetic mineral is ilmenite. In the Passi outcrops, some of the plagioclase-quartz porphyries have similar magnetic properties, namely low susceptibility and a higher Q-value (over 1) than in the sheared Rusakkokallio plagioclase-quartz porphyries, indicating the dominance of pyrrhotite. In some of the samples, the susceptibilities are significantly higher due to magnetite, which occurs together with only small amounts of pyrrhotite. Based on AMS data, the least altered quartz-plagioclase porphyrite in Rusakkokallio has the smallest degree of anisotropy, while the highest AMS degrees are found in the Passi outcrops. The higher values are probably due to the occurrence of magnetite, which increases the total magnetization and enhances the possibility to observe the AMS.

In the Uunimäki gabbroic occurrence, the highest magnetization values and conductivities correlate with strong IP anomalies, although the formation is weakly magnetized in general. Rock magnetic analyses show that in the samples of highest magnetization, which are believed to represent the most altered, Au-bearing part of the deposit, the only magnetic mineral is monoclinic pyrrhotite. The less altered areas show the dominance of ilmenite with minor amounts of pyrrhotite. At one site with the highest magnetization and IP values, the remanent magnetization has retained its original Svecofennian age direction, while at other sites the remanences are scattered due to the low intensity of remanence and due to deformation. Preservation of the original remanence may indicate a post-tectonic origin for the fluid that is responsible for the formation of pyrrhotite and, possibly, enrichment of gold. AMS directions are characterized by NW–SE-striking, approximately vertically dipping magnetic foliations and vertically plunging magnetic lineations.

In the Mäyrä occurrence, the magnetization of the shear zone has decreased due to hydrothermal alteration. The surrounding gabbros, whether coarse-grained dark gabbro or fine-grained lighter coloured gabbro, contain magnetite as the main magnetic mineral, while the shear zone also contains pyrrhotite in addition to magnetite.

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