Structure-related magnetic fabric studies: Implications for deformed and undeformed Precambrian rocks

Fredrik Karell

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STRUCTURE-RELATED MAGNETIC FABRIC STUDIES: IMPLICATIONS FOR DEFORMED AND UNDEFORMED PRECAMBRIAN ROCKS

by

Fredrik Karell

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Front cover: A sampled microgranular enclave within the Vehmaa rapakivi granite batholith.
Photo: Fredrik Karell, GTK.

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ABSTRACT

The aim of this thesis research was to gain a better understanding of the emplacement of rapakivi granite intrusions, as well as the emplacement of gold-bearing hydrothermal fluids in structurally controlled mineralizations. Based on investigations of the magnetic fabric, the internal structures could be analysed and the intrusion mechanisms for rapakivi granite intrusions and respectively different deformation stages within gold-bearing shear and fault zones identified.

Aeromagnetic images revealed circular structures within the rapakivi granite batholiths of Wiborg, Vehmaa and Åland. These circular structures represent intrusions that eventually build up these large batholiths. The rapakivi granite intrusions of Vehmaa, Ruotsinpyhtää within the Wiborg batholith and Saltvik intrusions within the Åland batholith all show bimodal magnetic susceptibilities with paramagnetic and ferromagnetic components. The distribution of the bimodality is related to different magma batches of the studied intrusions. The anisotropy of magnetic susceptibility (AMS) reveals internal structures that cannot be studied macroscopically or by microscope. The Ruotsinpyhtää and Vehmaa intrusions represent similar intrusion geometries, with gently to moderately outward dipping magnetic foliations. In the case of Vehmaa, the magnetic lineations are gently plunging and trend in the directions of the slightly elongated intrusion. The magnetic lineations represent magma flow. The shapes of the AMS ellipsoids are also more planar (oblate) in the central part of the intrusion, whereas they become more linear (prolate) near the margin. These AMS results, together with field observations, indicate that the main intrusion mechanism has involved the subsidence of older blocks with successive intrusion of fractionated magma during repeated cauldron subsidence. The Saltvik area within the Åland batholith consists of a number of smaller elliptical intrusions of different rapakivi types forming a multiple intrusive complex. The magnetic fabric shows a general westward dipping of the pyterlite and eastward dipping of the contiguous even-grained rapakivi granite, which indicates a central inflow of magma batches towards the east and west resulting from a laccolitic emplacement of magma batches, while the main mechanism for space creation was derived from subsidence.

The magnetic fabric of structurally controlled gold potential shear and fault zones in Jokisivu, Satulinmäki and Koijärvi was investigated in order to describe the internal structures and define the deformation history and emplacement of hydrothermal fluids. A further aim of the research was to combine AMS studies with palaeomagnetic methods to constrain the timing for the shearing event relative to the precipitation of ferromagnetic minerals and gold. All of the studied formations are dominated by monoclinic pyrrhotite. The AMS directions generally follow the tectonic structures within the formations. However, internal variations in the AMS direction as well as the shapes of the AMS ellipsoids are observed within the shear zones. In Jokisivu and Satulinmäki in particular, the magnetic signatures of the shear zone core differ from the margins. Furthermore, the shape of the magnetic fabric in the shear zone core of Jokisivu is dominated by oblate shapes, whereas the margins exhibit prolate shapes. These variations indicate a later effect of the hydrothermal fluids on the general shear event. The palaeo-magnetic results reveal a deflection from the original Svecofennian age geomagnetic direction. These results, coupled with correlations between the orientation of the NRM vectors and the magnetic and rock fabrics, imply that the gold-rich hydrothermal fluids were emplaced pre/syntectonically during the late stages of the Svecofennian orogeny.

Keywords (GeoRef Thesaurus, AGI): granites, rapakivi, emplacement, gold ores, shear zones, fault zones, magnetic properties, magnetic fabric, magnetic susceptibility, anisotropy, natural remanent magnetization, structural geology, Proterozoic, Åland, Vehmaa, Satulinmäki, Jokisivu, Koijärvi, Ruotsinpyhtää, Finland

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The original publications this thesis is based on are referred to in the text by their Roman numerals.

Paper I: Karell, F., Ehlers, C., Airo, M-L. & Selonen, O. 2009. Intrusion mechanisms and magnetic fabrics of the Vehmaa rapakivi granite batholith in SW Finland. Geotectonic Research 96, 53–68.

Paper II: Karell, F., Ehlers, C. & Airo, M.-L. (manuscript). Emplacement and magnetic fabrics of rapakivi granite intrusions within Wiborg and Åland rapakivi granite batholiths in Finland.

Paper III: Mertanen, S. & Karell, F. 2012. Palaeomagnetic and AMS studies on Satulinmäki and Koijärvi fault and shear zones. In: Grönholm, S. & Kärkkäinen, N. (eds) Gold in Southern Finland: Results of GTK studies 1998–2011. Geological Survey of Finland, Special Paper 52, 195–226.

Paper IV: Mertanen, S. & Karell, F. 2011. Rock magnetic investigations constraining relative timing for gold deposits in Finland. Bulletin of the Geological Society of Finland 83, 75–94.

THE AUTHOR'S CONTRIBUTION TO THE PUBLICATIONS

In Paper I, F. Karell carried out the AMS sampling, sample preparation and measurements. F. Karell had the main responsibility for preparing the manuscript, interpretations and conclusions.

In Paper II, F. Karell carried out the AMS sampling, sample preparation and measurements. F. Karell had the main responsibility for preparing the manuscript, interpretations and conclusions.

In Paper III, F. Karell carried out the fieldwork together with co-author S. Mertanen. The AMS interpretations were carried out by F. Karell and the palaeomagnetic interpretations by S. Mertanen. Rock magnetic interpretations were done in cooperation with the co-author.

The manuscript was jointly written together with the co-author.

In Paper IV, F. Karell carried out the fieldwork together with co-author S. Mertanen. The AMS interpretations were carried out by F. Karell and the palaeomagnetic interpretations by S. Mertanen. Rock magnetic interpretations were done in cooperation with the co-author.

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1 INTRODUCTION

The structure of rocks normally provides some information on the history of deformation and how the rock units have been emplaced. The study of geological structures has been relevant in understanding the dynamics of the Earth, as well as for economic purposes. One of the essential branches of investigation of geological structures is analysis of the petrofabrics of rocks. The fabric in a rock normally refers to components such as the texture, structure and preferred crystallographic orientation that spatially and geometrically make up a rock.

Rocks in natural outcrops provide structural information and can be further studied under the microscope to gain more information on their internal microstructures, the shapes and arrangement of crystals, in addition to their composition and mineralogy. Traditionally, field observations and thin section analysis of rocks have been and still are important sources of information for structural geologists studying the fabric of a rock. However, traditional studies on the preferred crystallographic orientation (PCO) have involved a rather difficult and time-consuming method to quantitatively measure larger numbers of specimens (cut into oriented thin sections). Neutron texture goniometry, more recent method used for bulk volume texture measurements of relatively large (up to several cm^3) samples, offers an opportunity to measure several pole figures simultaneously with a high penetration depth (Brokmeier 1997, Leiss et al. 2000, Brokmeier et al. 2011). This method has advantages over traditional methods (including microscopic and also X-ray goniometric methods), but is still rather uncommon due to its low accessibility to researchers. In addition to other techniques, analysis of the anisotropy of magnetic susceptibility (AMS) has proven to be an excellent tool for the further examination of mineral fabrics, magma flow and the deformation of rocks (Tarling & Hrouda 1993). The magnetic anisotropy of rocks depends on the anisotropy of individual grains and their spatial arrangement. It is a rapid, inexpensive method that can be systematically performed on all types of rocks.

In different geological terrains, rock magnetic studies can have a key role in resolving many compositional and structure-related geological problems. Magnetic properties provide information on compositional variations, while the magnetic fabric (examined by AMS analysis) reflects structural aspects within rock units. The results presented in this thesis deal with the magnetic fabrics of deformed and undeformed rocks. In some cases, such as rapakivi granites, their petrofabrics cannot be seen macroscopically, and even under a microscope the structural features are seldom detectable. The emplacement and intrusion mechanisms of rapakivi granites are poorly understood. The AMS studies included in this thesis provide new information on the mechanisms that have contributed to the emplacement of these rapakivi intrusions, which eventually form large batholiths. The thesis also comprises studies from auriferous shear zones that have a complex deformation history and structural context where AMS can provide additional information on the deformation. Together with palaeomagnetic data, it is possible to constrain the relative timing for these gold-forming events.

1.1 Magnetic properties of rocks

Rock magnetism has been an essential physical property for numerous Earth science studies over many decades. Rock magnetic properties provide information on the nature and behaviour of rocks and minerals that is essential in various geological disciplines. Magnetic properties describe the behaviour of a material under the influence of a magnetic field. Most natural rocks are heterogeneous in composition, with distinct physicochemical properties. Rocks and minerals are divided into diamagnetic, paramagnetic and ferromagnetic materials based on their magnetic structure and ability to become magnetized (O'Reilly 1984, Butler 1992, Dunlop & Özdemir 1997, Paranasis 1997, Schön 2004).

In diamagnetic minerals, the electron orbits in the complete electron shells generate magnetization in the opposite direction to the applied field, which produces a negative magnetic susceptibility. In paramagnetic minerals, the electrons spin in the incomplete electron shells and produce magnetization in the same direction as the applied field. This is seen as a positive magnetic susceptibility when an applied magnetic field is present. When the applied magnetic field is removed, the magnetization disappears. Therefore, paramagnetic minerals do not carry remanence. Ferromagnetic minerals have strong interactions between electrons that couple so that the alignments of the atomic dipole moments produce a net moment and a positive magnetic susceptibility. Depending on the configuration of the magnetic sublattices, ferromagnetic minerals can be subdivided into ferromagnetic, ferrimagnetic, antiferromagnetic and spin-canted antiferromagnetic minerals. Ferromagnetic minerals show a hysteresis loop of magnetization, as the magnetization is not linear with the external field. Ferromagnetic minerals lose their spontaneous magnetization at the Curie point (TC). Below the Curie temperature, ferromagnetic minerals have a high magnetic susceptibility and can carry remanence. Above the Curie point, these minerals become paramagnetic, their susceptibility decreases and the remanence disappears.

Magnetic susceptibility describes the ability of a material to become magnetized when exposed to an external magnetic field, while remanent magnetization measures the magnetization that has been stored in the rock after the crystallization of ferromagnetic minerals. The remanence of a magnetic material can therefore provide information on the magnetic past by recording the ancient magnetic field. Paramagnetic minerals do not carry remanent magnetization and cannot be used to determine old magnetizations.

1.1.1 Magnetic susceptibility (MS) and its anisotropy (AMS)

The magnetic susceptibility (MS) of rocks is controlled by the amount of magnetic minerals they contain. It can be controlled by ferromagnetic, paramagnetic and diamagnetic minerals. MS can, as a parameter, be used for several purposes, including mapping and research on geological events, such as petrological, metamorphic and metasomatic processes, as well as environmental studies. This is because the magnetic properties depend on the geochemical and mineralogical composition within a geological unit. The magnetic susceptibility (k) of rocks is defined as the relationship between induced magnetization (M) and the applied magnetic field (H): $M = k \times H$, and thus reflects the response of a material to the applied magnetic field. It has a dimensionless unit in SI, and susceptibility is normally expressed per unit volume, referred to as bulk or volume susceptibility.

Magnetic susceptibility is anisotropic in most rocks. Anisotropy is caused by a combination of the preferred orientation of grains, the spatial distribution of mineral grains and the intrinsic anisotropy of grains (shape or crystalline anisotropy). Textural anisotropy can cause anisotropy, for instance, when ferromagnetic minerals are closely aligned in specific patterns. The anisotropy of magnetic susceptibility (AMS) has been established as a useful method for the interpretation of petrofabrics since the mid-1950s, when Graham (1954) published his seminal work on the use of AMS as a tool for describing the fabric of rocks. Early research mainly focused on the application of AMS to the main structural features of sedimentary (Graham 1966) and igneous rocks (Stacey 1960). Since the 1950s, the AMS technique has been developed and proven to correctly and efficiently represent the fabric of rocks (e.g. Hrouda 1982, Tarling & Hrouda 1993, Borradaile & Henry 1997, Bouchez 1997, Martín-Hernandez 2004, Lanza & Meloni 2006, Borradaile & Jackson 2004, 2010). In polymineralic rocks, all minerals (diamagnetic, paramagnetic and ferromagnetic) contribute to the AMS of the rock. Earlier, it was considered that ferromagnetic components were mainly responsible for the observed AMS because of higher susceptibilities with respect to the dia- and paramagnetic matrix. However, following studies by Hirt et al. (2000), Martín-Hernández & Ferré (2007) and Hirt & Almqvist (2012), among others, it is now evident that in many cases the anisotropy is carried by paramagnetic or even diamagnetic phases.

AMS is mathematically described as a symmetrical second rank tensor, which can be visualized as an ellipsoid with three principal axes: maximum (k1), intermediate (k2) and minimum (k3) susceptibility (Fig. 1). 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 the corrected anisotropy degree parameter P', which ranges from one (isotropic sphere) upwards. The shape of the ellipsoid is described by parameter T, where the shape ranges from prolate or linear (T = -1) through neutral (T = 0) to oblate or planar (T = 1) (Jelínek 1981).

The anisotropy degree is defined as: $P' = \sqrt[2]{2(\ln k_1 - k_{mean})^2 + 2(\ln k_2 - \ln k_{mean})^2 + 2(\ln k_3 - \ln k_{mean})^2}$

where the mean susceptibility is expressed as: $k_{mean} = (k_1 + k_2 + k_3) / 3$

The shape of the AMS ellipsoid is defined as: $T = \left[\frac{2\ln(k_2 / k_3)}{\ln(k_1 / k_3)} \right] - 1$

1.1.2 Induced and remanent magnetization

The magnetization of rocks is composed of both induced magnetization (Ji) and remanent magnetization (Jr). Induced magnetization reflects the magnetization of rocks in the present Earth's geomagnetic field. Remanent magnetization is permanent magnetization and exists without an external field. The total magnetization (J) of a material is the vector sum of these two components: J = Ji + Jr. Remanent magnetization or natural remanent magnetization (NRM) reflects the past geomagnetic field that was blocked during the formation of the rock (Clark 1997, Schön 2004).

The Koenigsberger ratio, Q = Jr/ Ji, is the ratio between remanent and induced magnetization. The Q-ratio can be used to estimate the magnetic mineralogy of rock samples and, subsequently, also the significance of remanence within magnetic anomalies. If the Q-ratio is 1, the induced and remanent magnetization are equal. If the Q-ratio is larger than 1, remanence dominates and the magnetic anomaly is probably carried by fine-grained (single-domain) magnetite or pyrrhotite. If the Q-ratio is less than 1, induced magnetization dominates and the magnetization is probably carried by coarse-grained (multi-domain) magnetite (Puranen 1989).

Rocks have a magnetic memory, which may be preserved for billions of years. When a rock cools below its Curie temperature, e.g. 580 °C for magnetite, it records the primary remanent magnetization vector of the then-existing magnetic field and retains the direction as long as the temperature is below 580 °C. This phenomenon is known as thermal remanent magnetization (TRM). Later, the remanent magnetization of rock can be subjected to metamorphic and tectonic processes, and secondary remanence components will be acquired from these geological processes. In palaeomagnetic studies, one of the main tasks is to identify and separate these stable components. This is normally done by demagnetization techniques, either by using alternating field (AF) demagnetization or thermal demagnetization (Dunlop & Özemir 1997, Butler 1998, McElhinny & McFadden 2000). A stepwise increasing alter-

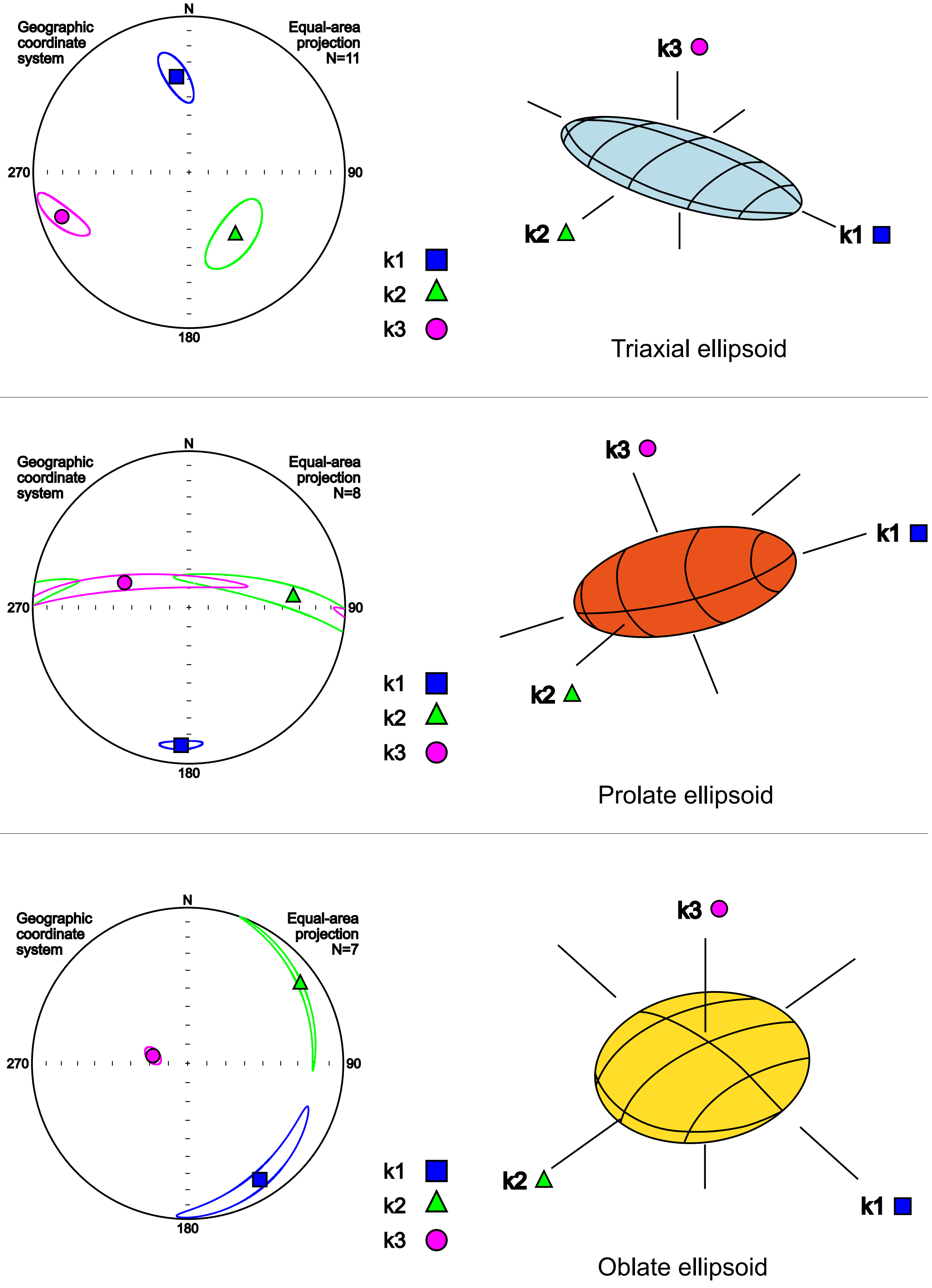

Fig. 1. The AMS ellipsoid. Modified after Tarling and Hrouda (1993).

nating field, typically up to 160 mT, removes soft viscous and other unwanted secondary remanences. In thermal demagnetization, the sample is gradually heated to higher temperatures, typically up to 400 °C, 600 °C or 680 °C. These techniques can isolate remanence components either due to their different coercivities by AF or due to the temperatures at which the remanence was acquired.

Because NRM may consist of separate components, they can represent different geological processes. For example, during hydrothermal events, new ferromagnetic minerals can be formed or existing minerals can be re-crystallized. These magnetizations of secondary origin, i.e. chemical (CRM) or thermochemical remanent magnetization (TCRM), can be produced from fluids or other geological processes. Even though TRM is typically a primary magnetization and CRM and TCRM are secondary, both types record the past geomagnetic field direction. By comparing the obtained secondary CRM or TCRM remanence directions (often below 300–400 °C) with known directions, the timing for the geological process in which the secondary remanence was formed can be established.

1.1.3 Magnetic mineralogy

Different ferromagnetic minerals can be identified on the basis of their characteristic Curie temperature (TC). In thermomagnetic analyses (k_{bulk}-T), 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, the thermal effect on magnetic minerals can be observed and the minerals identified.

Magnetic minerals can be further analysed by three-component isothermal remanent magnetization (IRM) studies (Lowrie 1990). In these studies, the specimens are subjected to three high magnetic fields (1.5 T, 0.4 T and 0.12 T) in different positions. The specimens are then thermally demagnetized step by step up to 680 °C. After each step, remanent magnetization is measured. The minerals are then identified based on their characteristic Curie temperatures. Besides mineral identification, the measurements also provide information on the domain states.

2 OBJECTIVES OF THE STUDY

The objective of this thesis is to present rock magnetic and, in particular, magnetic fabric studies that addressed magma emplacement and intrusion mechanisms in composite rapakivi massifs, as well as the emplacement of gold-bearing hydrothermal fluids in structurally controlled mineralizations. The studied rapakivi granite intrusions, namely Ruotsinpyhtää (Wiborg batholith), Vehmaa and Saltvik (Åland batholith), as well as the mineralized formations of Jokisivu, Satulinmäki and Koijärvi are shown in Figure 2.

Aeromagnetic data are essential for understanding the emplacement of rapakivi intrusions, but also for providing regional and local aeromagnetic frameworks for mineralized shear and fault zones. Aeromagnetic data provide valuable information on structures that can be further investigated in more detailed magnetic fabric studies. For large rapakivi granite batholiths, aeromagnetic images not only show the location of intrusion centres, but also give some compositional and structural information (Airo 2005) on the emplacement of the magma. Concerning gold-bearing deformed zones, the main structures are clearly detectable on aeromagnetic maps.

AMS is currently considered one of the most efficient methods for analysing fabrics in igneous rocks (Mamtami et al. 2012). AMS is a well-established method, and many studies have been conducted regarding the magnetic fabric of different kinds of geological applications. This thesis research, however, combined two subjects that have been focused on very little. Rapakivi granites are considered undeformed in the sense that no major orogeny has affected their original texture or mineralogical composition (Rämö & Haapala 2005), and no internal structures can be seen macroscopically or in microscopic studies. However, magnetic fabric studies revealed internal structures that explain the intrusion mechanisms for the three selected rapakivi granite batholiths in Finland (Papers I and II).

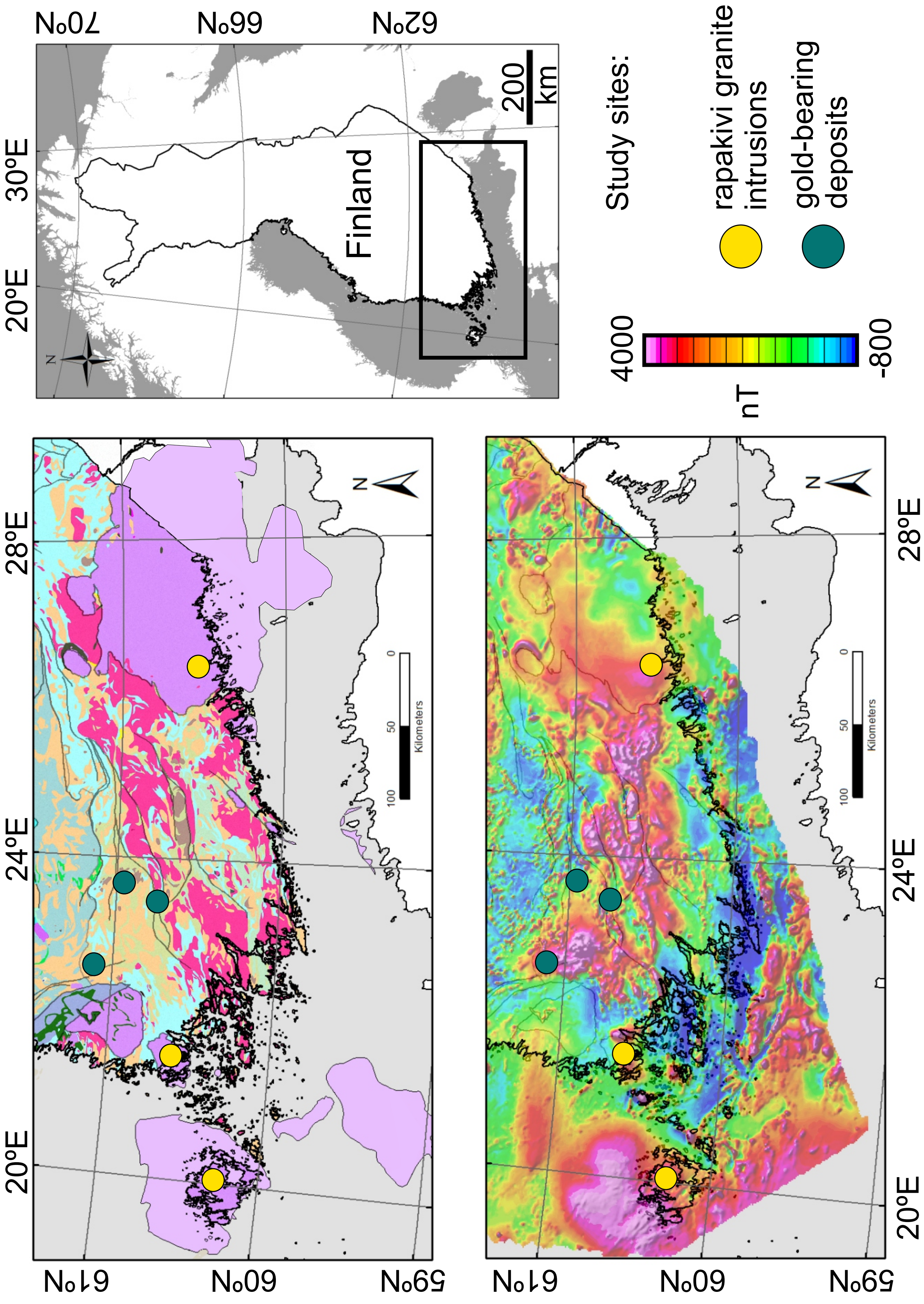

Fig. 2. Geological and aeromagnetic images of southern Finland. The geological map is modified after Korsman et al. (1997). Aeromagnetic data © Geological Survey of Finland.

This thesis also presents AMS investigations on the internal structures within mineralized gold occurrences, and their relationship with the emplacement of hydrothermal fluids (Papers III and IV). Structurally controlled gold occurrences in southern Finland have a very complex deformation history (Saalmann et al. 2009), and through detailed AMS measurements a more precise structural analysis has been presented. The magnetic fabric is also compared with NRM directions to constrain the timing of gold-related hydrothermal events.

2.1 Undeformed rocks (rapakivi granites)

Classical rapakivi granites are considered as a sub-group of A-type granites that are characterized by the presence, at least in larger batholiths, of granite varieties showing the rapakivi texture (Haapala & Rämö 1992, Rämö & Haapala 2005, Vigneresse 2005). Rapakivi intrusions typically have a bimodal composition. The intrusions are preceded by the injection of mafic dyke swarms and larger batholiths are associated with various mafic rocks (Elo & Korja 1993), showing mingling of silicic and mafic magmas (Eklund & Shebanov 1999). There have been many successful publications on the origin, geochemistry and petrogenesis of these classical rapakivi granites, ever since the pioneering studies of Sederholm (1891) in the late 19th century (Rämö & Haapala 1995, Haapala & Rämö 1999, Rämö & Haapala 2005 and references within). However, only few attempts to describe the emplacement and intrusion mechanisms of rapakivi granites have so far been published. In the mid-1980s, Ehlers and Bergman (1984) and Bergman (1986) proposed a cauldron-type subsidence model for the emplacement of Fjälskär and parts of the Åland rapakivi batholith. Selonen et al. (2005) adapted a similar model to the Vehmaa intrusion. Grocott et al. (1999) explained the emplacement of rapakivi granites of Greenland by floor depression and roof uplift of these tabular intrusions. Only two papers have been published on the application of AMS to rapakivi granites sensu stricto. Puranen (1991) estimated the magnetic fabrics of the Wiborg rapakivi batholith and the associated mafic rocks and roof pendants. In his studies, the actual emplacement of the rapakivi granites was not discussed in detail. Recently, Oliveira et al. (2011) published a successful investigation regarding emplacement on the Brazilian rapakivi pluton based on AMS and gravity studies. Only a few other AMS studies have been conducted on A-type granitic plutons (Geoffrey et al. 1997, Ferré et al. 1999, Bolle et al. 2003). Many models have been proposed for the emplacement of granitic plutons (e.g. Hutton 1996, Petford et al. 2000, Vigneresse 2004), of which diapiric growth, ballooning and stoping are among the forceful models. However, field observations from the studied rapakivi granites have not revealed any indications of forceful emplacement, as country rock xenoliths or deformation fabric within the studied plutons have been lacking. A more realistic model for rapakivi granites would be a cauldron subsidence model (e.g. Myers 1975, Roobol & White 1986, Johnson et al. 2002), which has already been proposed for rapakivi granites by Ehlers and Bergman (1984), Bergman (1986) and Selonen et al. (2005).

High-resolution aeromagnetic images (Figs. 3 and 5) reveal distinct structures within the Finnish rapakivi granite batholiths that can be resolved by magnetic susceptibility measurements. The distribution of magnetic minerals within distinct rapakivi granites and the anisotropy represented by magnetic foliations and lineations can uncover structures that cannot be macroscopically or even microscopically detected. AMS therefore provides valuable information to resolve the internal structures within the intrusions, and explain the emplacement of these rapakivi granites.

Within the context of the first part (undeformed rocks) of this thesis research, the following working hypotheses were tested:

Hypothesis 1: Fennoscandian rapakivi granites are paramagnetic ilmenite series granites.

Hypothesis 2: Rapakivi granites in Finland have been emplaced by cauldron subsidence (Ehlers & Bergman 1984, Bergman 1986, Selonen et al. 2005).

Hypothesis 3: The large rapakivi granite batholiths in Finland are comprised of large "homogeneous" masses with several stocks simultaneously emplaced as large complexes.

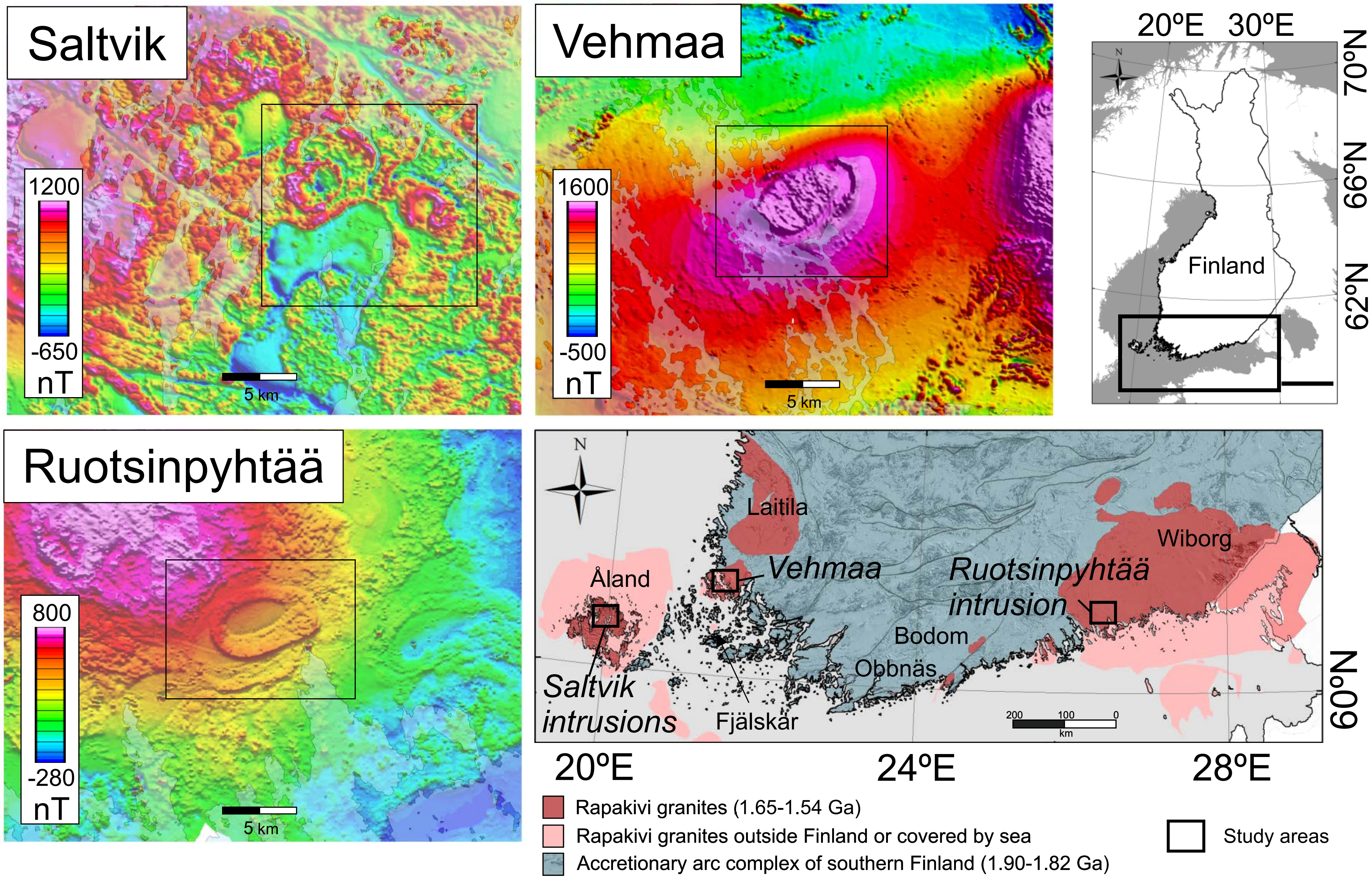

Fig. 3. Aeromagnetic images of studied rapakivi intrusions from Saltvik (Åland), Ruotsinpyhtää (Wiborg) and Vehmaa. Aeromagnetic data © Geological Survey of Finland.

2.2 Deformed rocks (gold mineralized shear and fault zones)

Finland has during the last ten years been profiled as one of the most attractive mining countries in the world with its good infrastructure, extensive data sets and good geological knowhow. In recent years, attention has also focused on southern Finland (Grönholm & Kärkkäinen 2012), which was previously considered relatively non-profitable in terms of economic geology. Today, many new studies are particularly evaluating the economic value of structurally controlled gold-bearing formations in southern Finland. The geology and ages of the host rocks are well known, but the actual timing of the gold precipitation is not very well known. Even though AMS is a well adapted method to investigate the structures of deformed rocks (see Borradaile & Jackson 2004, 2010), relatively few papers have applied AMS to structurally controlled mineral deposits within deformation zones (e.g. Zhang et al. 1997, Sandrin & Elming 2006, Skyttä et al. 2010, Jensen & Elming 2012).

As can be seen in Figure 4, the structurally controlled gold-mineralizations studied in southern Finland are located in the vicinity of larger shear zones, but are also characterized by strong local shearing and faulting (Saalmann et al. 2009). The host rocks of the studied mineralizations represent metamorphosed and deformed basic and intermediate volcanic rocks in Satulinmäki and Koijärvi, and a variety of quartz dioritic to gabbroic rocks in Jokisivu. Their petrofabrics are often macroscopically measurable in the field by traditional methods. AMS, however, can provide more precise structural numeric information about the directions related to the deformation of the rocks.

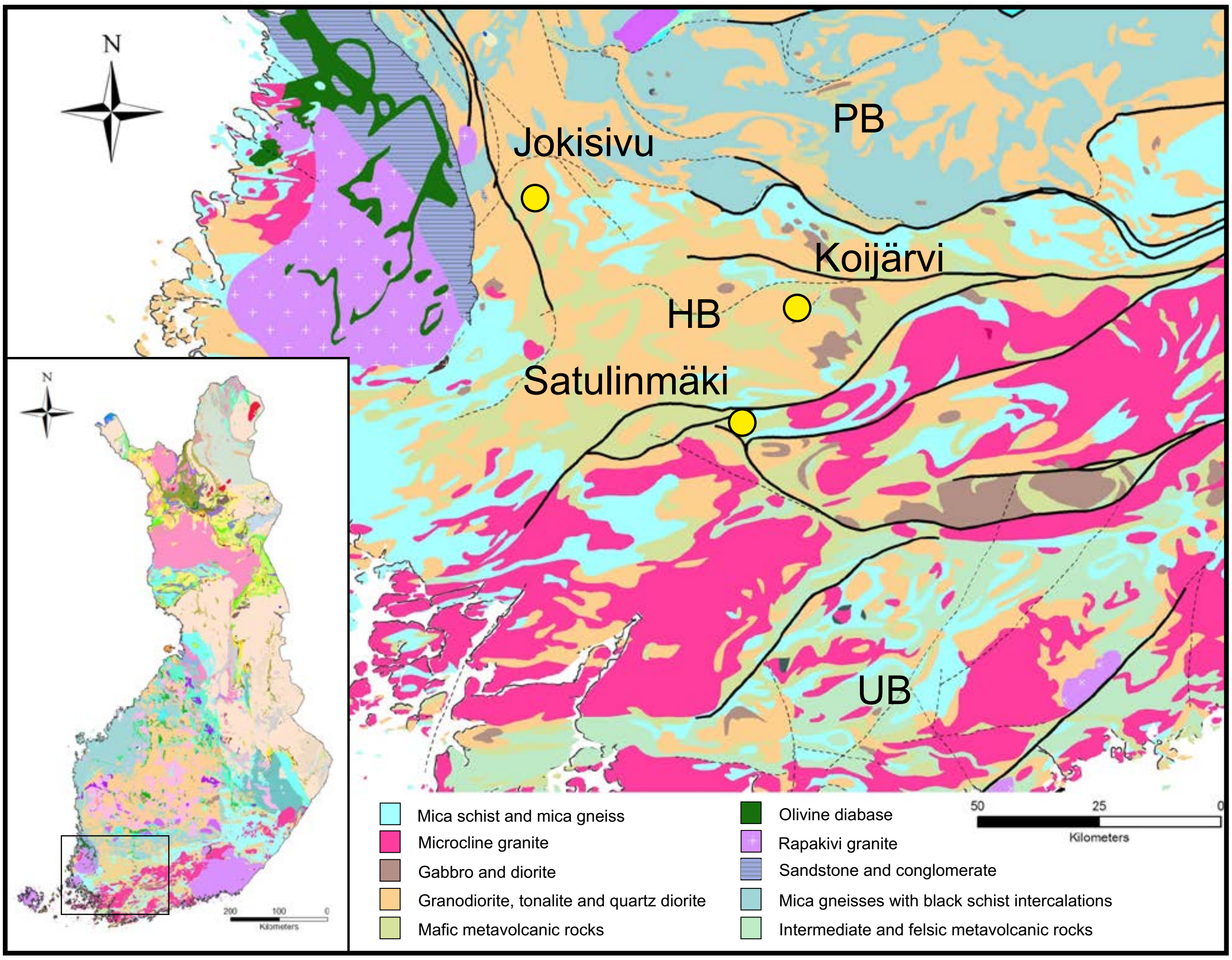

Fig. 4. Geological map of southern Finland (modified after Korsman et al. 1997). PB = Pirkanmaa Belt, HB = Häme Belt, UB = Uusimaa Belt. The Jokisivu deposit is located in the western part of the PB, Satulinmäki and Koijärvi deposits are located within the HB. The location of the map is shown as a square in the inserted geological map of Finland (Korsman et al. 1997).

In this thesis research, AMS investigations were carried out to define and investigate the internal structures of the auriferous zones. Furthermore, combined AMS with NRM studies were conducted in order to provide some age constraints for the gold-forming processes, coupled with studies on the genesis of magnetic minerals (Papers III and IV).

For the second part (deformed rocks) of this thesis research, the following working hypotheses were tested:

Hypothesis 4: Magnetic fabric analysis can reveal internal structures within shear zones.

Hypothesis 5: The precipitation of gold within shear zones was emplaced simultaneously with the tectonic stress that developed the shear zones.

Hypothesis 6: The gold mineralization in Satulinmäki took place at 1.82–1.79 Ga (Saalmann et al. 2009).

3 DATA SETS, SAMPLING AND LABORATORY EQUIPMENT

3.1 Data sets

The Geological Survey of Finland (GTK) carried out systematic airborne geophysical surveys during 1972–2007 that covered the entire country (Moore 2008). The aerogeophysical database provides high-resolution magnetic, electromagnetic and gamma ray spectrometric data (three-in-one) with a flight altitude of 30 m and a line spacing of 200 m for scientific and commercial use (Hautaniemi et al. 2005). The aeromagnetic data together with geological and gravity datasets by GTK, the data of the Geodetic Institute of Finland and the digital topographic data by the National Land Survey of Finland provide an extensive set of regional data that can be used for multipurpose geological interpretations. Furthermore, GTK also provides a national petrophysical register of more than 130 000 samples (Korhonen et al. 1997), which forms an important link between the aerogeophysical data and geological interpretations. At GTK, all geological and geophysical datasets are systematically stored in one metadatabase, and the combined use of multidisciplinary data by geographic information systems provides a tremendous amount of data for statistical and spatial analysis.

3.2 Sampling

All AMS and palaeomagnetic samples in the field were taken with a portable drill, the length of the cores typically being about 8–10 cm, thus allowing the preparation of approximately two to three cylindrical specimens of 2.1 x 2.4 cm (~11 cm^3) from each core. The cores were oriented using a combined magnetic and sun compass.

The AMS sampling of the rapakivi granites was mostly conducted within metre scale from each site, from which 3-5 drill cores were taken. Altogether, 26 sites from the Vehmaa rapakivi granite batholith, 45 sites from the Ruotsinpyhtää intrusion of the Wiborg batholith and 32 sites from the Saltvik intrusions within the Åland rapakivi batholith were sampled (Papers I and II).

For the deformed rocks, most of the samples were taken as profiles across the general trend of the structure, shear zone or the vein system (Papers III and IV). In addition to field samples, four borehole cores from the Loppi drill core depot of GTK were measured and examined (Paper III). Most samples from these cores were oriented, but some unoriented samples were also taken in order to examine their magnetic stability. The Loppi cores were prepared in the laboratory to form standard cylindrical specimens (~11 cm^3). All samples studied for rock magnetic properties (Papers I–IV) were prepared and measured in GTK's Geophysical Laboratory.

3.3 Laboratory equipment

Densities, magnetic susceptibilities, intensities of remanent magnetization and Königsberger ratios (Q, the ratio of remanent to induced magnetization) were determined for all specimens. Densities were defined based on Archimedes' principle (Kivekäs 1993). The volume susceptibility was measured with GTK's kappabridge (applied alternating field 48 or 130 A/m and frequency 1025 Hz, Puranen & Puranen 1977).

The samples in the database of GTK were measured with a GTK-built AC bridge, constructed and designed for larger hand samples and with an applied field intensity of 48 A/m. Samples for the basic petrophysical data (magnetic susceptibility and density) for Papers III and IV were measured using a GTK-built AC bridge designed for smaller cylindrical specimens with an applied field intensity of 130 A/m (Puranen & Puranen 1977).

The AMS measurements were conducted with a KLY-3S Kappabridge by Agico Inc. with an applied field intensity of 300 A/m, and the results were statistically analysed using ANISOFT software (Jelínek 1978, www.agico.com).

The thermomagnetic measurements were conducted using the Kappabridge KLY-3S combined with the CS-3 furnace apparatus (Agico, Inc.). In the measurements, crushed samples of ~0.5 g were used. Because of the relatively simple magnetic mineralogy, only selected specimens were measured at the low liquid nitrogen temperature (-192 °C). Samples were heated in an argon environment to reduce the formation of secondary magnetic minerals.

Remanent magnetization measurements (both laboratory IRM and palaeomagnetic measurements) were carried out using a 2G-Enterprises superconducting SQUID RF magnetometer. The IRMs were produced with a Molspin pulse magnetizer. For palaeomagnetic measurements, 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 remanence components were visually inspected from Zijderveld diagrams (Leino 1991, Zijderveld 1967) and the components were identified using principal component analysis (Kirschvink 1980). Mean remanence directions were calculated by using Fisher (1953) statistics.

4 REVIEW OF PAPERS

4.1 Paper I: Intrusion mechanisms and magnetic fabrics of the Vehmaa rapakivi granite batholith in SW Finland.

Paper I presents rock magnetic and AMS data together with field observations and geochemical data from the central part of the Vehmaa rapakivi granite batholith. The aim of the study reported in the paper was to examine the constraint of intrusion mechanisms using AMS and to delineate the internal structures of the most central magma batches that can be identified from high-resolution aeromagnetic data.

The magnetic properties separate two almost identical medium-grained rapakivi granites (inner and outer zone) based on their magnetic susceptibilities (Fig. 6) into two different magma pulses. Thermomagnetic measurements (Fig. 7) indicate that the high magnetic susceptibility of the inner zone is derived from magnetite and the low susceptibilities of the outer zone are derived from paramagnetic minerals (e.g. mafic silicates). The inner and outer zone granites also show a different geochemical character, with the inner zone being more evolved and fractionated. The well-defined magnetic fabric of the inner granite indicates that the magnetic foliations follow the concentric structure and dip gently outwards. The magnetic lineations dip gently away from the centre and strike along the slightly elongated inner granite mainly to the SW and NNE (Fig. 8). Field observations verify an almost complete lack of brecciation and contact deformation. The contacts dip gently outward and an umbrella pattern of gently outward dipping porphyritic aplite dykes on the outer margin of the batholith is observed. The geochemistry together with field observations verifies that the oldest granites occur at the margin and the youngest in the centre of the batholith.

These results indicate that the main intrusion mechanism involves the subsidence of older blocks with successive intrusion of fractionated magma during repeated cauldron subsidence. Magnetic lineations indicate an inflow of magma mainly from the SW and NNE.

4.2 Paper II: Emplacement and magnetic fabrics of rapakivi granite intrusions within Wiborg and Åland rapakivi granite batholiths in Finland

Paper II focuses on the magnetic fabric and the emplacement of the two largest rapakivi granite batholiths in Finland: Wiborg and Åland. The Ruotsinpyhtää intrusion was investigated in the Wiborg rapakivi granite batholith and the Saltvik intrusions in Åland. The studied intrusions within the batholiths are clearly visible on aeromagnetic maps (Fig. 3).

The Ruotsinpyhtää intrusion within the Wiborg batholith consists of a concentric rim of dark wiborgite around an even-grained rapakivi granite unit. The surrounding rapakivi granite is wiborgite. Magnetic susceptibilities and thermomagnetic measurements show that the dark wiborgite has higher magnetic susceptibilities derived from magnetite than the even-grained rapakivi granite, which is paramagnetic (Figs. 6 and 7). However, the susceptibilities of the dark wiborgite do not exceed 3 600 k(µSI). The magnetic fabric of the Ruotsinpyhtää intrusion shows that the magnetic foliations follow the concentric dark wiborgite and dip gently to moderately outwards in the south and more steeply in the north of the intrusion (Figs. 9a and 10a). These results, together with field observations, indicate that the main intrusion mechanism for the Ruotsinpyhtää intrusion was through a collapsing type of cauldron subsidence.

The Saltvik intrusions within the Åland batholith consist of a few intrusions of even-grained rapakivi granites and pyterlites within the surrounding wiborgite. The magnetic susceptibilities of the Saltvik intrusions are higher and paramagnetic varieties are less common (Fig. 6). By comparing magnetic susceptibilities in the database of petrophysical properties in Finland (provided by GTK), much higher magnetic susceptibilities (over 20 000 k(uSI)) are more frequent within the Åland batholith than within the other rapakivi batholiths in Finland. These results also demonstrate that the Finnish rapakivi granites are comprised of paramagnetic and magnetite-bearing rapakivi granites. The well-defined magnetic fabric of the studied intrusions within the Åland batholith shows that the magnetic foliations mainly dip inwards towards a central magma conduit (Fig. 9b). These results indicate that the intrusions of Åland show a more laccolitic emplacement than a classical cauldron subsidence emplacement, as in Ruotsinpyhtää.

Field observations from both study areas show no brecciation, signs of stoping or contact deformation near the contacts of the distinct rapakivi types. These observations, together with the AMS results, indicate that space for magma was predominantly created by collapse-type emplacement via repeated cauldron subsidence. Alternatively, gradual subsidence followed by repeated successive inputs of magma batches eventually formed these concentric intrusions (Fig. 10b).

4.3 Paper III: Palaeomagnetic and AMS studies on Satulinmäki and Koijärvi fault and shear zones

Paper III presents petrophysical, palaeomagnetic and magnetic fabric (AMS) results from two structurally controlled gold potential shear and fault zones in the late Svecofennian Häme Belt, southern Finland: the Satulinmäki formation in Somero and the Koijärvi formation in Forssa (Fig. 4). The aim of this research was to define the internal structures by AMS and to attempt a first-stage application to combine palaeomagnetic and AMS methods in evaluating the timing of the shearing event with respect to the precipitation of gold and associated magnetic minerals. The magnetic mineralogy of Satulinmäki and Koijärvi shear zones is dominated by monoclinic pyrrhotite, which is the carrier of the remanent magnetization and also responsible for the AMS. In Koijärvi, multidomain (MD) magnetite is also present. Samples that contain MD magnetite do not carry remanent magnetization, but could be responsible for AMS. Magnetite represents a primary mineral and pyrrhotite is related to the later hydrothermal activity, precipitated simultaneously with gold.

The results show that the overall AMS directions follow the general SW–NE shear structure. However, Au-rich samples from Satulinmäki show AMS foliations that cut the general fault and shear structure in an E-W direction. This E–W foliation represents a later shearing that took place within the shear zone. The Koijärvi samples also show internal variation of the magnetic foliations within the shear zone. Samples from the Koijärvi shear zone do not carry stable remanence, but an outcrop outside the heavily sheared area and samples from deeper parts (borehole cores between 10–96 m) have retained the primary Svecofennian direction. These well-preserved samples also show lower anisotropy degrees than samples from the shear zone. It is generally assumed that NRM results are not affected if the AMS degree (P') is less than 1.10, in which case the expected primary remanence direction may have been preserved and the remanence reflects the ambient geomagnetic field (e.g. McElhinny & McFadden 2000). The preservation of primary remanence is either due to the location in deeper parts of the crust or due to the survival of some well-preserved regions within the zones that are unaffected by shearing. Alternatively, it is also possible that the deeper parts experienced fracturing and post-tectonic fluid flow when new magnetic minerals were precipitated. However, in most samples of Koijärvi, the degree of anisotropy is very high, and the remanence directions are deflected. Nevertheless, both the strongly sheared rocks and the well-preserved host rocks generally show similar magnetic foliations and lineations, indicating they were both influenced by the same tectonic stress.

Previous studies by Saalmann et al. (2009) have estimated that the gold mineralization in Satulinmäki took place at 1.82–1.79 Ga. The expected remanence direction of undeformed late-Svecofennian rocks would be directed to the NW. The obtained NRM directions in Satulinmäki, however, are directed to the SW, which implies that the remanence was rotated due to the deformation of the shear and fault zones. The deflected SW directions of the remanence are aligned with the NE–SW-trending foliation plane, defined by AMS.

Because the NRM vectors are aligned along the magnetic and structural fabrics, a rotation of the initial Svecofennian remanence direction has taken place. As monoclinic pyrrhotite has a Curie temperature of 320 °C, and because rotation is unlikely in brittle conditions, the interpretation is that the deflection and rotation of the remanence direction must have taken place shortly after the last cooling and precipitation of pyrrhotite, simultaneously with the hydrothermal events in the late stages of the Svecofennian orogeny.

4.4 Paper IV: Rock magnetic investigations constraining relative timing for gold deposits in Finland

Paper IV presents results from the gold-bearing Jokisivu formation in southern Finland and elaborates on the previous studies from Satulinmäki (Paper III) in comparison with previous studies from the Palaeoproterozoic Central Lapland Greenstone belt (CLGB) in northern Finland (Airo & Mertanen 2008). The magnetic features of the Svecofennian orogenic gold deposits of Jokisivu and Satulinmäki are completely different from the CLGB; the magnetization in Jokisivu is carried by coarse- to fine-grained monoclinic pyrrhotite, similarly to Satulinmäki. The magnetization of the CLGB, on the other hand, is carried by magnetite.

The remanence directions from the Jokisivu deposit point to the NE and are therefore deflected and rotated from the expected Svecofennian-age directions. Previous studies (Paper III) have reported that the NRM directions from Satulinmäki are also deflected and rotated to the SW, lineated with the foliation plane measured by AMS. In the case of Jokisivu, the NRM directions are compatible with the magnetic lineations, which trend moderately to the NE. These features could be explained by the remanence direction already being blocked when the rotational processes occurred and the lineation was formed. However, this would require significant block rotations of the already brittle crust (under 320° C, the Curie temperature for pyrrhotite), which is not supported by other geological field data. Our suggestion is that the blocking of the remanence towards the direction of the obtained magnetic lineation direction took place simultaneously during the growth of the pyrrhotite grains from the hydrothermal fluids in the ductile-brittle transitional phase.

The magnetic fabric studies revealed deviating directions and shapes in the core of one of the auriferous shear zones (Fig. 12). The gold-rich shear zone core revealed E–W-striking magnetic foliations, lower anisotropy degrees and predominantly planar shapes instead of NNE-dipping foliations and linear shapes seen in the margins of the shear zone. Lower P' values and oblate shapes may be caused by heat from hydrothermal fluids, which resulted in coarser pyrrhotite grains that are not so profoundly aligned. These features indicate that the auriferous central core of the shear zone was later affected by the auriferous fluids with respect to the margins. It is consequently interpreted that gold was precipitated during the latest phases of the last deformational stage of the Svecofennian orogeny.

5 DISCUSSION AND SUMMARY OF CONCLUSIONS

The studies presented in this thesis demonstrated that AMS is an effective tool for displaying structural data on very distinct geological objects, from undeformed rapakivi granites to structurally controlled deformed Au-bearing shear zones. However, the results are not always straightforward to interpret. Complementary data to support the AMS results are also needed, such as geological field observations, magnetic mineralogy and thin section studies, geochemistry and gravity studies. Gravity and seismic studies combined with AMS investigations are in general a successful concept for describing the three-dimensional (3D) shapes and emplacement of granitic plutons (e.g. Ameglio et al. 1997, Vigneresse & Bouchez 1997, Ameglio & Bouchez 1999, Petford et al. 2000, Oliveira et al. 2008, 2010). Comprehensive methods and data are the key to interpreting the magnetic fabric of any geological object.

5.1 Aeromagnetic signatures

Aeromagnetic data reveal both regional and local-scale structures that are relevant to the tectonic environment and mineralogical composition (Airo 2005). The aerogeophysical dataset of GTK, together with information on density, magnetic susceptibility and remanent magnetization from the petrophysical database of GTK, have allowed us to further interpret structures of the Finnish bedrock, as well as the crustal evolution and tectonic environment (Airo 2005, Reeves 2005, Moore 2008).

In this thesis research, reported in Papers I and II, the aeromagnetic data allowed us to locate elliptical structures referred to as intrusions within these rapakivi granite batholiths (Fig. 5). The magnetic anomalies of the studied intrusions can most likely be explained by their magnetic susceptibility. Variations in the NRM data from rapakivi granites are relatively indistinct, with low Q-ratios (unpublished material), and do not contribute to the magnetic anomalies.

Besides intrusions, aerogeophysical data also reveal weakness zones, seen especially within the Åland rapakivi granite batholith (Figs. 3 and 5). Fault systems are generally important for magma transport and the emplacement of larger batholiths (Petford et al. 1993). The weakness zones that partly crosscut the rapakivi granites seen on aeromagnetic and topographic maps within the Åland batholith might be signs of older Svecofennian shear zones, and could have functioned as transport channels for the magma ascent. These zones are in most cases covered by vegetation or the sea. Aerogeophysical data from the Wiborg batholith revealed no relevant reminiscence of weakness or shear zones, but the intrusions tend to be elongated in the SW–NE direction. Especially in the northwestern part of the batholith, the shapes of the Artjärvi and Sääksjärvi intrusions (studied by Lukkari 2002) are prolonged in the SW–NE direction, whereas the intrusions in general are more concentric towards the centre. One possible explanation for this is that the asso-

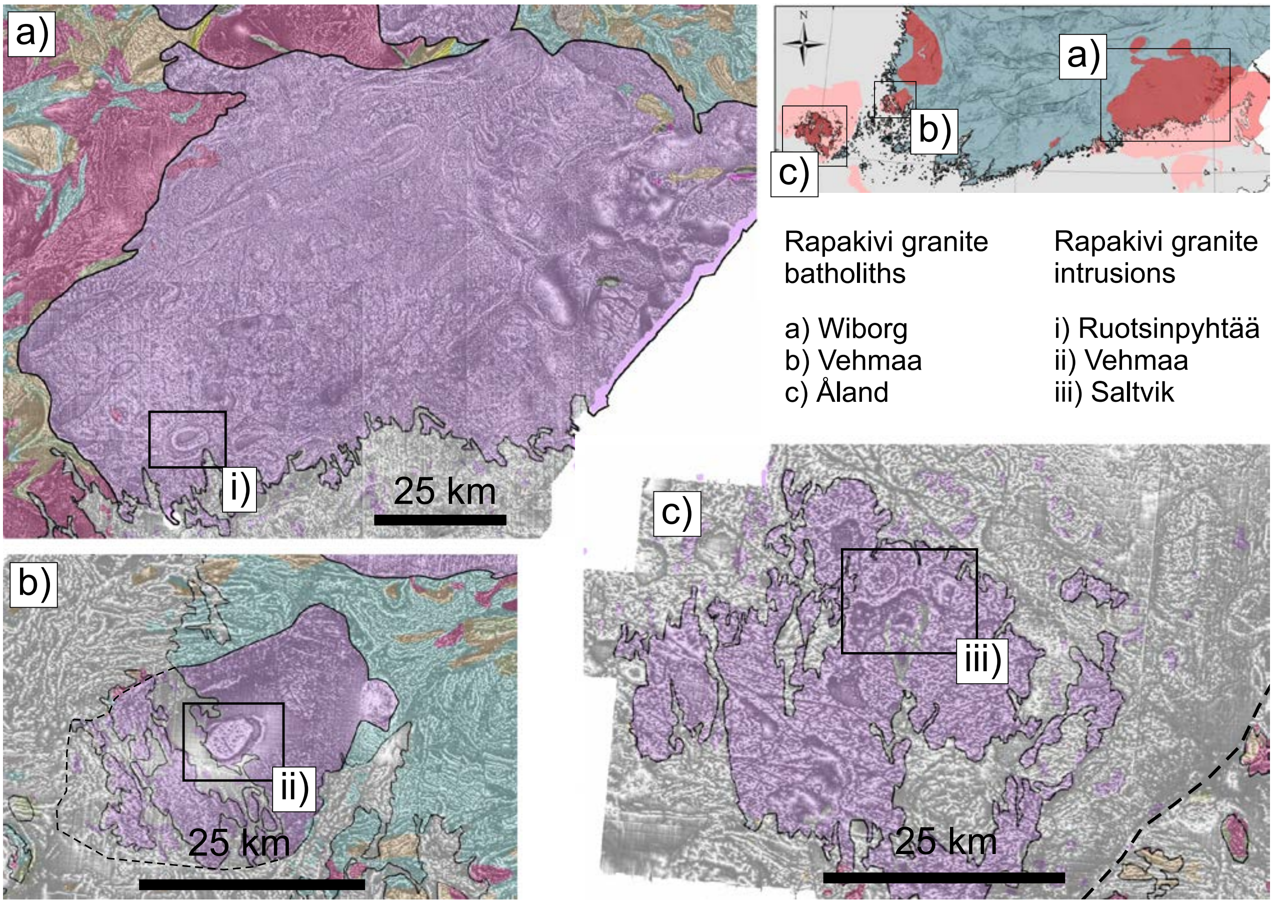

Fig. 5. Aeromagnetic tilt derivate image of a) Wiborg, b) Vehmaa and c) Åland rapakivi granite batholiths. The rapakivi granites are shown in violet. Study areas are marked with squares: i) the Ruotsinpyhtää intrusion within the Wiborg rapakivi granite batholith; ii) the Vehmaa intrusion; and iii) the Saltvik intrusions within the Åland rapakivi batholith. Aeromagnetic data © Geological Survey of Finland.

ciated NW-trending dyke swarms of Häme point to an extensional tectonic setting at the time of formation of the rapakivi granites. This might be the case in general, but possible another explanation for the extremely prolonged intrusions of Artjärvi and Sääksjärvi is that they have intruded into older tectonic structures (Hutton 1996) of the Svecofennian bedrock. Signs of deformation within these rapakivi granites were not, however, found in the field, and they have not previously been reported in the literature. One example of possible rapakivi emplacement along a still existing shear zone is the Obbnäs and Bodom rapakivi granite plutons (Fig. 3) located in the vicinity of the Porkkala–Mäntsälä shear zone (Laitakari et al. 1996, Kosunen 2004). Studies on secondary magnetizations by Preeden et al. (2009) have demonstrated that the Porkkala–Mäntsälä shear zone and adjacent faults have been reactivated during different times, with one primary component being acquired during the cooling of the bedrock in the late stages of the Svecofennian orogeny, and a secondary component being recorded at the time of rapakivi emplacement, as well as a later Permian component. However, their intrusion mechanisms have not yet been studied in detail, although their mode of emplacement might differ from the studied intrusions within larger batholiths because of the direct association with the reactivated shear zone.

5.2. Magnetic properties and AMS of undeformed rapakivi granites

Based on the studies reported in Papers I and II, AMS can be a very informative method for determining the internal structures and emplacement of undeformed "anorogenic" rapakivi granites. Emplacement studies on granitic bodies have already been successfully performed using AMS for decades (e.g. Chlupáčová et al. 1975, Archanjo et al. 1995, Bouchez 1997, Wennerström & Airo 1999, Ferre et al. 1999, Bolle et al. 2003, Mamtami & Greiling 2005, Žák et al. 2008, Stevenson et al. 2008).

Granites have earlier been divided into ilmenite (reduced) and magnetite (oxidized) series (Ishihara 1977) based on their magnetic mineralogy. More recently, Dall´Agnol and Oliveira (2007) classified rapakivi granites according to their magnetic appearance, defining Finnish rapakivi granites as reduced ilmenite series granites. In the case of Finnish rapakivi granites, magnetic susceptibility measurements indicate that all the studied intrusions are bimodal in their magnetic composition (Fig. 6). The thermomagnetic studies reported in Papers I and II demonstrated that magnetite together with paramagnetic mafic silicates was present in all the studied intrusions in Wiborg, Åland and Vehmaa rapakivi granite batholiths (Fig. 7). Magnetic susceptibility data from the petrophysical database of GTK also established that the majority of rapakivi granites from the Åland rapakivi granite batholith have high magnetic susceptibilities (Paper IV). The contributions of paramagnetic (mafic silicates) and ferromagnetic (magnetite) types of rapakivi granites are also related to the emplacement of distinct magma batches that eventually build up these large batholiths. In the central part of the Vehmaa batholith, the two almost identical magma batches have completely distinct magnetic properties (Paper I).

The studies from Papers I and II indicate that rapakivi granite types with a slightly higher proportion of ferromagnetic minerals are more suitable for reliable AMS results. It is considered that if the percentage of ferromagnetic minerals exceeds 0.1%, which can be referred to a magnetic susceptibility of about 3000–4000 μSI, the AMS is unaffected by the dia- and paramagnetic matrix. If the magnetic susceptibility is lower than 500 μSI, the matrix is dominant (Lanza & Meloni 2006). This feature is especially evident in the case of Ruotsinpyhtää, where only small amounts of magnetite are present and the paramagnetic and ferromagnetic components might be superimposed. Based on thin section analysis and thermomagnetic measurements, the magnetite grains are not oxidized or altered. Therefore, the low magnetic susceptibilities are related to a low magnetite content rather than the alteration of magnetite. In Vehmaa, specimens from the paramagnetic outer zone also show less confident AMS results. It is still an open question whether this feature could be resolved by separating paramagnetic and ferromagnetic components using high-field AMS measurements (Martín-Hernández & Hirt 2001).

The Finnish rapakivi granites generally lack any solid-state deformation features, and combined with low anisotropy degrees the magnetic fabric can be considered magmatic in origin. The studied rapakivi granites with only paramagnetic minerals may give AMS directions that are not very well defined due to their isotropic texture. However, magnetite does contribute to better-defined AMS directions, and in most cases the magnetic foliations and lineations can be determined with rather small confidence angles.

Investigation of the magnetic fabric provides information on the structures of the intrusions, which helps in determining the emplacement and intrusion mechanisms. The magnetic lineations from Vehmaa show indications of magma flow that was mainly intruded from the southwest and northeast (Fig. 8a). Prolate AMS shapes are observed near the outer margins, which become more oblate towards the centre (Fig. 8b). Together with the gently to moderately outward dipping concentric magnetic foliations, the AMS data indicate piston-type cauldron subsidence and intrusion of magma along the margins (Fig. 8c). A similar model for emplacement can be proposed for the Ruotsinpyhtää intrusion within the Wiborg rapakivi granite batholith (Figs. 9a and 10a). However, in this case the linear AMS data are not so well developed and cannot be interpreted as magma flow in the same sense as at Vehmaa. The Saltvik intrusions within the Åland batholith show a somewhat distinct pattern, where the magnetic lineations trend along the contact with moderate to gentle plunges. A proposed explanation for this is that space is provided by subsidence, but is still limited, and the magma flow is therefore emplaced

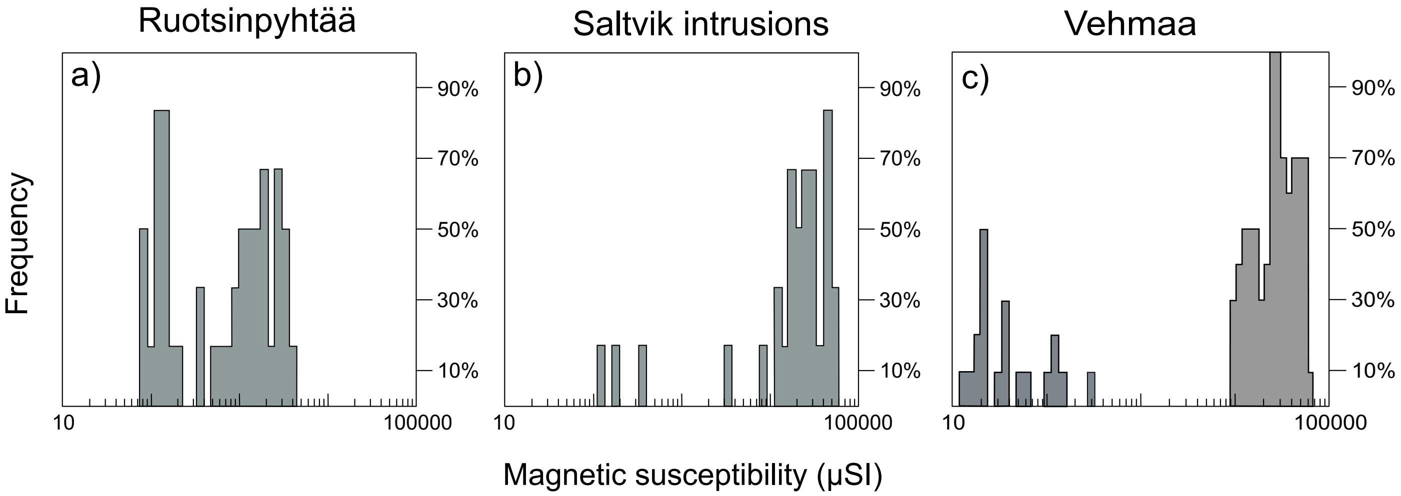

Fig. 6. Frequency histograms of magnetic susceptibilities from a) the Ruotsinpyhtää intrusion (Wiborg), b) the Saltvik intrusions within the Åland batholith and c) the Vehmaa intrusion.

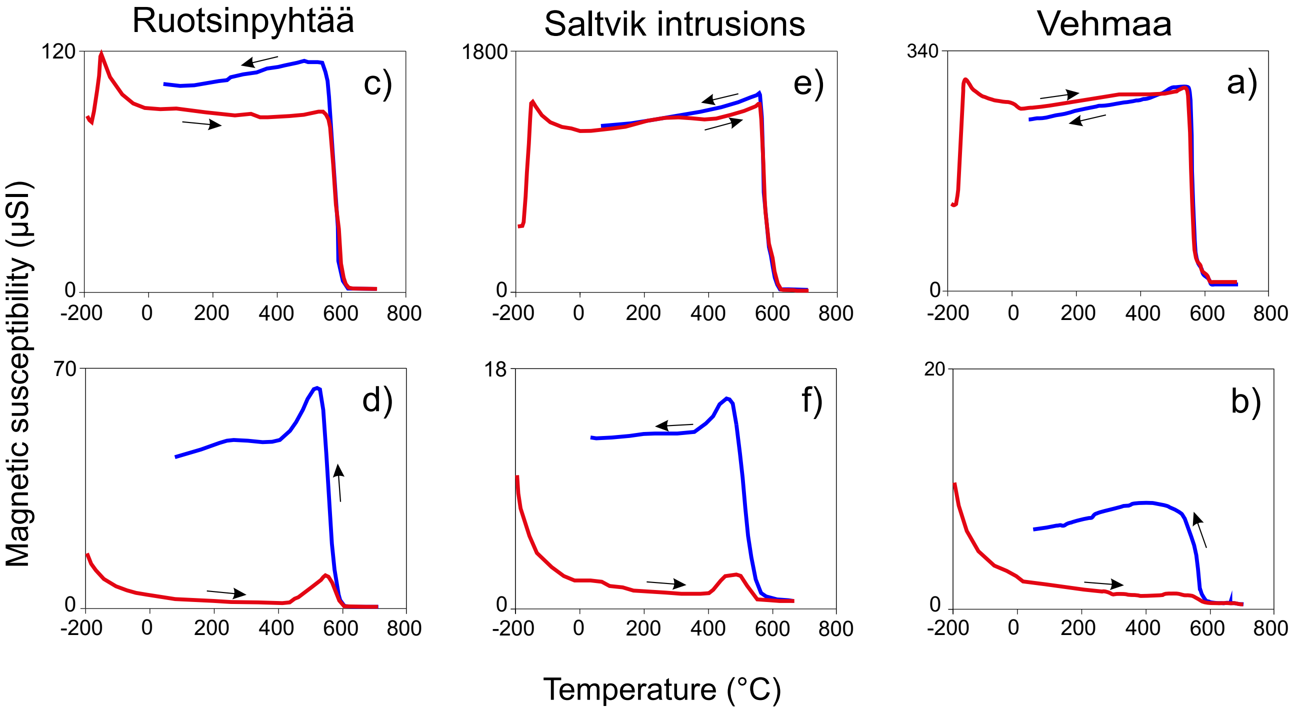

Fig. 7. Thermomagnetic measurements of rapakivi granites from the Ruotsinpyhtää (Wiborg), Saltvik (Åland) and Vehmaa intrusions. High susceptibility rapakivi granite types show a susceptibility curve typical for MD magnetite a), c) and d) with a Verwey transition at ca -150 °C. Rapakivi granites with low susceptibility from each study area b), d) and f) show a parabolic kbulk-T curve. The heating and cooling curves are marked with arrows. The samples were measured at liquid nitrogen temperature (from -192 °C to room temperature), and from room temperature to 700 °C and back to room temperature in an argon environment.

along the contacts. The magnetic foliations show both westward and eastward dipping of the distinct rapakivi granites, which indicates a laccolitic central inflow of magma batches mainly towards the west but also towards the east (Figs. 9b and 10b).

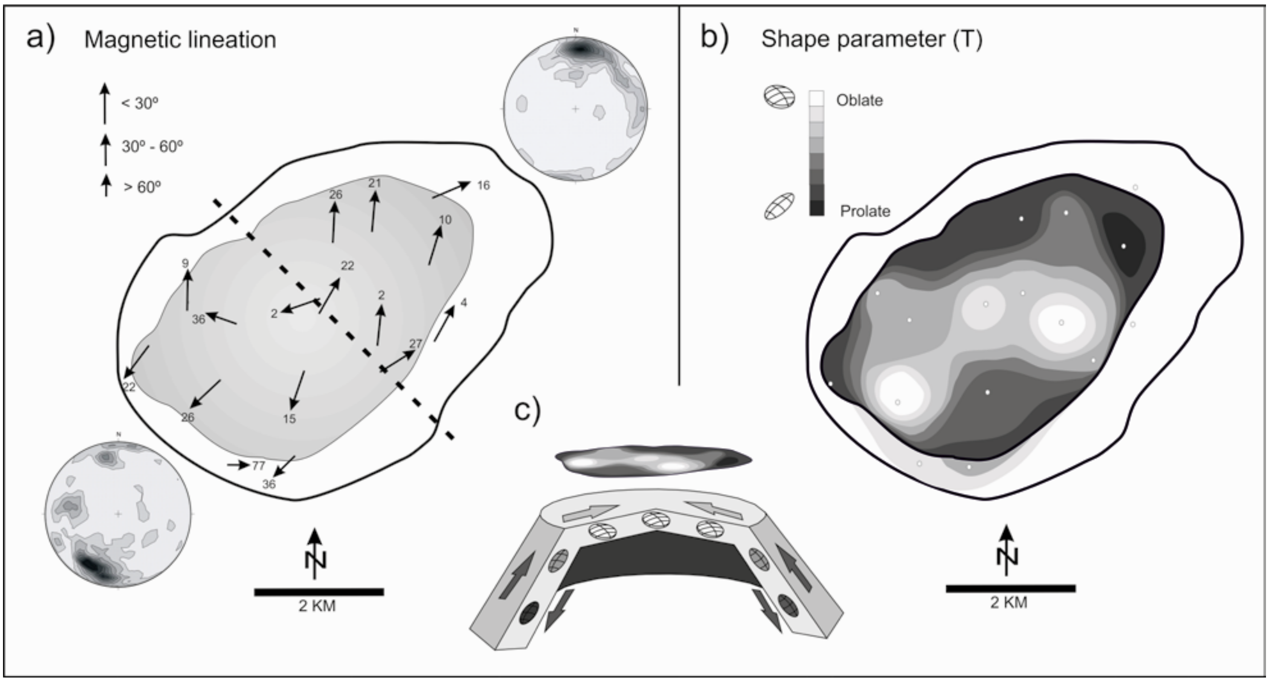

Fig. 8. a) Magnetic lineations as indicators of magma flow within the central part of the Vehmaa rapakivi granite intrusion. The mean magnetic lineations are calculated with Jelínek's statistics (Jelínek 1978). The northeastern part of the magnetic lineations points to the NNE (stereo plot) and the southwestern part of the magnetic lineations points to the SW. b) The AMS shapes indicate that the Vehmaa intrusion has prolate shapes around the margins and oblate shapes in the centre. c) Schematic figure of the expected magma flow directions during emplacement with prolate AMS shapes along the sides and oblate shapes in the centre.

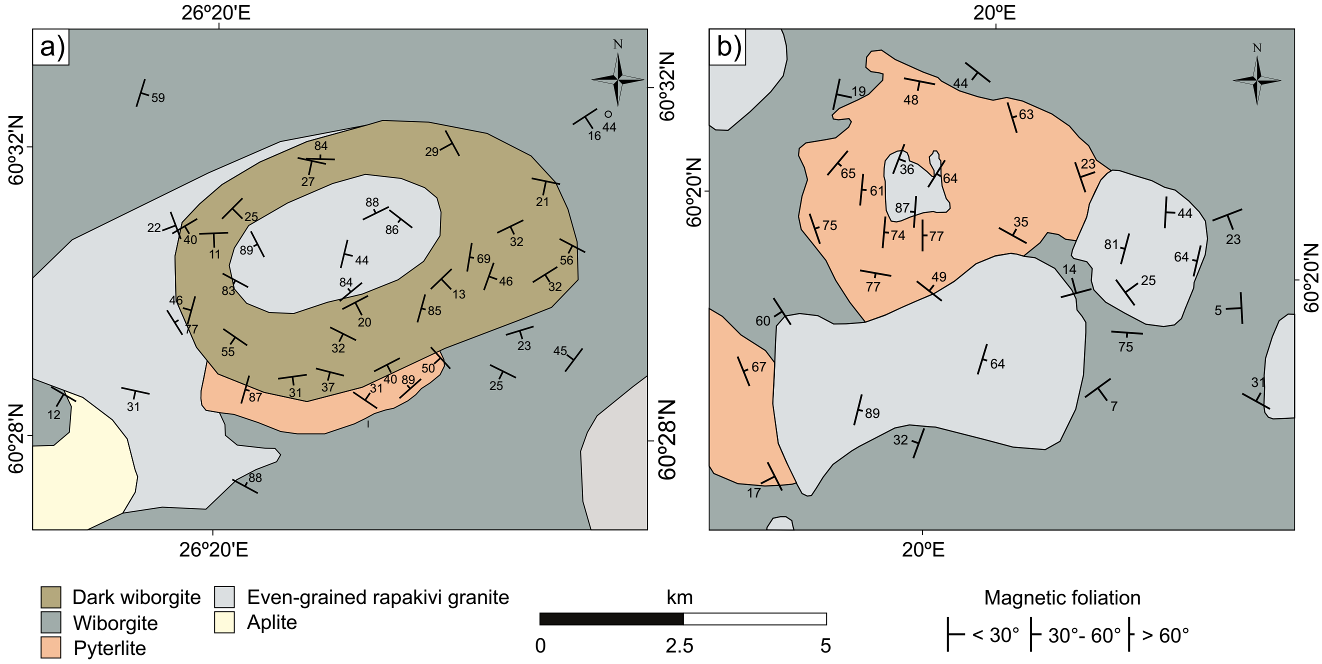

Fig. 9. Mean magnetic foliations calculated with Jelínek's statistics (Jelínek 1978) from a) the Ruotsinpyhtää intrusion within the Wiborg rapakivi granite batholith and the Saltvik intrusions within the Åland rapakivi granite batholith.

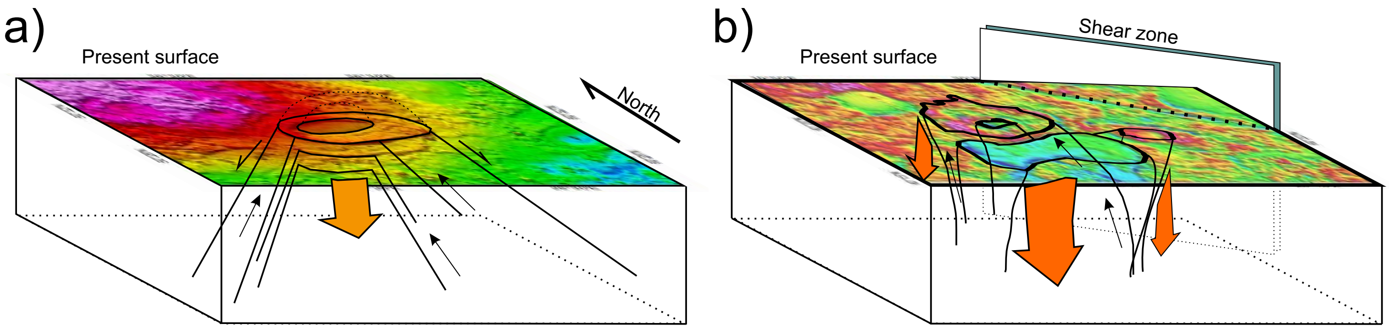

Fig. 10. A schematic sketch model for the emplacement of a) the Ruotsinpyhtää intrusion (Wiborg) and b) intrusions within the Saltvik area (Åland). Successive magma batches intrude (black arrows) in connection with repeated cauldron or gradual subsidence (orange arrows).

5.3. Internal structures and relative timing of gold mineralizations in deformed shear and fault zones

Many of the known Finnish gold occurrences have been quite well studied, but the timing of the actual ore formation is in many cases still open. As a tool for exploration, AMS can be effective in understanding the structures and deformation stages that are related to ore formations. AMS studies on deformed rocks have been widely used in order to describe the strain, kinematics and deformation history of various metamorphic terrains (Hrouda & Janák 1976, Borradaile 1991, Borradaile et al. 1992, Borradaile & Jackson 2004, Pares & van der Pluijm 2003, Borradaile & Jackson 2010, Skyttä et al. 2010).

In general, shear zones show a complex magnetic mineralogy due to deformation, recrystallization and fluid flow, which also affects the magnetic fabric of the rocks. The magnetic minerals responsible for the NRM and MS in the investigated structurally controlled gold-bearing shear and fault zones (Papers III and IV) are mostly monoclinic pyrrhotite. Pyrrhotite is strongly field dependent and affects the AMS results (de Wall & Worm 1993, Hrouda 2002, Martín-Hernandez et al. 2008, Hrouda 2009). The degree of anisotropy is most affected; however, the directional data and the symmetry of the AMS ellipsoid are not significantly affected by the field dependency (Hrouda 2002, 2009). In Satulinmäki, exceptionally high degrees of anisotropy were detected. A preliminary field dependency test (Karell et al. 2009) was conducted on a set of samples of different rock types. The test included samples from Jokisivu, Satulinmäki and Koijärvi. The selected samples were measured in different applied fields, namely ~13, 48, ~130 and 300 A/m. According to the results, some of the pyrrhotite-bearing samples were affected by the field dependency. These samples demonstrated that MS increases when measured in higher alternating fields. As a result of the test, the P' values have been interpreted with caution. Most of the interpretation of the AMS data has dealt, however, with differences in the shapes of the AMS ellipsoids and directions of the magnetic susceptibility vectors.

Both Satulinmäki and Jokisivu deposits show two directions of magnetic foliation within the shear zones: one that is parallel to the general shear zone direction and another that is slightly different. In both study areas, the exceptional magnetic foliations are derived from the Au-rich samples. As a structural tool, AMS provides detailed information that can explain rather straightforwardly many uncertainties in the development of different deformation stages within shear and fault zones. Papers III and IV describe how the AMS and NRM methods can be used to constrain the relative timing of the gold formation processes within the Palaeoproterozoic Svecofennian crust. The combined use of NRM and AMS studies reveals independent information on the processes that led to the formation of economic gold deposits. The magnetic mineralogy alone is relevant to understand because of its close association with the precipitation of gold. However, within structurally complex areas such as in Jokisivu and Satulinmäki, the interpretation of the palaeomagnetic (NRM) data is not straightforward because of the deviation of the magnetization caused by deformation. Therefore, we need a good understanding and background data to undertake interpretations and finally to draw conclusions on the relative timing of the gold-forming processes.

The studies in Papers III and IV revealed that the remanence directions in these formations were deflected from the original Svecofennian geomagnetic direction (Fig. 11). This deflection is related to the deformation history of these shear zones. Together with AMS data, field studies and information from other investigations (Luukkonen 1994, Saalmann et al. 2009, Grönholm & Kärkkäinen 2012), the deformation history within the shear and fault zones has been defined.

The directions of the NRM vectors are deflected in the direction of the magnetic lineation or along the magnetic foliation plane, which forms an easy plane of magnetization. The magnetic minerals responsible for both AMS and NRM vectors are in both cases monoclinic pyrrhotite (TC = 320 °C). Deflection of the blocked pyrrhotite grains under brittle conditions (< 320 °C) is not supported by other field observations. Our interpretation is that the growth and blocking of the pyrrhotite towards the general AMS directions took place in the ductile-brittle transitional phase (over or about (?) 320 °C) under the influence of hydrothermal fluids. Besides, the AMS data indicate that the most central part of the shear zone in Jokisivu and also the heavily altered Au-rich zones within the shear zone in Satulinmäki show magnetic foliations that are further rotated. This implies that a later event that took place immediately after the formation of the general structure. Particularly in the central part of the Jokisivu shear zone (Fig. 12), a change in the shapes of the AMS ellipsoids (from linear to planar) together with a rotation of the magnetic foliations indicate that a later hydrothermal event took place slightly after the actual deformation. In both Papers III and IV, the main result for the timing of the emplacement of these auriferous hydrothermal fluids was that the gold was precipitated in the late stages of the last deformation phase.

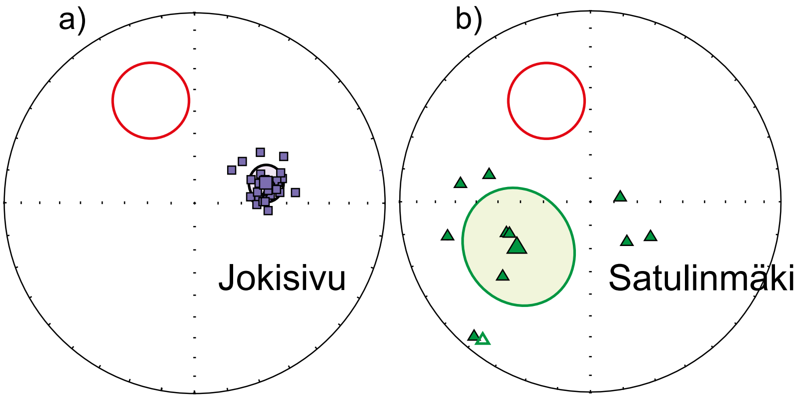

Fig. 11. Deflected NRM directions of Jokisivu and Satulinmäki. Sample mean remanence directions with an α95 confidence circle of the mean direction from a) Jokisivu and b) Satulinmäki. Red circles are the expected directions for the original Svecofennian age geomagnetic field direction (see Buchan et al. 2000, Pesonen et al. 2003, Mertanen & Pesonen 2005).

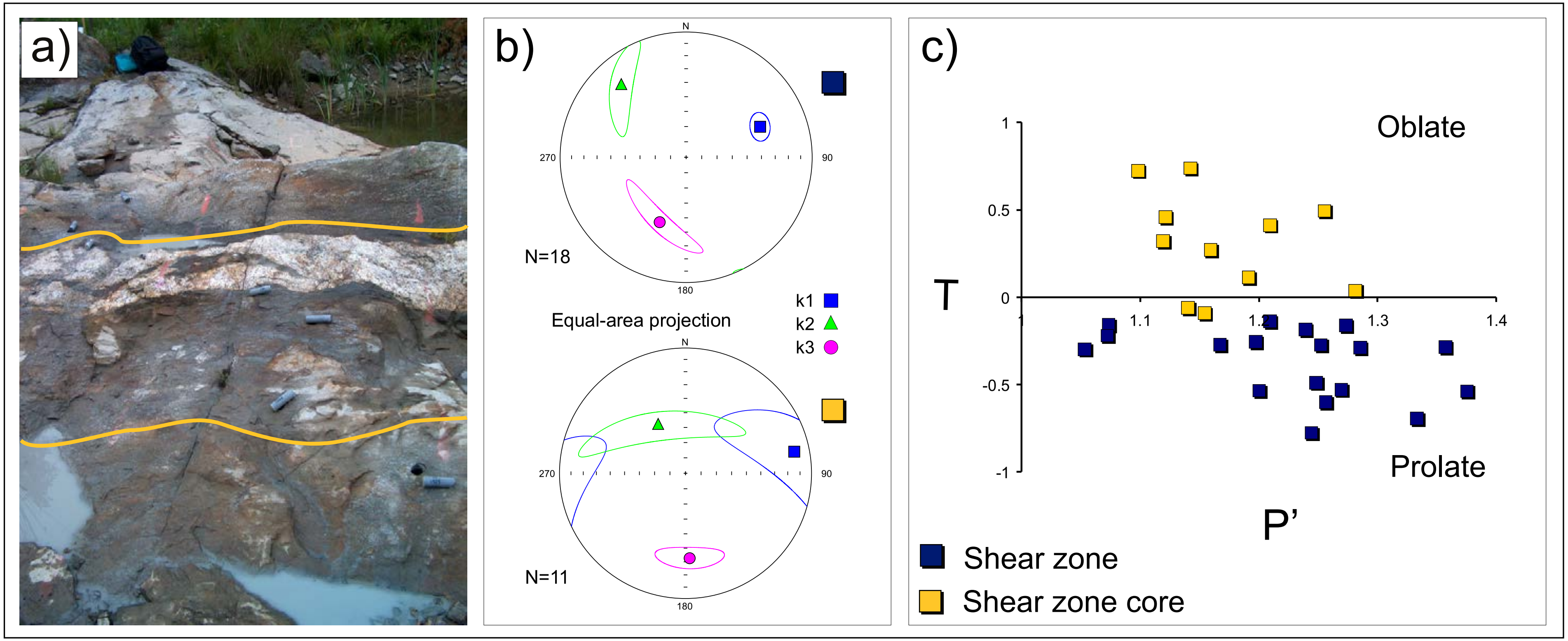

Fig. 12. AMS of the centre shear zone at Jokisivu. a) Sampling along a profile JO across the shear zone in Jokisivu. The shear zone core is between the yellow lines. View towards the NE. b) Mean AMS directions from the margins of the shear zone and from the core of the shear zone. c) Jelínek P'-T plot (Jelínek 1981) for samples grouped according to location in the shear zone core and its margins.

5.4. Applications and suggestions for future research

AMS is currently regarded as a very effective (sensitive, rapid and inexpensive) method that can be used to investigate the fabric of any type of rock or sediment (Hrouda 1982, Tarling & Hrouda 1993, Martín-Hernández et al. 2004, Lanza & Meloni 2006, Borradaile & Jackson 2010). Even though widely used around the world, AMS is still an infrequently used method in Finland, as only a handful of AMS studies have been published.

AMS studies on rapakivi granites have already been adapted to the natural stone industry within the Vehmaa batholith, where the results from Paper I have been used to understand the intrusion phases and their impact on the localization of natural stone quarries (Selonen et al. 2011). This model could be further adapted to other natural stone quarries. The different intrusion phases might play a significant role for future models regarding the quality and homogeneity of the natural stone occurrences within larger batholiths, or even within small intrusions where areas with natural stones of good quality might be limited.

The growing demand for urban planning, land use, transportation networks and underground constructions (should) set greater pressure on understanding the regional and local geology in Finland. Structural geology, in particular, is needed to constrain the effects of faults, joints and other weakness, shear and fault zones on the solidity of rocks. AMS is an effective tool that can be adapted for use on many ongoing and future prospects.

Aerogeophysical data are currently widely used at GTK to understand the lithological and tectonic framework of mineral deposits (Airo & Leväniemi 2012). The use of different processing techniques and prospectivity mapping enables more advanced modelling of mineral potentials. As models become more detailed and demanding, we also need more accurate field data and laboratory measurements to explain the anomalies and the processed data. The anisotropy of magnetic susceptibility together with magnetic modelling is an important tool for explaining magnetic anomalies related to any prospectivity map.

The combination of AMS with NRM to constrain the relative ages for the precipitation of mineralized ore deposits is one topic that should be further addressed in future research, especially when combining AMS with palaeomagnetic studies on deformed rocks (Raposo et al. 2003). However, as the results might not be as straightforward to interpret as desired, the addition of different rock magnetic methods in future prospects, e.g. high-field versus low-field susceptibility and anisotropy of remanent magnetization, could make the interpretation and quality of the results more accurate and less complicated.

Together with aeromagnetic data and enhanced prospectivity mapping, new prospects and the timing of mineralized zones can give improve our understanding of the evolution of our bedrock and mineral resources.

6 CONCLUDING REMARKS

The objective of this thesis is to present rock magnetic studies, in particular AMS, and their application to completely distinct geological objects. The thesis research examined magma emplacement and intrusion mechanisms in composite rapakivi batholiths, as well as the emplacement of gold-bearing hydrothermal fluids in structurally controlled mineralizations.

The hypotheses that were tested in the studied localities are summarized as follows:

Hypothesis 1: Fennoscandian rapakivi granites are paramagnetic ilmenite series granites.

Rock magnetic studies have revealed that Finnish rapakivi granites are intruded as repeated magma batches of bimodal magnetic composition: both paramagnetic (reduced ilmenite) and ferromagnetic (oxidized magnetite) series.

Hypothesis 2: Rapakivi granites in Finland have been emplaced by cauldron subsidence (Ehlers & Bergman 1984, Bergman 1986, Selonen et al. 2005).

The internal structures derived from AMS data together with field observations demonstrated that the main mechanism for space creation was predominated by collapse-type emplacement and repeated successive inputs of magma batches, either laccolitic or cauldron subsidence, that eventually formed these concentric intrusions.

Hypothesis 3: The large rapakivi granite batholiths in Finland are comprised of large "homogeneous" masses with several stocks emplaced simultaneously as large complexes.

Aeromagnetic data revealed that there are in fact numerous internal structures within the rapakivi granite batholiths that can be related to intrusions within the larger batholiths.

Hypothesis 4: Magnetic fabric analysis can reveal internal structures within shear zones.

The AMS data revealed internal structures that can be linked with different stages of deformation within the auriferous shear zones in terms of differences in the directional data and in the shapes of the AMS ellipsoids.

Hypothesis 5: The precipitation of gold within shear zones was emplaced simultaneously with the tectonic stress that developed the shear zones.

The AMS studies identified different deformation stages within the shear zones. Examples from Jokisivu and Satulinmäki show that the auriferous shear zone centers represent later deformation stages.

Hypothesis 6: The gold mineralization in Satulinmäki took place at 1.82–1.79 Ga (Saalmann et al. 2009).

The AMS results together with NRM directional data show that the gold-bearing fluids were emplaced during the estimated ages, but also that the precipitation of pyrrhotite and associated gold was emplaced in the late stages of the Svecofennian deformation phase within the studied deposits.

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This PhD thesis consists of a synopsis and four original papers dealing with magnetic fabrics of deformed and undeformed Precambrian rocks from southern Finland. The objective of this thesis is to present rock magnetic studies, in particular magnetic fabric investigations, and their application to completely distinct geological objects. The magnetic fabric studies reveal new information about the emplacement of rapakivi granite intrusions, as well as the emplacement of gold-bearing hydrothermal fluids in structurally controlled mineralizations.

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