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Rock magnetic investigations constraining relative timing for gold deposits in Finland

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Abstract

Palaeomagnetic and anisotropy of magnetic susceptibility (AMS) studies were carried out on a orogenic gold deposit in Jokisivu, located in the western part of the Pirkanmaa Belt in the Svecofennian domain of southern Finland. These results are compared with previous studies obtained from Satulinmäki, belonging to the Forssa Group in the western part of the Häme Belt, southern Finland and also results from the Central Lapland Greenstone Belt in northern Finland. The main aim of the studies was to test the capability of palaeomagnetic and AMS methods to provide relative age constraints about the structurally controlled gold formation processes. Palaeomagnetic data were used to obtain timing for the emplacement of hydrothermal fluids relative to geological structures. AMS was used to delineate the magnetic fabric. Petrophysical measurements and rock magnetic tests were carried out to define the magnetic minerals and their magnetic domain states as they have importance in preservation of the ancient remanent magnetization. Both the magnetic carriers and the remanence directions of the gold deposits in southern Finland deviate from those previously reported from the Central Lapland Greenstone Belt. The main magnetic mineral in the southern Finland deposits is coarse- to fine-grained monoclinic pyrrhotite whereas in the Central Lapland Greenstone Belt the magnetization is carried by fine-grained magnetite/titanomagnetite. The remanence directions in the southern Finland deposits are rotated and deflected so that no Svecofennian directions have been preserved. This, coupled with correlations between the orientation and orientation distribution of the magnetic and the rock fabric elements imply that the hydrothermal fluids were injected pre/syntectonically during the late stages of Svecofennian orogeny. This is contrasting to the Central Lapland Greenstone Belt, where previous works inferred that the well-preserved 1.88–1.84 Ga Svecofennian palaeomagnetic directions indicate that the gold-bearing hydrothermal fluids were emplaced in existing fractures during the late- or post-deformational stage of the orogeny.

Key words: gold ores, petrophysics, magnetic minerals, paleomagnetism, natural remanent magnetization, magnetic fabric, Paleoproterozoic, Jokisivu, Satulinmäki, Kittilä, Sodankylä, Finland

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1. Introduction

Economic mineral deposits typically incorporate specific magnetic signatures that are widely used for prospecting purposes. Aeromagnetic anomaly investigations of the Geological Survey of Finland (GTK), coupled with other geophysical and geological surveys, have demonstrated that ferromagnetic minerals such as magnetite and, especially, pyrrhotite form one of the characteristic minerals of the gold-rich zones. In several occurrences, it has been shown that pyrrhotite represents sulphidation related to gold mineralization (Kärkkäinen et al., 2006). Magnetite and pyrrhotite are among the main carriers of natural remanent magnetization (NRM, remanence), which reflects the Earth's magnetic field at a certain time. Therefore, by using NRM it may be possible to derive some age constraints for the gold formation processes. Anisotropy of magnetic susceptibility (AMS) is a well-know method to study the fabric of rocks, in particular the magmatic flow in the intrusive rocks, but also the sub-solidus state tectonic overprint (Hrouda, 1982; Borradaile & Henry, 1997; Borradaile & Jackson, 2004). Recently, Skyttä et al. (2010) have successfully applied AMS method to study the kinematic history of granitoid intrusions in northern Sweden. Because many structurally controlled gold-mineralizations are characterized by intense deformation, AMS can be used to give information on their structural style and to delineate the associated high-strain structures, shear zones in particular. As both NRM and AMS measure the orientation of magnetizations, their combined use for structural studies has been tested in selected prospect areas.

In this paper, we will present how the AMS and NRM methods can be used to constrain relative timing for the gold formation processes in different parts of the Palaeoproterozoic Svecofennian crust. All the studied formations represent Palaeoproterozoic orogenic gold deposits that were formed in different stages of the Svecofennian orogeny at ca. 1.9–1.8 Ga (Kärkkäinen et al., 2006; Ojala et al., 2007; Patison, 2007; Saalmann et al., 2009). The petrophysical properties of the rocks were investigated in all study objects in order to identify the magnetic minerals, their alteration and domain states. The first studies on gold mineralizations were carried out in the Palaeoproterozoic Central Lapland Greenstone Belt (CLGB) in northern Finland (Airo & Mertanen, 2008) (Fig. 1), and they only used NRM and petrophysics. Later on, the studies were extended to structurally controlled gold deposits in southern Finland where the gold occurrence of Satulinmäki, and the gold prospect area of Koijärvi were studied (Mertanen and Karell, 2012).

This paper aims to present the results from the latest study object, the Jokisivu formation in southern Finland, where three profiles across the auriferous shear zones were studied (Mertanen & Karell, 2009a,b). The studies in southern Finland comprise also the AMS investigations. The results from the Jokisivu prospect are compared with the results from Satulinmäki (Mertanen and Karell, 2008, 2012) and CLGB (Airo & Mertanen, 2008). As a whole, the NRM and AMS studies have been tested to obtain independent information on the processes that led to the formation of economic gold deposits. It will be shown that the combined use of NRM and AMS investigations can be applied to obtain timing for the hydrothermal system relative to tectonic events.

2. Geologic setting

2.1 Southern Finland

The Jokisivu and Satulinmäki areas form parts of the Paleoproterozoic Svecofennian island arc complex in southwestern Finland. The Jokisivu gold deposit is located in the Vammala migmatite zone in the western part of the Pirkanmaa Belt (Fig. 1). The Satulinmäki gold deposit belongs to the Forssa Group in the western part of the Häme Belt (Fig. 1).The major post-1.92 Ga orogenic events in southern Finland are divided into two main events. First, an early Svecofennian event at ca. 1.89–1.86 Ga, representing microcontinent collisions and accretion of island arcs (Lahtinen et al., 2005) or alternatively, prolonged semi-continuous orogenic activity (Saalmann et al., 2009 and references therein). The second tectonic event, the late Svecofennian

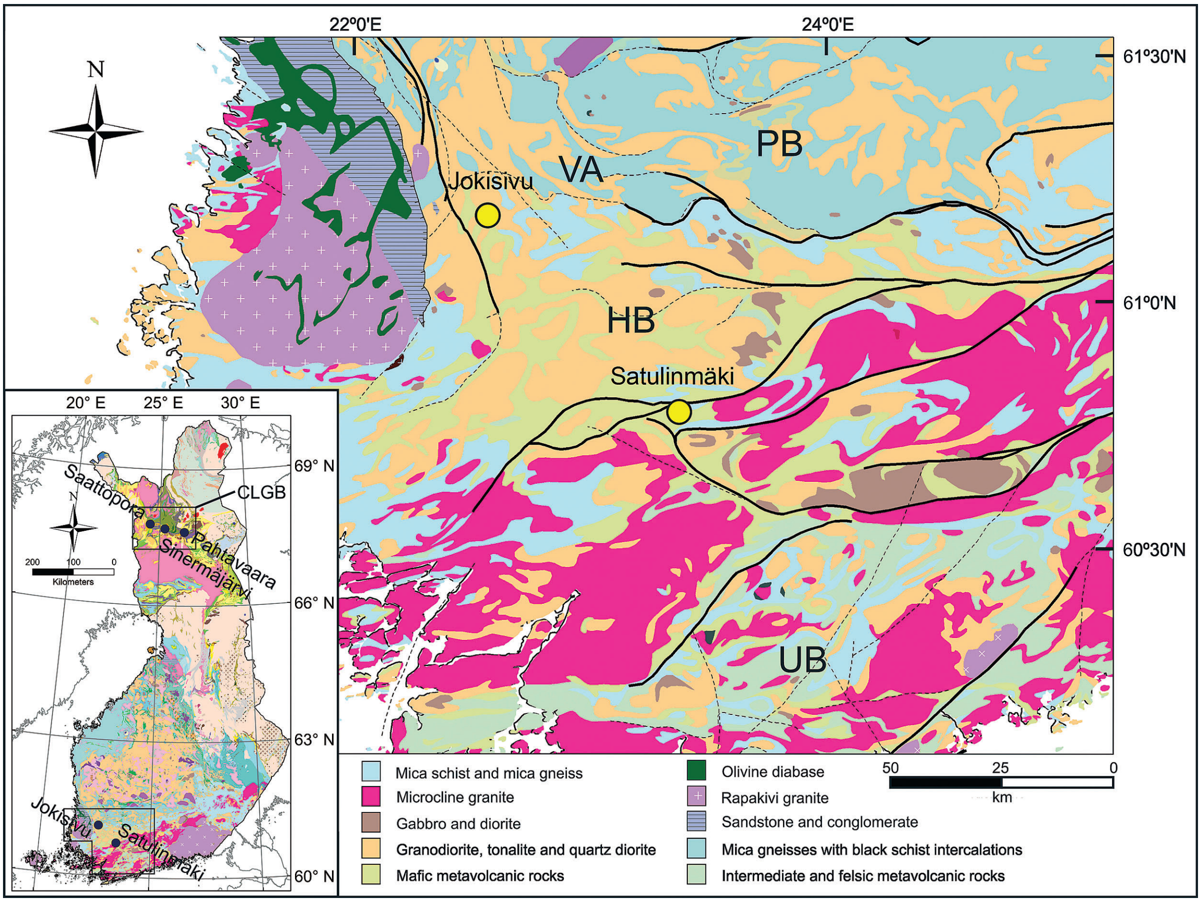

Fig. 1. Geological map of southern Finland (modified after Korsman et al., 1997). PB = Pirkanmaa Belt, HB = Häme Belt, UB = Uusimaa Belt. The Sinermäjärvi, Pahtavaara and Saattopora gold deposits are located in the Central Lapland Greenstone Belt (CLGB).

stage at 1.84–1.80 Ga, was delineated by peak metamorphism at 1.83–1.81 Ga, reaching granulite grade in the Uusimaa Belt and amphibolite-facies in the Häme and Pirkanmaa belts. On the basis of structural and geophysical data these two major events were separated by an extensional episode (Saalmann et al., 2009 and references therein).

2.1.1 Jokisivu

The host rock in the Jokisivu gold deposit varies from quartz diorite to gabbro in composition, but for clarity, the name diorite is used for all host rock samples in this paper. No isotope age data are available to give exact timing for the ore but according to Saalmann et al. (2009), there is a close spatial and temporal association of orogenic gold with ca. 1.8 Ga old pegmatitic dykes. The Jokisivu deposit area comprises two approximately NW-SE striking zones, the Kujankallio and Arpola Zones which are about 200 m apart (Fig. 2). Figure 2 shows the observed moderately (45–50°) NE trending lineations and moderately (40–60°) NE dipping NW-SE striking foliations (GTK database) from the Jokisivu deposit. The orogenic gold mineralisation is in the shear zones, the ore bodies comprising several auriferous quartz vein arrays surrounded by altered host rock (Goode, 2004). According to Luukkonen (1994) the shear zones post-date the main deformation stage D2, but predate deformation stages D3 and D4. The main lineation (Fig. 2) was formed during D2 and deformation D3 has featu-

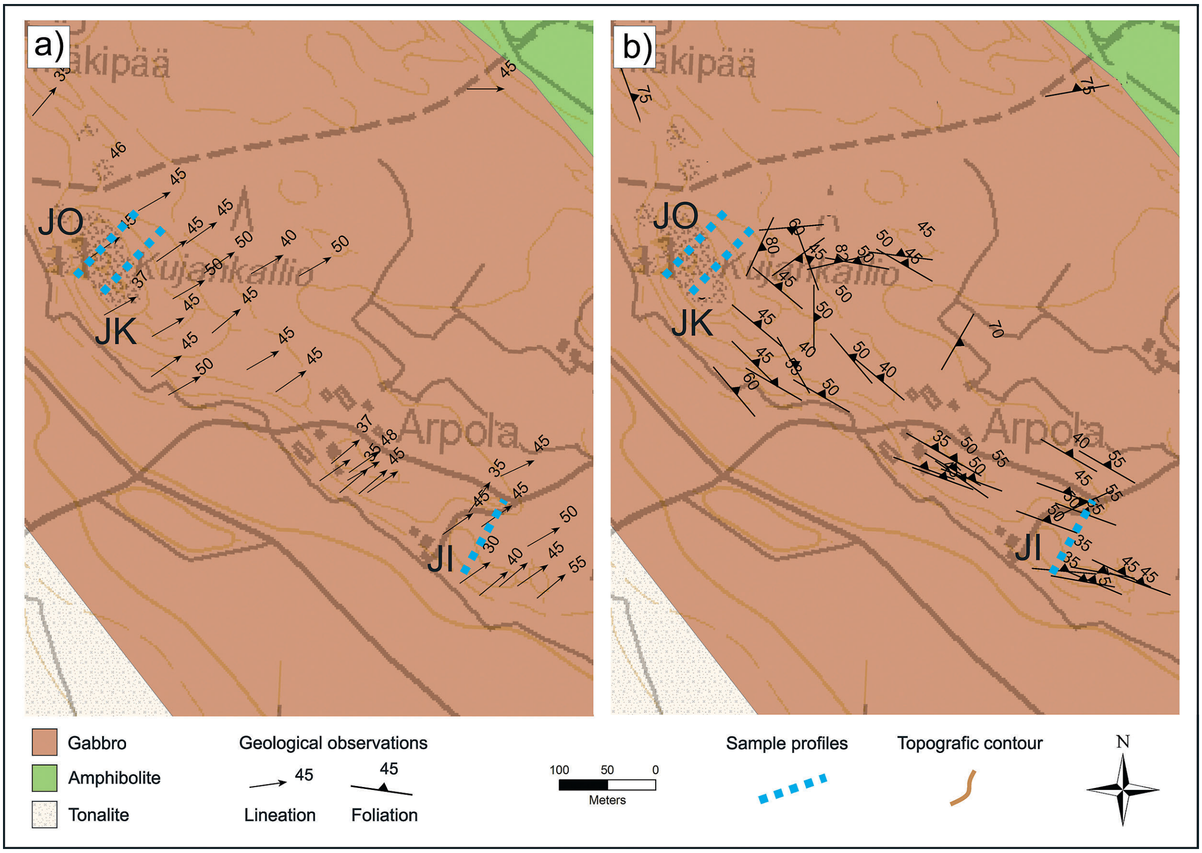

Fig. 2. Geological map of Jokisivu showing field observations of (a) lineations and (b) foliations (GTK database). Base map © National Land Survey of Finland, licence no. 13/MML/12.

res of a brittle deformation. The gold mineralization is regarded as syn-peak metamorphic, between D2 and D3 deformational stages. No auriferous veining is post-dating deformation (Luukkonen et al., 1992; Luukkonen, 1994; Eilu & Pakka, 2009).

2.1.2 Satulinmäki

The Satulinmäki deposit is composed of volcanic and mainly pelitic sedimentary rocks. The felsic volcanic rocks are dated at 1881 ± 3 Ma, and the metamorphism under amphibolite facies conditions is dated at 1.83 Ga (Saalmann et al., 2009). The Satulinmäki deposit represents an orogenic-type gold mineralization that was formed during the late-Svecofennian events dated at ca 1.82–1.79 Ga (Saalmann et al., 2009). The volcanic rocks are strongly deformed, and at Satulinmäki they are strongly sheared and hydrothermally altered and brecciated by quartz veins and tourmaline (Kärkkäinen et al., 2006). The gold mineralization is in many locations spatially related to the quartz veins and is structurally controlled by WSW–ENE to SW–NE and NW-SE trending shear zones and faults (Fig. 3), which formed during prolonged dextral oblique contraction in the late stages of Svecofennian orogenic evolution (Saalmann et al., 2009). The dominant lineations dip steeply to the SE or SW (Fig. 3a), and the steeply dipping (75–90°) foliations follow the trends of the shear and fault zones (Fig. 3b) (Saalmann, 2007).

2.2 Central Lapland Greenstone Belt (CLGB)

The known gold occurrences within the CLGB (Fig. 1) are orogenic greenstone-hosted gold mineralizations (Ojala et al., 2007; Patison, 2007). The ages

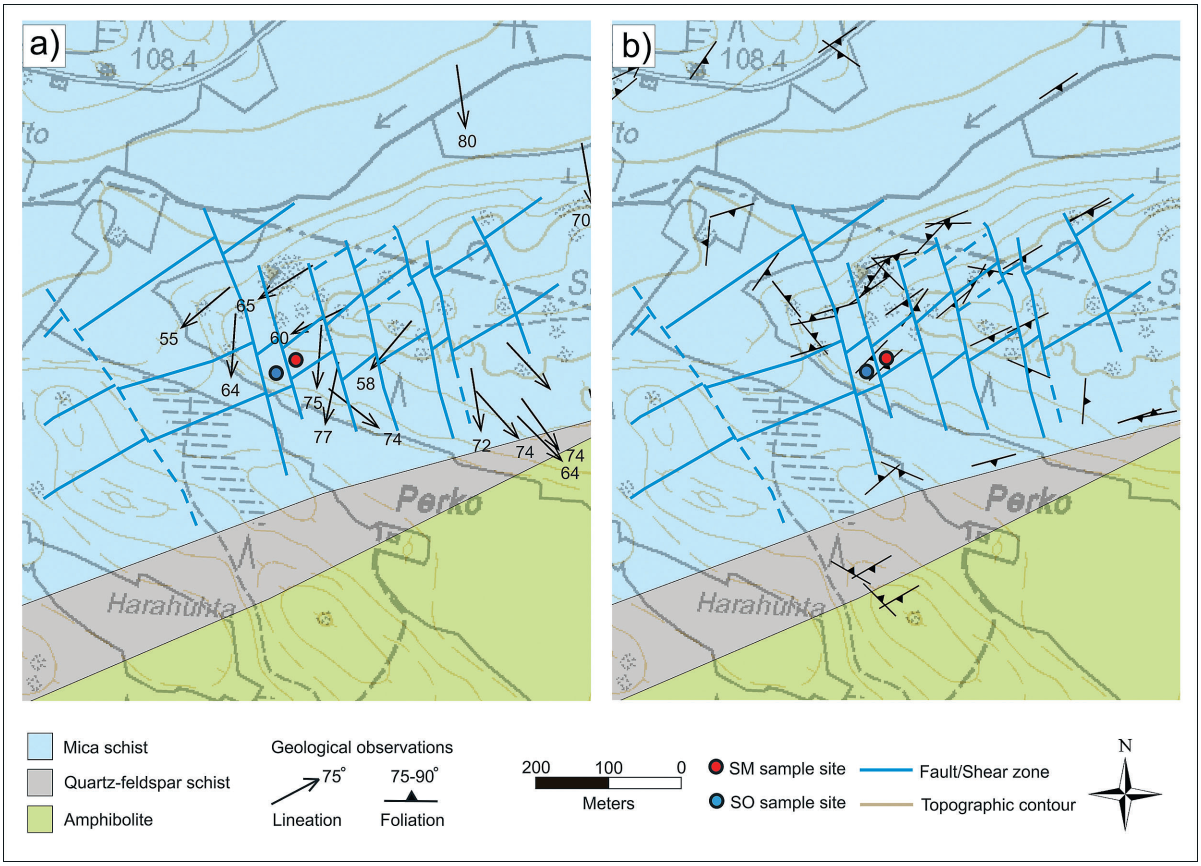

Fig. 3. Geological map of the Satulinmäki area showing the major fault and shear zones (from Saalmann et al., 2009) and field observations of (a) lineations and (b) foliations (GTK database). Base map © National Land Survey of Finland, licence no. 13/MML/12.

of the CLGB range from 2.5 Ga to 1.88 Ga. CLGB is delineated by greenstone facies metamorphism whereas the bordering schists in the south and north are indicative of amphibolite facies conditions (Hölttä et al., 2007). Two of the studied formations, the Saattopora and Sinermäjärvi deposits belong to the weakly magnetized tholeiitic Kittilä Group which is bordered in the south by highly magnetic rock units of the Savukoski and Sodankylä Groups (Lehtonen et al., 1998; Hölttä et al., 2007). The southern boundary of the Kittilä Group is characterized by gently southward dipping thrust faults and related shear zones, the so called Sirkka Trend (Fig. 4). It comprises a major thrust zone that extends for more than 100 km across Lapland. According to Patison (2007), location of Saattopora and Sinermäjärvi gold occurrences on or immediately adjacent to Sirkka Trend structures indicates a clear spatial relationship between shear zones and mineralised sites. The third studied formation, the Pahtavaara deposit, is sited in an altered komatiitic sequence in the Savukoski Group at the eastern part of CLGB (Fig. 4). It has many of the alteration characteristics of amphibolite-facies orogenic gold deposits and, as locating in an area of intense shearing, also an obvious structural control (Patison, 2007). The gold occurrences are typically related to D3 deformation events of the age of 1.9–1.77 Ga, which also coincide with the general CLGB-wide evolution from ductile to brittle deformation conditions (Patison, 2007). Chemical alteration in the greenstone belt is spatially closely associated with brittle rock fabrics and commonly restricted to narrow zones being tens of meters in width (see also Airo & Mertanen, 2008).

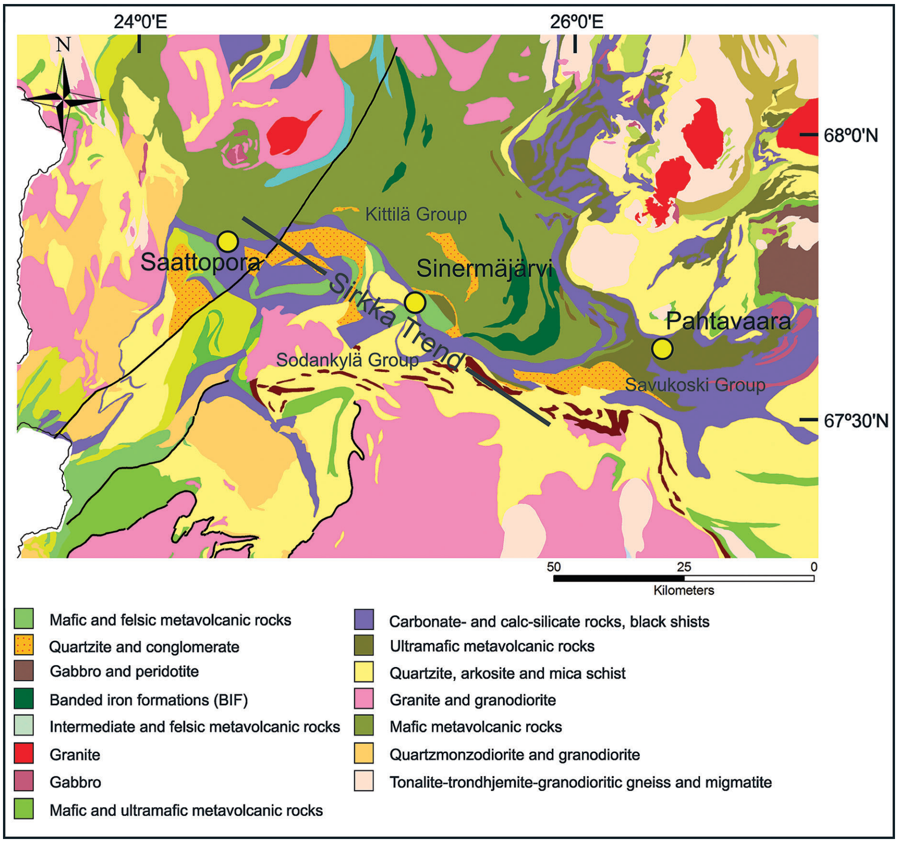

Fig. 4. Geological map of the Central Lapland Greenstone Belt, CLGB (modified after Korsman et al., 1997) showing the study areas (Saattopora, Sinermäjärvi and Pahtavaara) of Airo and Mertanen (2009). The Saattopora and Sinermäjärvi gold deposits are located in the vicinity of the Sirkka Trend between the Kittilä Group and Sodankylä Group. Pahtavaara is located within the Savukoski Group.

3. Sampling and methods

In Jokisivu, samples were taken from two sites at the Kujankallio zone and from one site at the Arpola zone (Fig. 2). At all three sites, samples were taken as profiles across the vein system and general NW-SE trending structure. At site JO, 7 samples were taken from the stacked lode system, comprising of heavily sheared rock type, and 4 samples from the more homogeneous dioritic host rock. From the host rock, the samples were taken at distances of ca. 7 m, 1 m and 0.5 m to the first alteration zone. At site JK, altogether 7 samples were taken from sheared zones, and 7 samples from the intervening diorite. One sample was taken from the pegmatite dyke that continues at site JO. At site JI in Arpola, altogether 16 samples were taken, 5 from the auriferous zones, 9 from the intervening diorites and two from an ultramafic rock. All samples were taken with a portable mini-drill and oriented with magnetic and sun compass.

Data of samples from Jokisivu are compared with data from Satulinmäki, where samples were taken at two outcrops, SO and SM (Fig. 3). The outcrops are located 50 meters apart and may represent continuation of the same NE-SW trending structure. There, too, samples were taken as profiles across the structure. The main rock type is intermediate volcanic tuff that at both sites is partly heavily oxidized. For more details of sampling, see Mertanen and Karell (2012).

In the laboratory, in general three specimens were cut from each core. Measurements of petrophysical properties including density, magnetic susceptibility and the intensity of remanent magnetization, as well as the Koenigsberger ratio (Q, the ratio of remanent to induced magnetization) were performed for all specimens. Magnetic susceptibility (k) of rocks is defined as the relation between induced magnetization (M) and the applied magnetic field (H): $M = k \times H$. The magnetic susceptibility measurements were carried out with different alternating (applied) field intensities. Specimens for the basic petrophysical data were measured with a GTK-built AC bridge with an applied field intensity of 130 A/m. The AMS measurements were conducted with a KLY-3S Kappabridge apparatus with an applied field intensity of 300 A/m and the results were statistically evaluated using ANISOFT software (Jelínek, 1978; www.agico.com).

Different ferromagnetic minerals can be identified on the basis of their characteristic Curie temperature. In thermomagnetic analyses, magnetic susceptibilities are continuously measured during heating from liquid nitrogen temperature (-192 °C) to room temperature, and further from room temperature to higher temperatures (up to 700 °C), and subsequently during cooling back to room temperature. In the obtained susceptibility-temperature curves (k_{bulk}-T), the thermal effect on magnetic minerals can be observed and the minerals identified. For more accurate identification of magnetic minerals, three-component isothermal remanent magnetization (IRM) studies, the Lowrie tests (Lowrie, 1990), were carried out on selected samples. In these tests, the samples are subjected to three different high magnetic fields (1.5 T, 0.4 T and 0.12 T, respectively) and subsequently heated to increasing temperatures (typically up to 680 °C). The minerals are then identified based on their characteristic highest unblocking (Curie) temperatures. The measurements also give information on the domain states of the minerals that have importance for the preservation of ancient remanent magnetization. The IRMs were produced with a Molspin pulse magnetizer. Remanent magnetization measurements (both laboratory IRM and palaeomagnetic measurements) were carried out using a 2G-Enterprises superconducting SQUID RF magnetometer.

In the palaeomagnetic measurements (remanent magnetization), the samples were gradually demagnetized either by increasing the alternating field (AF, mainly up to 160 mT) or by subjecting the samples to temperatures increasing stepwise from room-temperature up to 600 °C. The purpose of demagnetization is to isolate the remanence components formed in different geological processes and to separate the stable ancient remanent magnetization from more recent viscous magnetization. The remanence components were separated by using principal component analysis (Kirschvink, 1980; Leino, 1991; Zijderveld, 1967).

Anisotropy of magnetic susceptibility (AMS) is a well-established tool to investigate the magnetic fabrics of rocks. AMS is described mathematically as a symmetrical 2nd rank tensor, which can be visualized as an ellipsoid with three principal axes; maximum (k_1), intermediate (k_2) and minimum (k_3) susceptibility. The long axis is often referred to as the magnetic lineation and the short axis as the pole to the magnetic foliation (Tarling & Hrouda, 1993). Two parameters are frequently used to describe the magnetic fabric. The magnitude of the anisotropy is described by parameter P', which ranges from one (isotropic sphere) upwards.

$$P' = \sqrt[2]{2(\ln k_1 - k_{mean})^2 + 2(\ln k_2 - \ln k_{mean})^2 + 2(\ln k_3 - \ln k_{mean})^2}$$

The shape of the ellipsoid is described by parameter T, where the shape ranges from prolate (T = -1) through neutral (T = 0) to oblate or planar (T = 1) (Jelínek, 1981), corresponding to constrictional, plane and flattening-strain regimes of structural geology, respectively.

$$T = \left[\frac{2\ln(k_2 / k_3)}{\ln(k_1 / k_3)}\right] - 1$$

The AMS analysis can confirm the general structural field measurements taken from GTK's database from the study area and provide some detailed information on the structures. Each mineralogical component of the magnetic fabric has its own anisotropy, and the magnetic anisotropy of a rock is affected by all the magnetic minerals present (Tarling & Hrouda, 1993). In general, shear zones show a complex magnetic mineralogy due to deformation mechanisms, recrystallization and fluid flow, which also affects the developed magnetic fabric. Especially pyrrhotite is strongly field-dependent and affects the AMS results (deWall & Worm, 1993; Hrouda, 2002; Martín-Hernandez et al., 2008; Hrouda 2009). In particular, the degree of anisotropy is mostly affected; however, the directional data and the symmetry of the AMS ellipsoid are not significantly affected by the field dependency (Hrouda, 2002; 2009).

4. Results

Petrophysical, paleomagnetic and AMS results from Jokisivu deposit are given in Tables 1–3, which also give the average site mean data for the Satulinmäki formation. Specimen data from Satulinmäki are shown in Mertanen and Karell (2012). The previously obtained results from Satulinmäki and CLGB are shortly described in Chapter 5.

4.1 Petrophysics

Table 1 shows the site mean petrophysical properties of the Jokisivu and Satulinmäki deposits, and specimen data from both formations are shown in Figure 5. The samples from Jokisivu are predominantly pyrrhotite-bearing with magnetic susceptibilities below 10 000 µSI (Fig. 5). Susceptibility versus density diagram (Fig. 5a) principally describes compositional variation. Rock density increases with an increasing mafic mineral and iron content (Puranen, 1989) and, typically, with an increasing sulphide (pyrite, pyrrhotite) concentration (Airo, 2002; Clark, 1997). In Jokisivu, the densities of the diorites are slightly higher than those of the shear zones (Table 1), which is probably due to considerably high amounts of Fe-Mg-silicates in the diorites. On the other hand, susceptibilities and remanence intensities (Fig. 5b) of the shear zones, derived from the sulphides, are typically higher than those of the host rock. Due to higher remanence intensities, the Q values of the shear zones are also generally higher than those of the host rock (Fig. 5c). The Q ratios are in general > 1, which indicates that remanent magnetization dominates and, therefore, stable remanences can be expected.

4.2 Magnetic mineralogy

Thermomagnetic analyses (k_{bulk}-T curves) for the Jokisivu samples show that ferrimagnetic monoclinic pyrrhotite, with a Curie temperature of ca. 320 °C, is the main magnetic mineral (Fig. 6a). Small amounts of hexagonal pyrrhotite are also present in some samples. Likewise, three component IRM diagrams show that the samples from the Jokisivu

Table 1. Petrophysical properties of Jokisivu and Satulinmäki deposits

Site	n	k(µSI)	D (kg/m³)	NRM (mA/m)	Q
Jokisivu					
JO Host rock	11	1485	2884	454	6.16
JO Shear zone	7	3150	2897	1350	8.93
JO Shear zone core	11	1651	2839	489	7.13
JK Host rock	15	2297	2853	1173	9.41
JK Shear zone	17	2760	2816	1259	11.45
JI Host rock	24	1567	2917	473	6.01
JI Shear zone	10	5763	2827	2116	9.17
Satulinmäki					
SO Host rock	5	645	2673	517	12.88
SO Shear zone	9	894	2721	798	8.16
SM Host rock	9	991	2722	1058	15.89
SM Shear zone	11	2720	2735	2454	17.80

n is the number of specimens.
k is magnetic susceptibility (µSI).
D is density (kg/m³) and NRM natural remanent magnetization (mA/m).
Q is the dependence between remanent/induced magnetization

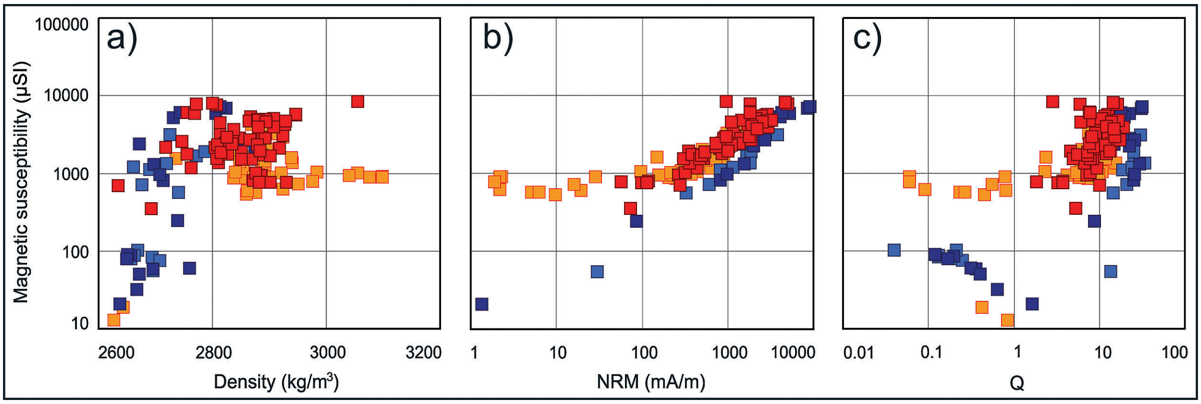

Fig. 5. Petrophysical properties of the specimens from Jokisivu (red = shear zone, orange = host rock) and Satulinmäki (dark blue = shear zone, blue = host rock) gold deposits. (a) Magnetic susceptibility (µSI) vs. density (kg/m^3). (b) Magnetic susceptibility (µSI) vs. intensity of natural remanent magnetization (NRM) (mA/m). (c) Magnetic susceptibility (µSI) vs. Koenigsberger value (Q).

(Fig. 6b) deposit are characterized by monoclinic pyrrhotite that unblocks at 300–350 °C. In all cases, pyrrhotite occurs in coarse multi-domain (MD) grains that are shown as the highest intensity curves of the low coercivity x-component. The MD grains can more easily lose their original remanence and are, therefore, not good recorders of the ancient geomagnetic field. However, since the samples also carry a small fraction of harder coercivity pseudo-single-domain (PSD) or single-domain (SD) magnetic grains (y and z components, respectively), some ancient remanence has been preserved. The studies on the magnetic mineralogy of Jokisivu indicate that although the magnetization (both magnetic susceptibility and remanence intensity) may be very low, it mainly resides in the magnetic, monoclinic pyrrhotite.

4.3 Palaeomagnetism

All the samples of the Jokisivu deposit show a characteristic moderately downward ENE pointing remanence direction (Table 2; Fig. 7a). The remanence is only stable in low coercivities, and was isolated in AF fields of 0–40 mT. In thermal demagnetizations (Fig. 7b), the remanence is typically isolated at temperatures of 100–300 °C, consistent with pyrrhotite as the remanence carrier. The remanent magnetization directions are extremely consistent between different samples, whether taken from the

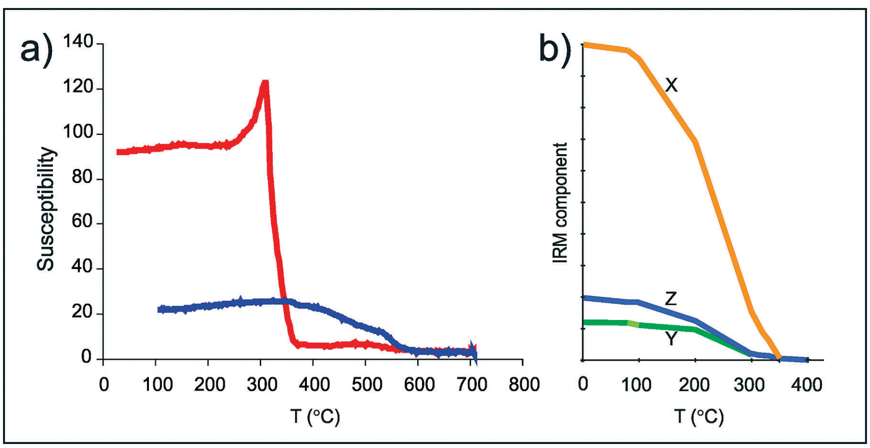

Fig. 6. Identification of magnetic minerals from Jokisivu by rock magnetic tests. (a) Thermomagnetic (k_{bulk}-T) curves showing magnetic susceptibility (µSI) vs. temperature (°C). Red (blue) line denotes heating (cooling) curve. (b) Three axes isothermal magnetization (IRM) vs. temperature (°C). Magnetizations were produced along three orthogonal directions; Z component in magnetizing field 1.5 T, Y component in field 0.4 T and X component in field 0.12 T.

shear zone or from the more homogeneous diorite. The occurrence of the characteristic remanence component is not directly related to the intensity of magnetization, because the samples with very low magnetizations, due to very small amounts of pyrrhotite, also give corresponding remanence directions to the highly magnetic samples.

4.4 AMS

In the Jokisivu deposit, the anisotropy degree (P') is typically higher in the shear zones than in the host rock. (Table 3; Fig. 8a). The samples from Jokisivu show equally either oblate or prolate AMS shapes (Fig. 8b). The mean Kmax orientation plunges moderately to ENE, and the mean magnetic foliation dips moderately to NNE with a large scatter of Kmin values along a SE-NW girdle (Fig. 8c).

Table 2. Mean palaeomagnetic results from Jokisivu (Lat 61.1 N, Long 22.6 E) and Satulinmäki (Lat 60.8 N, Long 23.5 E)

Site	N/n	D (°)	I (°)	α 95 (°)	k
Jokisivu					
JO	10 [a]/22	66.4	58.9	4.6	113.7
JK	12 [a]/28	83.3	58.2	3.3	174.7
JI	9 [a]/15	75.8	55.8	5.1	103.4
Mean	3[a]/31/65	75	57.8	7.3	286.1
Satulinmäki					
Mean	11[a]/17	238	52.1	24.7	4.4

N/n is the number of samples/specimens of the site where a ChRM was isolated. [a] denotes the used statistical level. D and I are declination and inclination, respectively. α95 is the radius of the circle of 95 % confidence, k is Fisher's (1953) precision parameter.

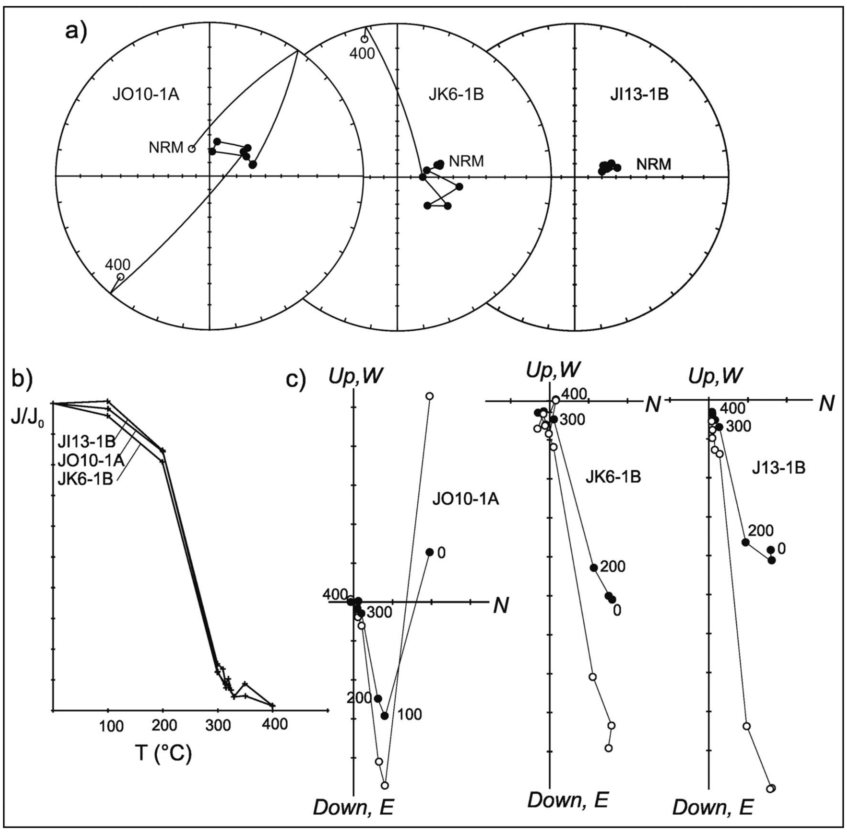

Fig. 7. Examples of remanence behaviour during thermal demagnetizations of samples from Jokisivu: (a) stereoplots, (b) intensity decay curves of thermal demagnetization, (c) orthogonal vector plots where open (closed) symbols denote vertical (horizontal) planes. Numbers refer to temperatures (°C).

Magnetic signatures from the shear zone core and margins (Fig. 9a) differ in their orientations; Kmax from the margins plunges moderately to ENE and the magnetic foliation dips moderately to NNE, whereas the core displays a gently east-plunging Kmax orientation and a north-dipping magnetic foliation (Fig. 9b). Furthermore, the shape of the magnetic fabric in the shear zone core is dominated by an oblate signature, which contrasts to the prolate signature recorded from the margins (Fig. 9c). P'

Table 3. AMS data of Jokisivu and Satulinmäki deposits

Site	n	Scalar data		Directional data					
		P'	T	k1		k2		k3	
				D/I (°)	α 95 (°)	D/I (°)	α 95 (°)	D/I (°)	α 95 (°)
Jokisivu									
JO Host rock	11	1.207	-0.379	71.0 / 39.6	11.1 / 5.9	334.3 / 8.1	30.9 / 9.9	234.8 / 49.3	31.1 / 6.1
JO Shear zone	7	1.261	-0.356	64.8 / 32.5	7.7 / 6.1	300.8 / 41.3	11.9 / 6.7	177.9 / 31.7	12.0 / 4.5
JO Shear zone core	11	1.170	0.313	78.7 / 13.0	55.2 / 18.6	329.9 / 54.3	55.2 / 9.6	177.2 / 32.6	19.8 / 7.9
JK Host rock	15	1.171	-0.220	60.5 / 33.7	16.0 / 5.2	297.5 / 39.2	22.3 / 14.2	175.8 / 32.7	21.8 / 7.5
JK Shear zone	18	1.280	-0.102	57.7 / 33.3	22.9 / 11.4	291.6 / 41.9	27.1 / 19.5	170.1 / 30.2	27.1 / 16.9
JI Host rock	25	1.153	0.054	74.0 / 44.0	18.8 / 16.3	338.2 / 6.0	38.9 / 17.5	242.0 / 45.3	38.8 / 15.7
JI Shear zone	10	1.207	0.016	87.2 / 42.2	18.3 / 13.1	183.4 / 6.8	70.6 / 12.2	280.8 / 47.0	70.7 / 8.2
Satulinmäki									
SO Host rock	6	1.484	-0.324	198.4 / 86.7	4.4 / 2.3	338.4 / 2.5	72.1 / 2.8	68.5 / 2.1	72.1 / 0.6
SO Shear zone	12	1.258	-0.398	104.8 / 81.6	6.6 / 1.9	230.1 / 4.9	33.5 / 2.2	320.7 / 6.8	33.6 / 2.3
SM Host rock	11	1.597	-0.255	154.4 / 80.7	3.2 / 1.1	44.3 / 3.2	5.9 / 1.2	313.8 / 8.7	6.3 / 2.1
SM Shear zone	13	2.462	-0.372	159.9 / 82.1	7.5 / 4.0	258.7 / 1.2	18.3 / 6.7	348.8 / 7.8	18.2 / 4.1

n is number of specimens. P' is the anisotropy degree and T is the shape parameter. D and I are declination and inclination, respectively, for each axis of the AMS ellipsoid. α95 is the 95 % confidence angles of D/I.

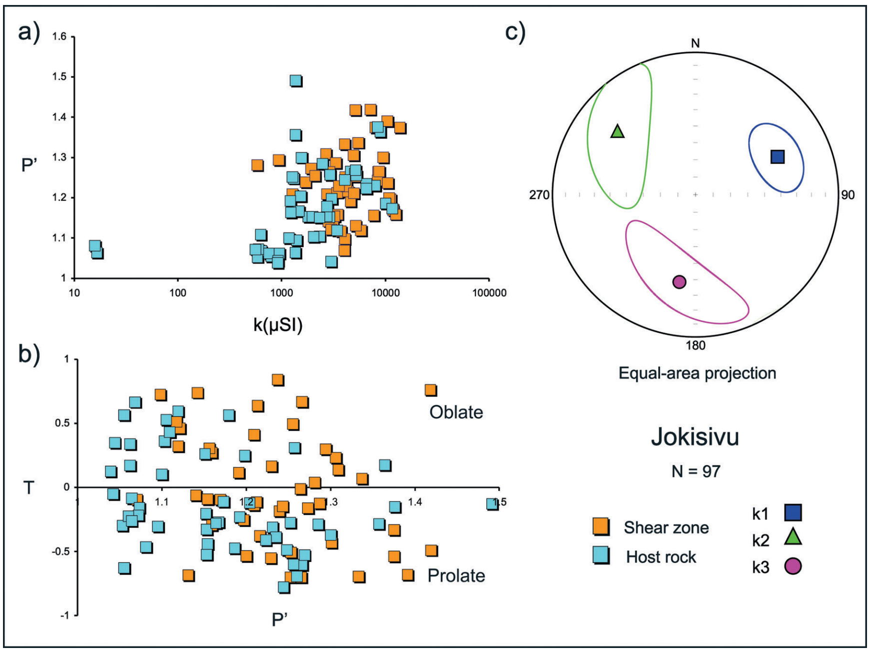

Fig. 8. AMS data from Jokisivu. (a) Anisotropy degree (P') vs. magnetic susceptibility (μSI). (b) Shape of the AMS ellipsoid (T) vs. anisotropy degree (P'). (c) Mean directions of the principal axes k1, k2 and k3 with their α95 confidence ellipses.

values from the shear zone core are lower than those from its margins (Table 3).

5. Previously obtained results

5.1 Petrophysical, AMS and NRM results from Satulinmäki

In Satulinmäki deposit (Mertanen and Karell, 2012), one population has low susceptibility values; ~100 µSI, and another population higher susceptibilities; ~1 000–7 000 µSI (Fig. 5). The grouping reflects samples that are dominated by paramagnetic mafic silicates or ferrimagnetic pyrrhotite, respectively. The samples with higher susceptibilities carry also stronger remanence, which shows that in Satulinmäki the amount of remanence carrying minerals controls the remanence intensity. The Q-values vary between ca. 0.1 and 20, and are clearly higher (~20) for samples with higher susceptibilities and higher remanence. However, the host rock and shear zone do not show any clear differences in their petrophysical properties as for the Jokisivu samples (Fig. 5). The samples from Satulinmäki have a high, or locally even exceptionally high anisotropy degree (P') typical of deformed rocks (Fig. 10a; Table 3; Borradaile & Jackson, 2004). The exceptionally high P' values may also be an effect due to field dependency associated with pyrrhotite. The samples show predominantly prolate AMS signatures with tightly-clustered, sub-vertically plunging Kmax axes (Fig. 10b). The average magnetic foliation plane strikes NE-SW and dips sub-vertically to SE (Fig. 10c). Two principal directions of the magnetic foliation may be separated: one that is parallel to the NE-SW shear zones and another with a E-W strike within the Au-rich heavily oxidised zone (Fig. 11). The average remanent magnetization direction in Satulinmäki has a SW pointing declination and moderate positive inclination (Fig. 12), although the directions are very scattered. The remanence is stable only in low AF fields and temperatures, and resides in monoclinic pyrrhotite. Those samples that were taken from the heavily oxidised rocks in the auriferous zones carry a corresponding magnetization values as well as remanence direction to the samples with less oxidation.

5.2 Petrophysical and NRM results from CLGB

In general, the rocks of CLGB display bimodal magnetic property distributions, typical for magnetite bearing lithologies (Airo & Mertanen,

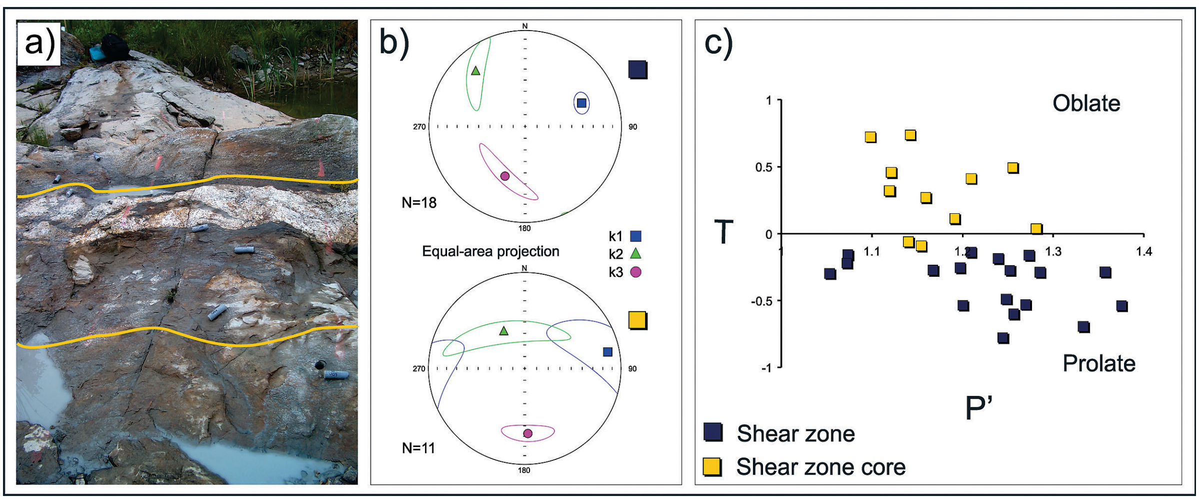

Fig. 9. (a) Sampling along a profile JO across the shear zone in Jokisivu. The shear zone core is between the yellow lines. View towards NE. (b) Mean AMS directions from the margins of the shear zone and from the core of the shear zone. (c) Jelínek P'-T plot (Jelínek, 1981) for samples grouped according to location in the shear zone core and its margins.

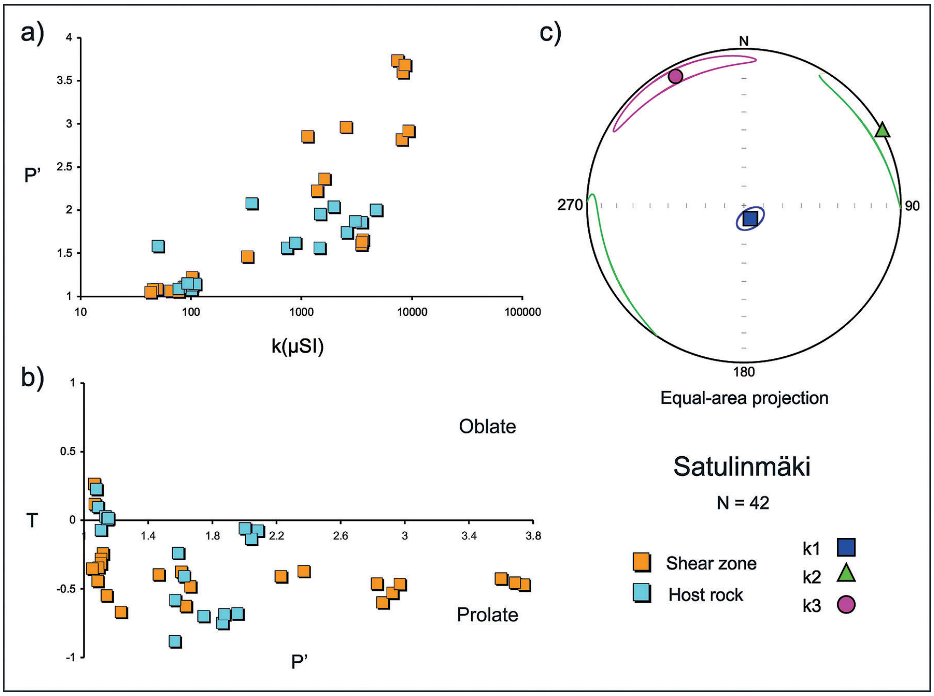

Fig. 10. AMS data from Satulinmäki. (a) Anisotropy degree (P') vs. magnetic susceptibility (μSI). (b) Shape of the AMS ellipsoid (T) vs. anisotropy degree (P'). (c) Mean directions of the principal axes k1, k2 and k3 with their α95 confidence circles.

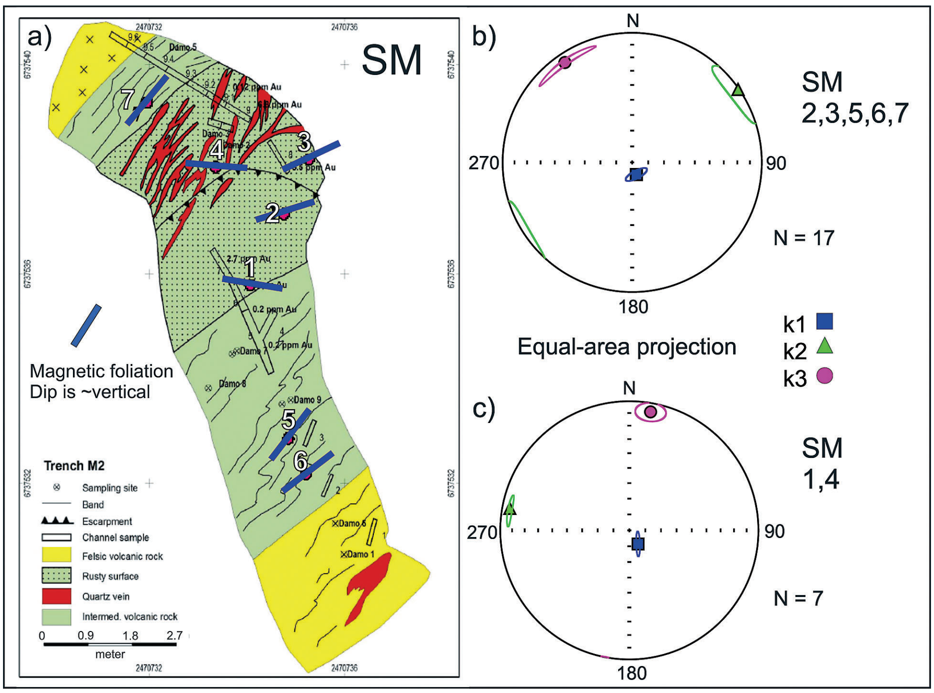

Fig. 11. (a) Geological map of site SM in Satulinmäki (Trench M2, modified after Kärkkäinen et al., 2006), where the strike of the magnetic foliations are plotted. (b) Mean magnetic foliations of specimens from the less rusty rocks. (c) The magnetic foliations of more heavily oxidized rocks.

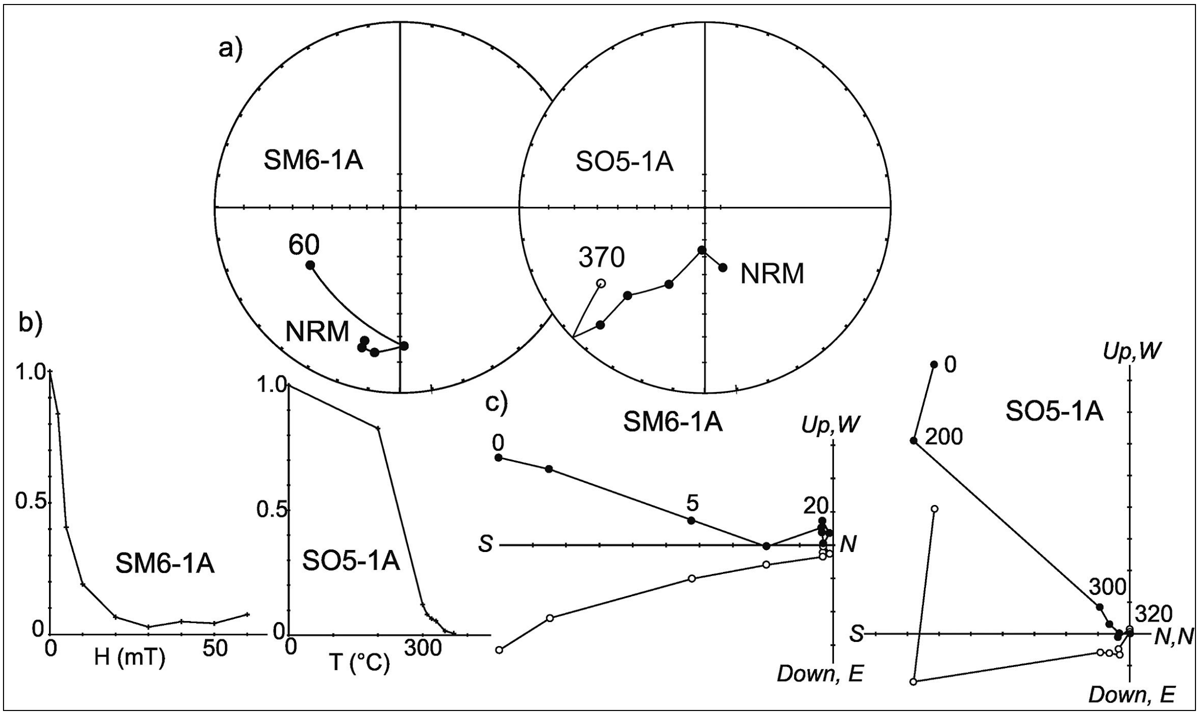

Fig. 12. Example of remanence behaviour during alternating field (AF) and thermal demagnetizations of samples from Satulinmäki: (a) stereoplots, (b) intensity decay curves of AF demagnetization (left) and thermal demagnetization (right), (c) orthogonal vector plots where open (closed) symbols denote vertical (horizontal) planes. Numbers refer to AF fields (mT, left) and temperatures (°C, right).

2008). The magnetic susceptibilities of CLGB rocks are commonly 20 000–400 000 μSI, and their remanence intensities vary from 1 to 8 A/m. The magnetic signatures of the altered ultramafic rock sequences are predominantly controlled by partial or total destruction of ferrimagnetic minerals, or replacement minerals having lower magnetic intensities (Airo & Mertanen, 2008). In the Saattopora, Sinermäjärvi and Pahtavaara mines, remanent magnetization was isolated with a moderate downward direction to the NW (Fig. 13a), and based on intensity decay curves, it was implied that the remanence is carried by fine-grained magnetite or titanomagnetite (Airo & Mertanen, 2008).

6. Discussion

In the Central Lapland Greenstone Belt in northern Finland, gold was inferred to have precipitated from hydrothermal fluids late during the Svecofennian deformational events (e.g. Ojala et al., 2007; Patison, 2007). The palaeomagnetic poles (Fig. 13b) form a coherent group around the 'key poles' obtained from isotopically dated Svecofennian 1.88–1.84 Ga intrusions and dykes in central Finland (Buchan et al., 2000; Pesonen et al., 2003). Accordingly, acquisition of the remanent magnetization of the CLGB poles took place at ca. 1.88–1.84 Ga. The data suggest that, because remanent magnetization correctly records the direction of the Earth's geomagnetic field during the Svecofennian time, the rocks have not been involved in deformation after the remanence was blocked. It was, therefore, implied that the hydrothermal fluids were emplaced into already existing brittle structures in the post-tectonic stage. Alteration related to brittle structures was also interpreted from aeromagnetic data (Airo & Mertanen, 2008) and is supported by geological

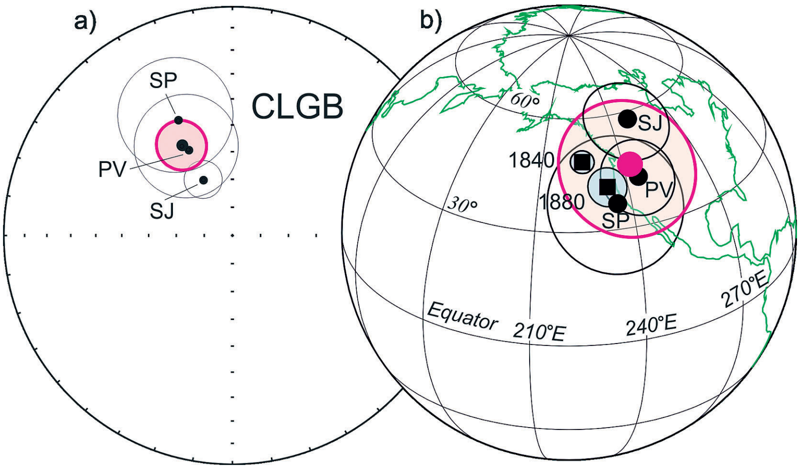

Fig. 13. (a) Mean remanence directions with α95 confidence circles from the Central Lapland Greenstone Belt (CLGB), from sites Sinermäjärvi (SJ), Saattopora (SP) and Pahtavaara (PV). (b) Mean palaeomagnetic poles from sites SJ, SP and PV and their mean pole (red) with A95 confidence circles. The 'key' poles from isotopically dated 1880 Ma and 1840 Ma formations of Fennoscandia (Buchan et al., 2000) are shown with blue confidence circles. From Airo and Mertanen (2008).

observations that indicate that the vein-hosted gold mineralizations are products of the late D3 deformational stage (Patison, 2007).

The magnetic signatures in the Svecofennian orogenic gold deposits of southern Finland are totally different from that of Lapland; the main magnetic mineral is pyrrhotite instead of magnetite, and the remanence directions point towards ENE (Jokisivu; Fig. 14a) or SW (Satulinmäki; Fig. 14b) instead of the typical Svecofennian age (1.88–1.84 Ga) NW-directions (Fig. 13). The varying orientations imply that the remanences in these formations are deflected from the original Svecofennian age geomagnetic field direction. Thereby it is proposed that the main reason for the deflection is deformation that took place synchronously with, or after the emplacement of hydrothermal fluids.

In addition to the pure deformational impact, the strong intrinsic anisotropy of pyrrhotite has to be taken into account as a cause for the deflection of remanence. The remanence of pyrrhotite does not necessarily reflect the palaeofield direction, but its direction rather follows geological structures as shown by several studies (Hargraves, 1959; Lowrie et al., 1986; Cogné, 1988; Thomson et al., 1991; Raposo et al., 2003). Because the studied formations have been intensely deformed, this factor is of great importance. The effect of intrinsic anisotropy of pyrrhotite is to rotate the remanence away from the ambient field direction towards the direction of the fault or shear structure, which forms an easy plane of magnetization. In Jokisivu, the major structural elements are NW-SE striking intense foliations and ENE plunging lineations (Figs. 2 & 15), and

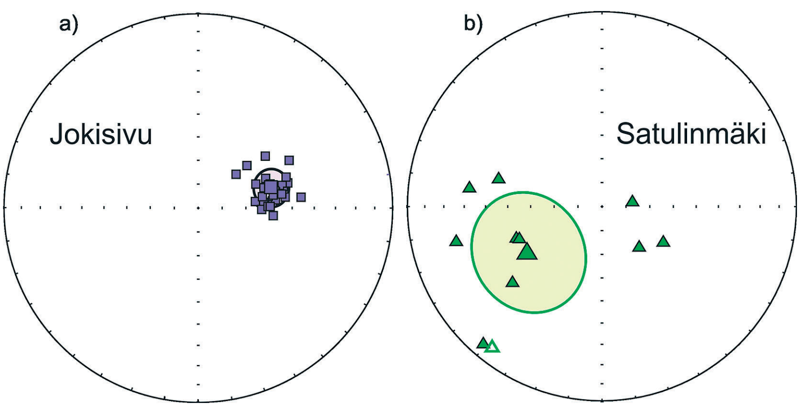

Fig. 14. Sample mean remanence directions with α95 confidence circle of the mean direction from (a) Jokisivu and (b) Satulinmäki.

in Satulinmäki, SW-NE striking foliation with a sub-vertical lineation (Figs. 3 & 16). As the mean remanence directions at both formations are aligned with these geological structures, it is possible that the deflection was also affected by them. Furthermore, AMS and remanence are related so that if the anisotropy degree is more than 10 % it is likely that the direction of remanence is deflected and does not reflect the ambient field correctly (e.g. McElhinny & McFadden, 2000). Hence, the locally extreme anisotropy degree (up to 2.5; Fig. 10a, Table 3) in Satulinmäki apparently affected the remanence and contributed to its overall direction. However, this is considered to be only of local significance. Consequently, we attribute the ambient stress field during the growth of pyrrhotite grains as the main factor controlling the deflection of remanence.

In Jokisivu, the linear and planar magnetic fabric elements (Fig. 15a) are parallel to the rock fabric elements (Fig. 15b), indicating that the magnetic fabric is a deformationally induced phenomenon. The preferred orientation of the pyrrhotite grains suggests their pre- or syndeformational formation (Clark & Tonkin, 1994). The remanent magnetization also resides in pyrrhotite, and the overall ENE pointing palaeomagnetic direction (Fig. 13a) coincides with the AMS Kmax axes as well as with the

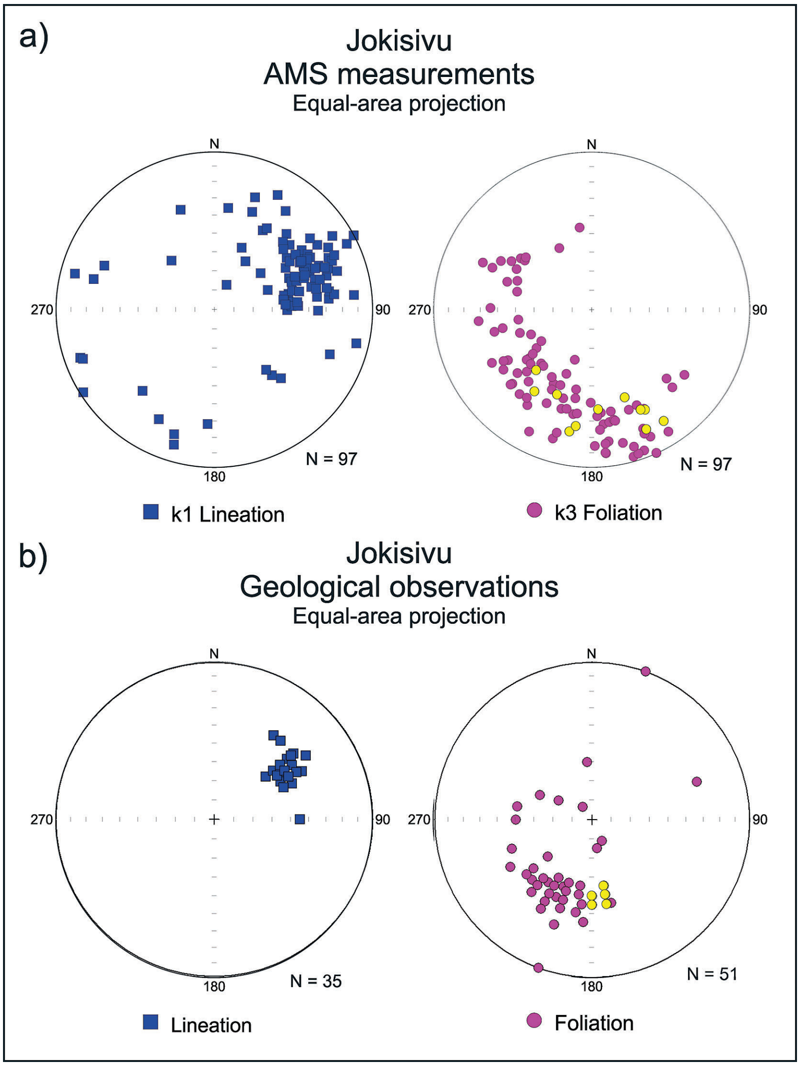

Fig. 15. (a) AMS data of all specimens from Jokisivu showing stereoplots of AMS Kmax axes (k1) and poles to the magnetic foliations (k3) (see Fig. 12c for the mean directions). Yellow dots show specimens from the shear zone core (see Fig. 13c for the mean directions). (b) Geological observations (lineation and foliation) from map area in Figure 2. Yellow dots represent a younger foliation. Geological data is from the GTK database.

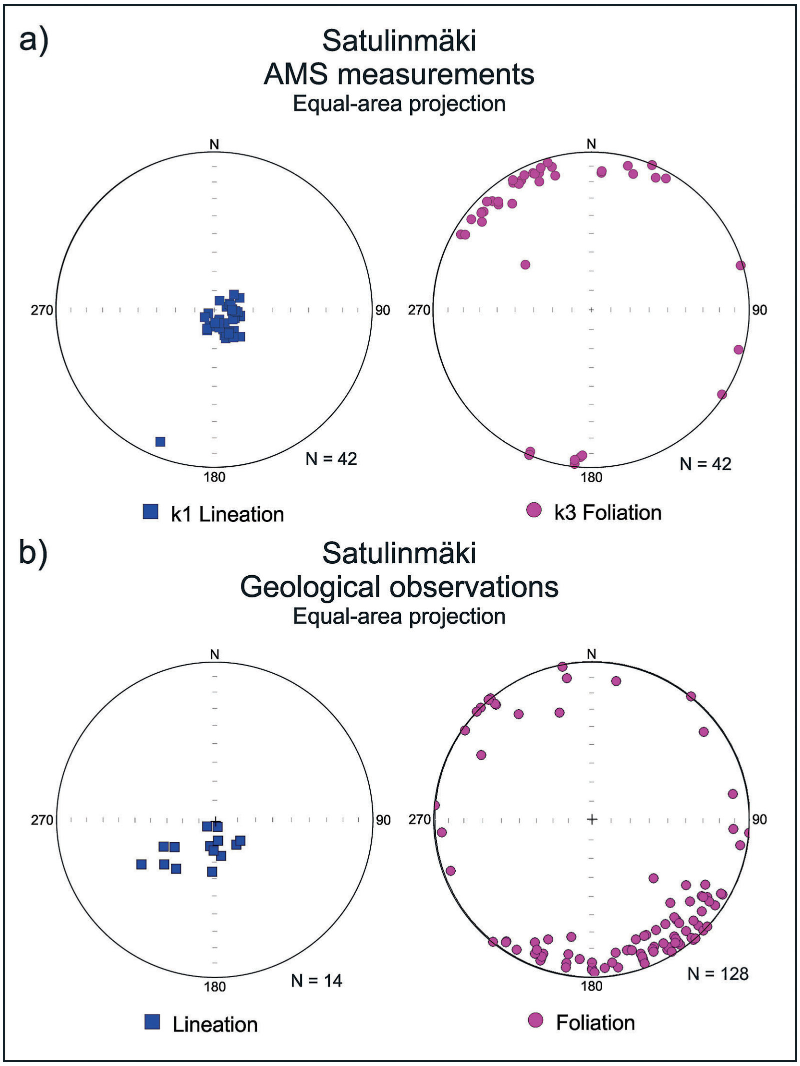

Fig. 16. (a) AMS data of all specimens from Satulinmäki showing magnetic lineations and poles to the magnetic foliations (see Fig. 14c for the mean directions). (b) Geological observations (lineation and foliation) from map area in Figure 3. Geological data is from the GTK database.

rock lineation (Fig. 15). It could, therefore, be possible that the already blocked remanence was rotated by the rotation of the pyrrhotite grains when the lineation was formed. However, this would have required significant block-rotations of the crust under brittle conditions (< 320 °C temperatures; Curie temperature of pyrrhotite). This is not, however, supported by other field data and, consequently, we suggest that the blocking of remanent magnetization towards the direction of AMS Kmax orientation took place simultaneously during the growth of pyrrhotite grains in the ductile-brittle transitional phase. The remanence was formed when the grains grew from the hydrothermal fluids in the existing stress field. Accordingly, the main conclusion from the palaeomagnetic/AMS data is that hydrothermal activity and the formation of pyrrhotite, and possibly gold, took place simultaneously with the formation of the rock lineation, thus, probably during the D2 deformation, and continued through D3 deformation, as shown below.

The ENE trending Kmax orientations are aligned parallel to the rock lineations in Jokisivu (Fig. 15a), but the magnetic foliation scatters locally significantly more with respect to the more homogeneously distributed rock foliation (Fig. 15b). This scattering may be attributed to deformation partitioning between the shear zone core and its margin observed at one sampling locality (JO; Tables 1-3). The E-W magnetic foliation observed in the shear zone core is parallel to the rock foliation from the GTK database (Fig. 15d). The lower anisotropy degree (P') in the shear zone core (Table 3) may be caused by the prolate-oblate transition or by the relaxation (heat) of the magnetic fabric by the hydrothermal fluids. One reason for the lower degree of anisotropy in the central part may also be the coarser grain sizes of pyrrhotite, which may prevent profound alignment of the grains. Furthermore, the coarser grain sizes may indicate that the minerals precipitated without strong stress, which would otherwise produce small broken grains. This may further imply that in the central part the hydrothermal fluids were emplaced later with respect to the general structure. Furthermore, the remanence directions of samples from the central part are more dispersed from the mean direction than the other samples, which may also support this interpretation from AMS. The results are in agreement with geological studies, which have implied that the outer alteration zone shows more conspicuous lineation compared to the inner alteration zone characterized by flattened structures and abundant boudinaged quartz veins, associated with gold (Eilu & Pakka, 2009). Based on this, it has been implied that the gold is slightly younger, probably formed during D3, than the formation of the main D2 lineation.

In Satulinmäki, the magnetic signatures and geological structures are in general agreement (Fig. 16) and largely correspond to the case in Jokisivu (Mertanen and Karell, 2012). Reminiscent of Jokisivu, it is assumed that pyrrhotite was formed simultaneously with gold. Therefore, it is implied that the remanence was blocked and deflected from the ambient geomagnetic field during the transitional stage from ductile to brittle deformation that took place simultaneously with the emplacement of the hydrothermal fluids. Accordingly, it is possible that the final blocking of remanence took place during the brittle stage, the minimum age of the last faulting and shearing event being about 1.79–1.78 Ga (K. Saalmann, personal communication, June 2008). The remanent magnetization is, therefore, regarded to be syntectonic and, by assuming that gold was formed in the same process, it also has similar timing.

7. Conclusions

1) Magnetization in the Jokisivu gold deposits in southern Finland is carried by coarse- to fine-grained monoclinic pyrrhotite.

2) The remanence directions in the Jokisivu deposit are rotated and deflected from the typical Svecofennian-age directions.

3) The AMS directions and structural field directions are compatible with palaeomagnetic directions in the Jokisivu deposit and previously studied Satulinmäki deposit in southern Finland. Based on this, it is implied that the hydrothermal fluids are syn-deformational. This differs form the Central Lapland Greenstone Belt deposits, which have previously shown to be late- or post-deformational.

4) In Jokisivu, the AMS data shows deviating directions at one site in the core of an auriferous shear zone. Based on the directional parameters, it is implied that the central part experienced later auriferous fluid infiltration after the main orogenic stage.

5) Combined palaeomagnetic and AMS studies have the potential to provide an additional tool in resolving the relative timing for structurally controlled gold deposits.

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