Magnetic signatures related to orogenic gold mineralization, Central Lapland Greenstone Belt, Finland

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Abstract

A number of lode–gold occurrences are hosted by hydrothermally altered greenstones along the southern boundary of the Palaeoproterozoic Central Lapland Greenstone Belt. The hydrothermally altered and mineralised zones are related to a major thrust and shear zone system that extends much across northern Finland. Spatial correlation between mineralized zones, brittle structural features and chemical alteration was explored and identified from high-resolution aeromagnetic data, in combination with airborne electromagnetic and gamma-ray spectrometric data and coupled with petrophysical and palaeomagnetic studies. The most prominent magnetic, ductile signatures formed during the Svecofennian Orogeny (1900–1800 Ma), resulting in elastic, curved, continuous magnetic patterns. These elastic anomaly patterns were disturbed by tectonic stress from S–SW, resulting in parallel, regularly oriented fracture families and thrust faults normal to the main stress direction. According to aeromagnetic, palaeomagnetic and structural evidence, the thrust zone was active during the latest stage of the orogenic event, but was also reactivated at a later date. Airborne gamma-ray data reveals zones of potassic alteration in the ultramafic rock units in the vicinity of cross-sections of these two fault sets. Chemical and mineralogical changes during alteration and metamorphism strongly affected the mafic and ultramafic host rocks throughout the deformation zone. The strong potassium enrichment and coinciding destruction of magnetic minerals resulted in enhanced potassium concentration and reduction of magnetic anomaly amplitudes. Palaeomagnetic results indicate that the remanent magnetization for the altered ultramafic rocks along the thrust zone is of chemical origin (CRM) and was acquired at 1880–1840 Ma, which is presumed also to be the age of the chemical alteration related to gold mineralization.

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1. Introduction

The Palaeoproterozoic Central Lapland greenstone belt (CLGB) in northern Finland (Fig. 1) hosts several orogenic lode–gold occurrences, whose relationships to the main deformational stages in northern Finland are known in broad outline (Ward et al., 1989; Sorjonen-Ward et al., 1992; Eilu, 1999). Although mostly small in volume, the gold-deposits include also a large one: the recently discovered Suurikuusikko deposit (Fig. 1b) is currently the largest in Europe, with reserves approaching million ounces. The Suurikuusikko deposit as well as other gold-prospective areas in Finnish Lapland have been described in more detail in a recent edition volume (Ojala, 2007).

Central Lapland is poorly exposed, but the coverage of high-resolution multi-parameter aerogeophysical data offers outstanding material for exploration purposes. Systematic airborne surveys, conducted by the Geological Survey of Finland (GTK), started at the 1970’ies and now cover the whole Finland (for more details see www.gsf.fi/aerogeo). The surveys were flown by a fixed-wing aircraft at a height of nominal 35 m with a line spacing of 200 m, and they include simultaneous magnetic, frequency-domain electromagnetic and gamma-ray spectrometric measurements (Hautaniemi et al., 2005). In the course of 30 years, the geophysical instruments have been under continuous development. Magnetic, electromagnetic and radiometric survey data were processed using standard processing methods and corrections. The survey data are interpolated to 50 m by 50 m data grids, from which the data sets covering Central Lapland were extracted. Flights over study area were...
carried out at different stages during the systematic surveys of the whole country. The magnetic recording was made in the 1970s by a proton magnetometer and since 1992 by Cesium magnetometers. The electromagnetic dual frequency unit applies frequencies $\sim 3$ kHz and $\sim 14$ kHz and vertical coplanar coil configuration. The primary EM components, in-phase and quadrature, are transformed to apparent resistivity using a half space model and can be used for visual interpretation of conductive areas. The equipment and measuring specifications through the years have been more thoroughly described in Hautaniemi et al. (2005). Mapping and classification of geological formations can be based on these data in a wide range of scales. Because gold is typically associated with small-scale structural features, dense, good-quality airborne data and sharp positioning are important when searching an ore body. Small structural features are reasonably well defined even from the data flown at 200 m line spacing, particularly because for the last twenty years, a horizontal magnetic gradiometer has been in routine use. Recent experimental surveys with line spacing decreased to 75 m have shown a still more detailed picture of the tectonic features of the uppermost crust.

Gold mineralization in the greenstone belt is associated with the contact zone between greenstones and graphite-bearing volcano-sedimentary schists (Lehtonen et al., 1998). These schists are electrically conductive, and therefore airborne electromagnetic data are important in outlining the zones of...
interest. Intense multi-stage chemical alteration characterizes the gold-prospective host rocks. The alteration has locally influenced the magnetic responses. In some places chemical alteration has involved the addition of potassium in the mafic and ultramafic rocks, in which case it has been possible to use airborne gamma-ray spectrometric for outlining the alteration zones. Chemical alteration in the greenstone belt is closely associated with brittle rock fabrics and commonly restricted to narrow zones — tens of meters in width. Integration of airborne radiometric and magnetic data, together with digital topographic data, has brought some promising results in locating alteration zones (Airo, 2002, 2007; Airo & Mertanen, 2001). Although radiometric data are strongly affected by overburden features, they have been shown to correlate reasonably well with the underlying lithology, and are gradually gaining a footing in exploration and tectonic studies also in Finland.

Petrophysical data are commonly utilized when estimating the mineral compositions of anomaly sources, magnetic mineralogy (composition and grain size), and the importance of remanence in the magnetic anomaly shape and intensity. In order to aid geological interpretation of airborne geophysical data in Finland, GTK maintains a national petrophysical database, which contains results of petrophysical laboratory measurements for more than 130,000 rock samples, including bulk density, magnetic susceptibility and intensity of remanent magnetization, together with coordinates of the sampling site and the lithological name (Korhonen et al., 1993). Summaries based on large amounts of petrophysical laboratory measurements show that the petrophysical properties for various rock types share common, typical features (Puranen, 1989; Henkel, 1991; Clark, 1997; Airo, 1999). This information makes it possible to evaluate the local changes and their importance with reference to the common properties of a certain rock type.

Integrated geodata interpretation is commonly approved as a powerful tool in mineral exploration (Jaques et al., 1997; Groves et al., 2000). In the present paper, the magnetic interpretation is complemented by petrophysical and palaeomagnetic studies in order to define the geophysical characteristics for targeting new prospects and the search of blind ore bodies. The paper deals with the influence of various factors on aeromagnetic signature with respect to gold occurrences in Finnish Lapland, in particular regional aspects. In a broad sense, these factors are either compositional or structural: concentration and composition of magnetic minerals depend on lithology, metamorphic history and chemical alteration of the host rocks of gold mineralizations. The structural pattern is controlled by rock and mineral texture and fabrics, thus reflecting the tectonic history of the rock. In principal, the magnetic responses of mineralized zones depend on the fact that magnetite is either created or destroyed in hydrothermal alteration associated with gold mineralization (Gunn and Dentith, 1997; Clark, 1997, 2001). For the CLGB, the characteristic features are the strong potassium enrichment in mafic and ultramafic rocks and coinciding magnetic reduction. The large number of known gold occurrences suggests that more similar deposits are to be found, if the relationship between the chemical alteration zones and the structural control can be solved.

2. Aerogeophysical signatures related to rock type

The aeromagnetic image of the wide greenstone belt in Finnish Lapland shows the weakly magnetic, tholeiitic province of the Kittilä Group (Fig. 1b), bordered in the south by a belt of more highly magnetic mica schists, conglomerates, mafic plutonic rocks and ultramafic, komatiitic units belonging to the Savukoski and Sodankylä Groups (Lehtonen et al., 1998; Hölttä et al., 2007)). According to regional gravity modelling, the greenstones comprise a sequence of about 5–7 km thick (Gaál et al., 1989). Archean gneisses (AG) are exposed as tectonic inliers surrounded by the Proterozoic assemblages. The southern boundary of the Kittilä Group is characterized by gently southward dipping thrust faults and related shear zones, comprising a major thrust zone that extends for more than 100 km across Lapland. Most of the CLGB gold occurrences are spatially related to this thrust zone. It is often called as the Sirkka Thrust Zone or the Sirkka Line, but in the present paper the thrust zone will be referred to as the Sirkka Trend. This is because in geophysical sense the zone is composed of several parallel thrust zones and connecting normal faults, forming together a structural Z-pattern. The thrusts are represented both by magnetic, topographic and gravimetric linear indications with the main strike of N60°W. Where the thrust faults coincide with the structurally weak lithological contact between altered ultramafic rocks and graphite-bearing schists, as between Loukinen and Sinermäjärvi (Fig. 1b), they dip gently towards SW. According to interpretations of the Polar seismic and gravity profile (Gaál et al., 1989), the Sirkka Trend dips southwards, at least in the profile area, towards the western end of the greenstone belt. The connecting faults striking N60–70°E are more steep, they disrupt the magnetic stratigraphy and their expression is magnetically sharp. They are represented also in regional gravity data as deep faults, which outline the greenstone-related gravity high.

The structural pattern of the Kittilä Group, dominated by subhorizontal folds and foliations, can be recognized both from airborne magnetic (Fig. 2a) and apparent resistivity data (Fig. 2b). Several gold occurrences in Central Lapland are found along the boundary between the strongly magnetic, mafic to ultramafic (komatiitic) rock units and magnetically weak, mainly tholeiitic volcanic rocks and sedimentary–volcanic associations, including tuffites, phyllites and black shales. These are associated with intensive electrical conductivity and may produce weak magnetic anomalies based on variable abundance of monoclinal pyrrhotite. Despite the mainly paramagnetic mineralogy of the tholeiites, their banded magnetic pattern is visible. Abundant monoclinal pyrrhotite may bring the graphite-bearing schists and tuffites a different magnetic and radiometric behaviour from that of magnetite-dominated rocks. The ultramafic rock units were originally still more highly magnetic due to their great abundance of magnetite, but polyphase chemical alteration has gradually destroyed their magnetite and reduced their magnetization. At its utmost, intense chemical alteration and simultaneous deformation have resulted in brecciated ultramafic units that totally lack magnetite.

On magnetic total field maps the influence of chemical alteration is seen as disruption of former magnetic anomalies,
leaving only isolated remnant anomalies behind. An even greater intensity of alteration results in overall weakened and smoothened anomaly pattern, ultimately leading to totally negative magnetic anomalies. Potassium enrichment in association with the decreased magnetic anomaly amplitude is particularly clearly defined in aerogeophysical data for ultramafic rock units.

Fig. 2. (a) Aeromagnetic map, (b) apparent resistivity half-space model (frequency ~ 3 kHz). The highly magnetic ultramafic unit separates the Kittilä and the Savukoski Groups. White solid lines represent the Sirkka Trend; dashed lines indicate fault systems trending N60–70°E, N15°E and N30–40°E. Frame outlines the area represented in Fig. 6. Aerogeophysical data by the Geological Survey of Finland.
along the Sirkka Trend. By examination of potassium, uranium and thorium radiation data and individual flight line data, there is an increase in K concentration coinciding with a local decrease in Th, resulting in locally increased K/Th ratios (Airo, 2007). Also, Dickson and Scott (1997) report that thorium may be mobilized during mineralization process in areas of K-alteration. As for the sulphide- and graphite-bearing schists of CLGB, their U- and Th-variation are much more informative than K for producing their aeroradiometric signatures. Since airborne radiometric data are strongly affected by overburden, there is another possible explanation for the anomalous radioelement ratios close to the brecciated ultramafic units or sulphide-bearing schists: these are easily eroded and thus dispersed into the surrounding overburden thus enhancing the radiation representing the underlying bedrock. Several occurrences of strongly altered ultramafic units – not previously known – were located on the basis of correlation between aeromagnetic signatures and airborne radiometric results, and one of them directed to further exploration and locating a mineralized zone (Airo, 2007).

The Svecofennian Orogeny (ca. 1900–1800 Ma) caused a strong magnetic overprinting on the Precambrian basement rocks in the eastern Fennoskandian shield (Mertanen et al., 1999). Komatiitic, ultramafic rocks tend to be originally highly magnetic due to their primary, mainly coarse-grained magnetite, and carry both high induced and remanent magnetizations. Secondary magnetite, produced during prograde metamorphic processes, appears commonly as fine-grained, introducing increased remanence intensities. Remanent magnetization may therefore also play an important role in the magnetic anomaly signatures. The greenstone belt was mainly subjected to greenschist facies metamorphism, and the bordering schists in the south and north reached amphibolite facies metamorphic conditions (Höltä et al., 2007). The low metamorphic grade is for the most part regarded as the explanation for the weak magnetization of the Lapland greenstones, as has been shown for greenstones in general (Grant, 1985; Clark, 1997). Where metamorphism reached amphibolite facies, secondary magnetite may have been produced, thus increasing the magnetic anomaly intensity. This is seen as increased magnetic intensity but it doesn’t greatly affect the shape of anomalies, because the known Svecofennian remanent magnetization direction does not significantly differ from the present Earth’s field direction. Locally, the greenschist-grade mafic rocks in Lapland may also represent a high magnetic intensity.

3. Petrophysical properties

The primary magnetic mineralogy in the CLGB rocks has been affected by several metamorphic, tectonic and hydrothermal alteration events (Eilu, 1999; Lehtonen et al., 1998). Since all of these influence the mineral composition of rock, some inferences concerning these processes can be obtained by examination of their petrophysical properties – the bulk rock densities and magnetic properties. The abundance, grain fabrics and texture of magnetic minerals explain the magnetic properties of rocks. Other influencing factors are the degree of alignment of magnetic minerals in a rock and the deformation history, as well as the metamorphic grade and type and intensity of chemical alteration. For better understanding of how signs of chemical alteration could be detected in airborne geophysical data, we studied altered and unaltered rocks of similar composition and compared their magnetic properties and rock densities.

According to petrophysical laboratory measurements based on more than 8000 rock samples, the CLGB rocks display bimodal magnetic property distributions, as illustrated by scatter diagrams of magnetic susceptibilities versus densities and Koenigsberger ratios (Q-ratio = the ratio of the remanent to the induced magnetization) in Fig. 3. The grey background samples in the diagrams denote samples derived from the national database and the black samples represent the investigated CLGB samples attributed to different degrees of chemical alteration. For comparison, black schists (metamorphosed black shales) from Central Lapland are included. These graphite- and sulfide-bearing schists are important key horizons adjacent to the gold-bearing host rocks because of their electrical conductivity. In CLGB they are mainly weakly magnetic, whereas elsewhere in Finland they are typically more strongly magnetic. Opposite to magnetite bearing rocks, there is a linear correlation between the magnetization and monoclinic pyrrhotite content (Airo, 2002). The magnetization of graphite- and sulfide-bearing schists increases together with the increase in pyrrhotite abundance. Also the rock densities tend to increase as the abundance of sulfides increases. Monoclinic pyrrhotite produces a distinct magnetic and radiometric behaviour from that of magnetite-dominated rocks.

The densities in Fig. 3a grow with the proportion of mafic silicates, so that more silica-rich rock types appear at lower densities and mafic rocks types have higher densities — gabbros and ultramafic rocks the highest. The densities of unaltered komatiites and metaultramafites are mainly between 2750–3000 kg/m³. The susceptibilities are divided broadly into two groups, namely the weakly magnetic group with susceptibilities of about less than 1000×10⁻⁶ (SI) and the highly magnetic group with susceptibilities of about 10000–100000×10⁻⁶. The magnetic bimodality is typical for magnetite bearing lithologies also elsewhere in Finland and depends on the content of magnetic carriers in the rocks. In the highly magnetic group of CLGB ultramafic and mafic rocks, the main ferrimagnetic mineral is almost pure magnetite (Airo, 1993) while in the weakly magnetic group the samples contain practically not enough magnetite for creating magnetic anomalies. Their magnetization is due to the paramagnetism of (Fe,Mg)2 SiO₄. The remanence intensities of the CLGB rocks vary from 1 to 8 A/m. Q-ratios for the highly magnetic group in Fig. 3b are mainly below ten and concentrate at 0.1–1. Low Q-ratios refer to coarse-grained magnetite. Increased remanence intensities have been observed to be related to irregularly shaped, broken magnetite grains. Fig. 3b represents also a large number of samples having Q-ratios >1 but low susceptibilities. These samples are not able to cause notable magnetic anomalies. For samples having low amount of magnetic carriers, also remanences may be low, and as a result, the ratio of these two low values becomes high.

Magnetic signatures of the hydrothermally altered ultramafic rock sequences of the CLGB are predominantly controlled by
partial or total destruction of ferrimagnetic minerals, or replacement minerals having lower magnetic intensities. Ultramafic lavas were originally more highly magnetic due to their great abundance of magnetite, but polyphase chemical alteration gradually destroyed magnetite and reduced the magnetization. Intense chemical alteration and simultaneous deformation resulted in brecciated ultramafic units and chrome marble that now mainly lack magnetite. The partial destruction of magnetite affects remanent magnetization in an opposite way, since smaller magnetite grain size or broken grain shapes may increase the remanence intensity (Airo, 1993). Consequently, the increasing Koenigsberger ratios ($Q$-ratios) for altered samples (Fig. 3b) may
be related to an increasing degree of alteration. At the same time, the rock densities increase because the abundance of heavy Mg- and Fe-bearing carbonates increases at the expense of the lighter mineral talc. Talc is introduced in the beginning of alteration (“soapstone”), and it is progressively replaced by carbonates. Two petrophysical trends related to alteration were observed (Fig. 3a): 1) progressive decrease in magnetic susceptibility associated with the increase in the amount of talc, succeeded by increasing occurrence of carbonates, results in paramagnetic susceptibilities because in practise all magnetite is destroyed; 2) although magnetite content decreases, the rock densities increase as the amount of heavy Fe- and Mg-bearing carbonates increases.

4. Palaeomagnetic studies

Geological observations imply that gold was probably precipitated from the hydrothermal fluids coupled with chemical alterations in the late stages of metamorphism of the area. The main aim of the palaeomagnetic studies was to define a palaeomagnetic age for the chemical alteration. During hydrothermal alteration processes new magnetic minerals can be crystallized or be formed from previously existed minerals, and a new chemical remanent magnetization (CRM) may be blocked in the rocks. Provided that the newly formed remanent magnetization is stable through time, the age of the magnetization and consequently, the age of the fluid and gold may be defined.

The remanent magnetization was measured with 2G RF SQUID magnetometer. Demagnetization was carried out by using alternating field (AF) up to 160 mT. Thermal demagnetizations did not give stable results, probably due to low intensities of remanence. Remanence directions were inspected visually by Zijderveld diagrams (Zijderveld, 1967) and the components were separated by principal component analysis (Kirschvink, 1980) using the Tubefind program (Leino, 1991). Stable results were obtained from three studied gold mines: Saattopora, Sinermäjärvi and Pahtavaara (Fig. 1). In all sites the directions of remanent magnetization are rather scattered between samples. However, for most of the samples the intensity decay curves show hard coercivities, which is interpreted to indicate the occurrence of small amounts of fine-grained magnetite or titanomagnetite. Examples of remanence behavior during alternating field demagnetization are shown in Fig. 4. The remanence directions are shown in Table 1.

At the Saattopora mine altogether ten samples were taken from two types of altered graphite bearing tuffites which contain different proportions of Fe-rich carbonate veins. The first rock type contains an older, folded vein system. The second rock type consists of a younger set of thin, 2–3 cm Fe-rich carbonate veins that cut the older veins. The younger veins host the gold. In both types the $Q$-values are high, ca. 5, indicating a fine magnetic grain size. Stable remanence directions were obtained from six samples. No clear difference can be observed in the remanence directions of the two rock types, possibly because in both of them the remanence directions are widely scattered. Nine samples were collected from the Sinermäjärvi mine, all of which are of intensely carbonatized and sericitized komatiite (chrome marble). Stable results were obtained from six samples.

Fig. 4. Examples of demagnetization behaviour of CLGB rocks during alternating field demagnetization. Specimen SP4-2A is from Saattopora, PV8-1A from Pahtavaara and SJ2-1A from Sinermäjärvi. (a) stereographic projection where closed (open) symbols indicate downward (upward) pointing remanence direction, (b) relative NRM intensity decay curves upon AF demagnetization, (c) orthogonal vector projections where solid dots denote projections onto horizontal and open dots onto vertical planes. Numbers at demagnetization steps denote peak alternating field (mT). The Present Earth’s magnetic Field (PEF) at the sampling locality is shown as a star.
The mean remanence direction is less scattered than at Saattopora. However, the inclination of the Sinermäjärvi rocks is much higher than in the Saattopora rocks which may be due to contamination of an uncleaned present Earth’s magnetic field (PEF) direction. At the Pahtavaara mine, seven samples were taken from altered komatiites containing Fe-rich carbonate veins. The remanence directions obtained from four samples are less scattered than in the Saattopora samples and the pole is close to the Saattopora pole.

On the basis of remanence directions, chemical alteration in the studied locations has totally destroyed the original remanent magnetization of the rocks (age of the rocks ca. 2200–2000 Ma), probably due to fluid circulation. In most samples the characteristic remanence direction (ChRM) is similar to the direction typically obtained from Svecofennian age rocks, ca.1900–1800 Ma (Mertanen et al., 1999). The palaeomagnetic poles, calculated from the ChRM, form a coherent group (Fig. 5) around the ‘key poles’ of the age of 1880 and 1840 Ma (Buchan et al., 2000). Thus, according to the pole positions, the latest acquisition of remanent magnetization took place at the late stages of the Svecofennian Orogeny. There are no indications of other stable remanence directions. The palaeomagnetic age is consistent with ages based on lead isotopic results (Mänttäri, 1995).

### 5. Magnetic signatures related to deformation

Aeromagnetic data for the CLGB were investigated by applying shaded relief images, horizontal derivatives at different angles and upward continuation for outlining structurally coherent provinces, fault and fracture zones and local brittle fracturing. Magnetic upward-continuation images were used for identifying regional fault zones or thrust faults that disturb the magnetically coherent provinces. The separation of magnetic anomalies due to deep or shallow sources was done on the basis of the laboratory measurements of magnetic properties representing different outcropping magnetic source rocks. Magnetic classification of deep and shallow structures in Lapland was aided by comparing the magnetic horizontal derivative images and topographic terrain model with the upward-continued magnetic data. Not the maximum anomalies but the trends of positive magnetic anomalies or of the breaks observed in horizontal derivative images were analysed when classifying fractures and lineaments in processed aeromagnetic data.

Subhorizontal folding of the CLGB greenstones is represented by continuous sets of magnetic formlines (Figs. 1b and 2). These build up coherent structural bedrock provinces, which are outlined by shear or thrust zones or deep faults. Crustal-scale shear zones are associated with negative or weak curved, regional magnetic anomalies where magnetite was destroyed from previously magnetic rocks. These zones may be traced for tens of kilometres in length. Within the magnetic provinces, the geological fabric is demonstrated by local, often attenuated magnetic anomalies or breaks in magnetic patterns. The breaks correspond to fracturing or jointing representing systematic trends. These provinces are traversed by linear faults, which in many cases can be traced as weakly magnetic lineaments for tens of kilometres, suggesting that they have considerable depth extent.

According to interpretation of airborne magnetic and electromagnetic data, the CLGB consists of regions separated either by thrust zones or by linear or slightly curved fault zones. The thrust faults, indicated by linear magnetic N60°W trending steps (Figs. 2a and 6a), are associated with a systematic, linear...

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### Table 1 Palaeomagnetic results

<table>
<thead>
<tr>
<th>Formation</th>
<th>Rock type</th>
<th>N</th>
<th>Dec (°)</th>
<th>Inc (°)</th>
<th>α95 (°)</th>
<th>K</th>
<th>Plat (°)</th>
<th>Plon (°)</th>
<th>A95 (°)</th>
<th>dp (°)</th>
<th>dm (°)</th>
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<tr>
<td>Saattopora (SP)</td>
<td>Fe-rich carbonate veins</td>
<td>6</td>
<td>334.3</td>
<td>31.3</td>
<td>21.4</td>
<td>10.8</td>
<td>36.5</td>
<td>235.5</td>
<td>17.9</td>
<td>13.4</td>
<td>23.9</td>
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<tr>
<td>Sinermäjärvi (SJ)</td>
<td>Chrome marble</td>
<td>6</td>
<td>331.6</td>
<td>58.7</td>
<td>8.8</td>
<td>59.4</td>
<td>57.7</td>
<td>248.7</td>
<td>11.3</td>
<td>9.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Pahtavaara (PV)</td>
<td>Fe-rich carbonate veins</td>
<td>4</td>
<td>330.1</td>
<td>41.1</td>
<td>10.3</td>
<td>80.0</td>
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<td>244.5</td>
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<td>Key pole 1880 Ma</td>
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Note. Key poles are obtained from isotopically well-dated igneous rocks where the remanence is primary, the magnetization age corresponding to the isotopic age (see Buchan et al., 2000). N = number of samples, Dec = declination, Inc = inclination, α95 = the radius of the circle of 95% confidence, k = Fisher’s (1953) precision parameter, Plat = palaeolatitude, Plon = palaeolongitude of the palaeopole, A95 = the radius of the circle of 95% confidence about the mean palaeopole, dp, dm = the semiaxes of the oval of 95% confidence.

Fig. 5. Palaeomagnetic poles obtained in this study are shown as circles. SP is Saattopora, PV Pahtavaara and SJ Sinermäjärvi. The 1880 Ma and 1840 Ma old reference poles of the Fennoscandian Shield (e.g. Buchan et al., 2000) are shown as squares with shaded A95 confidence circles.
change of magnetic field intensity — at places this change is only a few nanoteslas. The faults are defined as almost linear magnetic gradients in long-wavelength magnetic data and they are tens of kilometres long, suggesting a considerable depth extent. These thrust faults were possibly formed under semi-brittle conditions post-dating the main metamorphic stage, since reactions involving magnetic minerals were still able to take place. They are also related to elevated topography, expressed in the regional landscape by delineating wide depressions. These thrust faults are cut by several sets of NE–SW trending faults, which also have topographic indications. Together these thrusts and faults produce the Z-structure of the Sirkka Trend. The N60–70°E trending set of faults is more characteristic within the region of the Savukoski Group; these faults have a more fractured magnetic appearance, and they seem to be associated with hydrothermal alteration. The N30–40°E trending set of sharp, deep normal faults (Figs. 2a and 6a) are found mainly in magnetic data, within the region of the Kittilä Group. The N15°E trending systematic fault set is particularly clearly expressed in electromagnetic data. The set of almost N/S trending, slightly bending, faint structures cuts all the other structures within the Kittilä Group and continues into the Savukoski Group (Fig. 6b). According to geological field observations, these structures have both ductile and brittle characteristics, and seem to mark some late N/S shearing.

Orogenic gold deposits worldwide are characterized by structures transitional in style across the ‘brittle–ductile boundary’. In the aeromagnetic data of the CLGB, brittle deformation is observed as almost linear, faint magnetic anomaly trends in the filtered short-wavelength aeromagnetic data. Typically they appear as sets of parallel small fractures, disturbing all the earlier structures. It was found that within the CLGB area, linear sets of small fractures are mainly divided into three families on the basis of their orientation (Fig. 6c). The fracture families 1) accompany the strike of the topographic steps (N60°W) related to the Sirkka Trend; 2) follow the N60–70°E strike of the sharp faults; 3) are systematically oriented according to the N30–40°E striking fractured fault zones. In general the fracturing is most intensive along the main strike of foliation in the various greenstone units. The fracture zones associated with altered ultramafic units and sulphide-bearing schists have been enhanced by erosion since both of these rocks tend to weather and erode easily. Thus they coincide with topographic weakness zones—valleys, drainage patterns or lake shorelines. The related magnetic minima are partly due to the removal of magnetic rock material during erosion. Measurements of magnetic susceptibility on outcrops close to fracture zones revealed no systematic decline when approaching the magnetic expression of the zone.

6. Summary

The magnetic method records structural information and gives answers to both regional and local scale hypothesis. In Central Lapland, many gold occurrences are spatially related to the regional-scale structural feature, the Sirkka Trend and the related brittle fabrics of very local scale. Magnetic signatures describe the general mineral composition and magnetic mineralogy – including concentration, grain texture and magnetic fabrics – through their contribution either to induced or
remanent magnetization. Particularly in metamorphosed terrains, remanent magnetization may play an important role by influencing the magnetic anomaly intensity and shape.

Based on palaeomagnetic evidence and aeromagnetic interpretation and compared with the results of Höltä et al. (2007), the magnetic signature of the CLGB was formed during two main deformational stages: 1) the main metamorphic stage, when the continuous magnetic patterns were produced, and 2) NE to N directed late or post metamorphic tectonic movement associated with thrusting, resulting in regional magnetic breaks denoting thrust, shear and fracture zones and brecciation of ultramafic rock units. Since then, brittle fracturing and jointing has developed related to earlier faults and mirroring the CLGB fabrics. According to palaeomagnetic investigations, the latest acquisition of remanent magnetization of the studied CLGB rocks took place at the late stages of the Svecofennian Orogeny, suggesting the same timing for the chemical alteration related to gold mineralization. Alteration in turn can be connected to brittle fracturing interpreted from aeromagnetic data.

Fig. 7 summarizes the supposed magnetic deformation history of the CLGB. The greenstones originate from 2200–2000 Ma, when ultramafic and tholeiitic volcanites were deposited one upon the other (1). The ultramafic units became rich in magnetite, whereas the tholeiites were primarily magnetite-poor due to the compositional differences. The second magnetically important stage (2a) was the Svecofennian orogeny (1900–1800 Ma). The total magnetization of ultramafic units was probably increased as a result of formation of fine grained secondary magnetite. Ultramafic units are responsible for the most prominent aeromagnetic anomalies of the CLGB. The later stages (2b) of the Svecofennian orogeny, at 1880–1840 Ma, are delineated by hydrothermal alteration post the main orogenic peak. Influence of alteration on magnetic signature was to diminish the magnetic anomaly amplitude, because magnetite was either destroyed or oxidized to maghemite or hematite. Partial destruction of magnetite results in softened, smooth magnetic signatures or a fringed magnetic anomaly texture. Chemical alteration totally destroyed the primary NRM in the altered greenstones, but new secondary fine-grained titanomagnetite, able to carry CRM, precipitated from the hydrothermal fluids. Further, Fe–carbonate veins intruding the brecciated ultramafic rocks, may contain some small amounts of hematite which is also a possible carrier of CRM. However, their effect on aeromagnetic signatures is minor.

The following magnetic signatures have proven to be characteristic of lode-gold occurrences in the Central Lapland greenstone belt:

1. Continuous magnetic formlines define the folded internal magnetic structure of fractured bedrock provinces, whose boundaries are represented by thrust zones, crustal-scale shear zones or strike-slip faults.
2. Local-scale brittle features, such as local joints or faults, are spatially related to magnetically more impressive deeper structures. The regional tectonic framework tends to control the formation and geometry of later structures. The brittle structures, interpreted from aeromagnetic data, correlate with features interpreted from topographic and

\[\text{Fig. 7. Suggested magnetic evolution discussed in text.}\]
airborne radiometric data and also with geological field observations. The approximately north-south trending, brittle-ductile shear zones seem to cut all the other structures. They are found systematically all over the greenstone area, and their role as gold-prospective zones must be considered carefully.

(3) Chemically altered zones, related to brittle CLGB fabrics, are well-defined by airborne magnetic and radiometric data. Anomalous radioelement ratios, differing from the general lithological background radiation, have been shown to correlate with regions rich in sulphides or with hydrothermally altered ultramafic rocks.

(4) Due to the alteration, the primary NRM was replaced by a CRM. In most of the studied samples small amounts of fine-grained magnetite or titanomagnetite were precipitated from the circulating hydrothermal fluids. The associated remanent magnetization is of chemical origin and its age of 1880–1840 Ma can be presumed to denote the age of the hydrothermal alteration. The characteristic remanence direction is similar to the direction typically obtained for Svecofennian age rocks, ca.1880–1840 Ma.

References


