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Magnetic susceptibility of crystalline basement and soil, Loviisa area, southern Finland

Master thesis

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Introduction

The magnetic susceptibility of soil and crystalline bedrock in the Loviisa area, southern Finland, was studied in order to understand effects of proven (Cook et al., 2011) polymetallic mineralization to magnetic properties of soil and bedrock. The work is a contribution to the research project *Polymetallic mineralization associated with anorogenic magmatism in Southern Finland,* led by professor Krister Sundblad at the University of Turku and sponsored by the K.H. Renlund Foundation.

The objectives of the work were to:

1) study the magnetic susceptibility (MS) of the crystalline basement in bedrock outcrops (i) to analyse the relations between magnetic susceptibility and lithological features and (ii) to provide data for modelling the shapes of magnetic bodies and
2) study the MS of soil in order to (i) analyse correlations of MS to chemical elementary data of soils and (ii) to improve sampling strategy.

Measurements of MS in soil samples are used as a complementary tool to soil geochemistry. Soil sampling is used in order to detect areas hosting metal enrichments derived originally from bedrock and delivered to soil by glacial processes. Susceptibility measurements were used to provide a fast assessment for identifying samples with anomalous metal contents.

The magnetic susceptibility of bedrock was measured to obtain a better understanding of the magnetic properties of the rock types in the study area. The rock types tend to have characteristic MS distributions, which make it possible to distinguish them from neighbouring lithologies. The susceptibility data will be benefited for modelling shapes of magnetic bodies by fellow students involved in the research project.

Polymetallic mineralization is documented in the western part of Wiborg Batholith as polymetallic hydrothermal greisen veins, polymetallic quartz veins and massive lenticular magnetite-sphalerite ore. These occurrences are of interest for their contents of Zn, In, Ag, Sn, and Cu, of which In offers particular interest due to its rare appearance in the Fennoscandian Shield. Indium is a metal used in electronic industry; it is obtained as a by-product of base metal mining and there are no indium deposits known in Europe (Cook et al., 2011).

Measurements of susceptibility of soil are widely used in mapping and monitoring (heavy) metal pollution of soils with respect to elevated concentrations of Zn, Cu, Cd, As, Pb, Co, Cr and many other metals (Hanesch and Scholger, 2002; Naimi and Ayoubi, 2013). Such studies have been carried out in areas related to human activities – roadsides, factories, mines, power plants, etc. When relations between certain MS levels and high concentrations of metals are proven, MS can be used in order to map the contaminated soils without expensive and time-demanding chemical analyses (Lu et al., 2008). Elevated metal concentrations related to ores are also a kind of heavy metal pollution, except there is no human influence included. Many studies are focused on pedological characterization of soils and use MS to help describing soil profiles (Lourenço et al., 2014), some studies have used MS of glacial till to describe glacier retreat in areas, where traditional methods are not applicable (Gurney and White, 2005).

Measuring magnetic susceptibility of rocks in the field is fast and considered to be more practic than taking samples to laboratory for time- and cost-demanding analyses. Field assessment of MS can reveal magnetic disturbances from magnetic bodies or enclaves, visually unseen changes in lithology and alterations (Hrouda et al., 2009). Field MS measurements can also be used as a preliminary evaluation of rock types, when macroscopical parameters do not reveal the rock type, for example when distinguishing between different granitic rock types because granitic rocks can be divided into: 1) the magnetite series, characterized by the occurrence of magnetite and 2) ilmenite series, characterized by the occurrence of ilmenite or hemo-ilmenite (Ishihara, 1977).

Not the least, MS field measurements are used in various tasks in exploration of mineral resources, in particular ore occurrences related to mineralization of ferromagnetic minerals, which tend to accumulate in ore deposits. Magnetometry (measurements of Earth's magnetic field and crustal effects to it) is also frequently used for such purposes. In most cases ferromagnetic minerals however create haloes and indicate to ore deposits indirectly (Hrouda et al., 2009). Magnetic susceptibility is also frequently used in modelling the shapes of magnetic bodies detected by magnetometry since it is the main magnetic characteristic of substances and affects magnetic field anomalies the most (Lanza and Meloni, 2006).

1. Geological setting

1.1. Regional background

The Loviisa area lies on the south-eastern bank of Fennoscandian Shield, also known as Baltic Shield (Figure 1). Further into the south and south-east, the Precambrian basement dips at a shallow angle and is covered by Phanerozoic platform sediments. The Fennoscandian Shield consists of Precambrian crystalline rocks, often metamorphosed and related to multiphase orogenies. It is roughly divided into: 1) Archean, 2) Svecofennian, and 3) Southwest Scandinavian domains. In this work, the focus is on the easternmost parts of the Svecofennian and the westernmost parts of the Wiborg Batholith. The Svecofennian island arc systems in southern Finland are represented by 1.9 Ga granitoids and volcanics, metamorphosed during the Svecokarelian orogeny at 1.80 to 1.87 Ga. As a relic from the previously existed mountain chain with relatively light rocks, the Svecofennian crust is exceptionally (65 km) thick. The dominating Svecofennian rock types in the Loviisa region are amphibolites (probably representing mafic volcanic rocks), which occur as WNW-ESE-trending belts embedded by granitoids (Lehtinen et al., 2005).

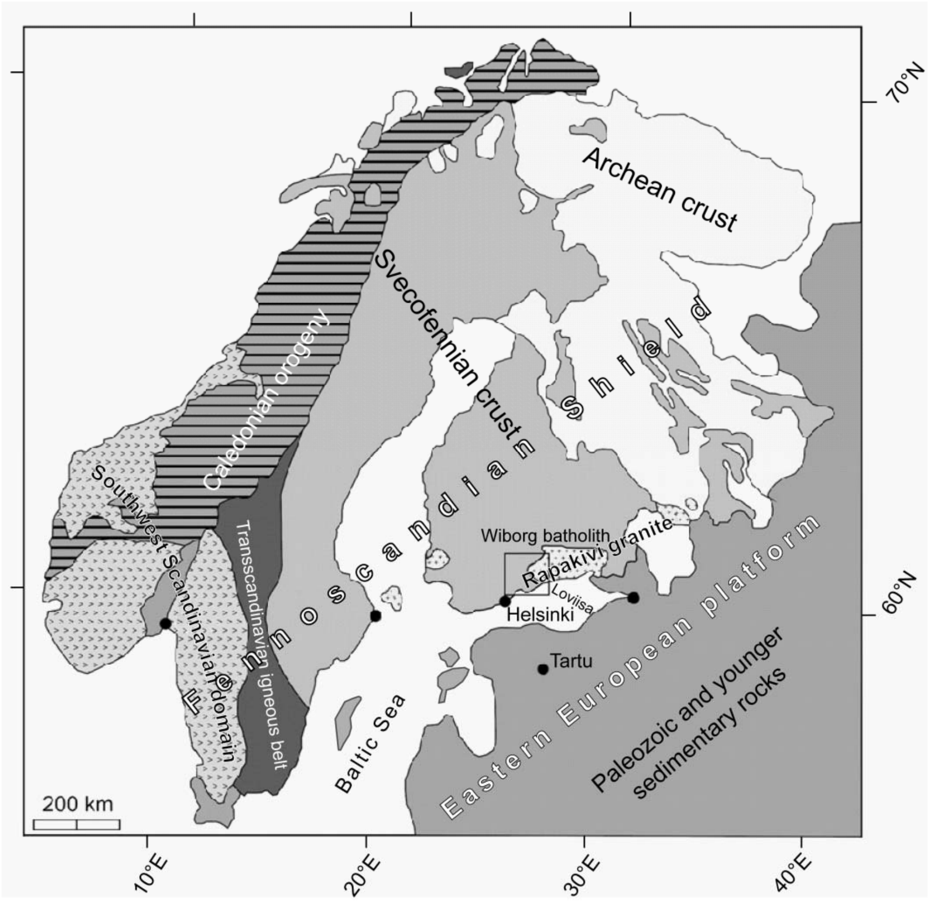

Figure 1. Geological overview of the Fennoscandian Shield (Cook et al., 2011). The study area is marked with a rectangle.

After the erosion of the Svecofennides, anorogenic rapakivi granites were emplaced at c. 1.64 Ga within the Wiborg Batholith, which is the largest rapakivi batholith in Finland. Rapakivi magmatism took place as a series of plutonic events in the mid-Proterozoic (1.67 to 1.47 Ga) over the Fennoscandian Shield, extending from central Sweden to Karelia. The plutons and batholiths consist of several A-type granites with various textures of which the wiborgite is the most common, having the characteristic rapakivi texture: ovoidal alkali feldspar phenocrysts, surrounded by plagioclase rims in a more fine-grained matrix. In addition, several even-grained varieties (with fine to coarse textures) also occur. Other characteristic features of the rapakivi granite are 1) early-formed drop-like quartz crystals, 2) mafic silicates (biotite and hornblende) between the feldspars and quartz (crystallized earlier), and 3) usually massive texture. Locally (but not in the Loviisa area), bimodal magmatism has created both felsic and mafic magma. Rapakivi intrusions are related to thinned crust and bulging of the upper mantle. Their genesis could be caused by magmatic under-plating and partial melting of the deep crust. Causes of the thermal activity could have been triggered by deep mantle plumes or convergent processes (Lehtinen et al., 2005).

1.2. Local setting

The western margin of the Wiborg Batholith contains a number of vein-type polymetallic (Zn, In, Ag, Cu, and Sn) mineralizations, hosted by a variety of rapakivi granites. Three ore types have been distinguished: 1) indium-bearing magnetite-sphalerite lenses, 2) polymetallic greisen veins, and 3) polymetallic quartz veins, all thought to be late expressions of igneous activity. Chemically and mineralogically the veins divide into: 1) Cu-bearing Zn-poor veins where bornite and other Cu-sulphides form and the carrier of In is roquesite ($CuInS_2$) and 2) veins with high Zn concentrations where sphalerite forms and is the main carrier of In (Cook et al., 2011).

Several areas have been studied in this project (Figure 2). Lillträsket, Marviken, Strömslandet, and Högberget were distinguished by soil chemical anomalies of Fe, Zn, Ag, Sn, Cd, Mo, Cu, and other metals. Bäckas-Grinda and Lappträsk were studied due to presumed metallic mineralizations, but did not reveal any particular soil chemistry anomalies (Sundblad et al., 2011).

The Sarvlaxviken area hosts a number of Cu, As, and In mineralizations and is the primary research target of this thesis. It surrounds the Sarvlaxviken bay on the northern coast of the Gulf of Finland 5 km SW of Loviisa and 90 km east of Helsinki. On the eastern side of the bay (**Högberget** area), several 1 … 2 cm thick polymetallic quartz veins occur in coarse-grained wiborgitic rapakivi granite. The veins are characterized by high contents of In, Cu, As, and Bi, locally by a number of other metals within a mineral matrix of quartz and K-feldspar. When the In/Zn ratio is low, indium is hosted by sphalerite but when the In/Zn ratio is high, roquesite ($CuInS_2$) is the main In carrier (Cook et al., 2011). In the centre of the Sarvlaxviken Bay, there is a barren, late rapakivi intrusion of even-grained granite (Sundblad, pers. comm.).

In the **Marviken** area, soil chemistry anomalies of Zn, Cd, In, Fe, Mn, Sn, and Pb, associated with elevated magnetic field values, have been recognized in an area dominated by a coarse-grained wiborgite and an even-grained rapakivi granite stock (Sundblad et al., 2011).

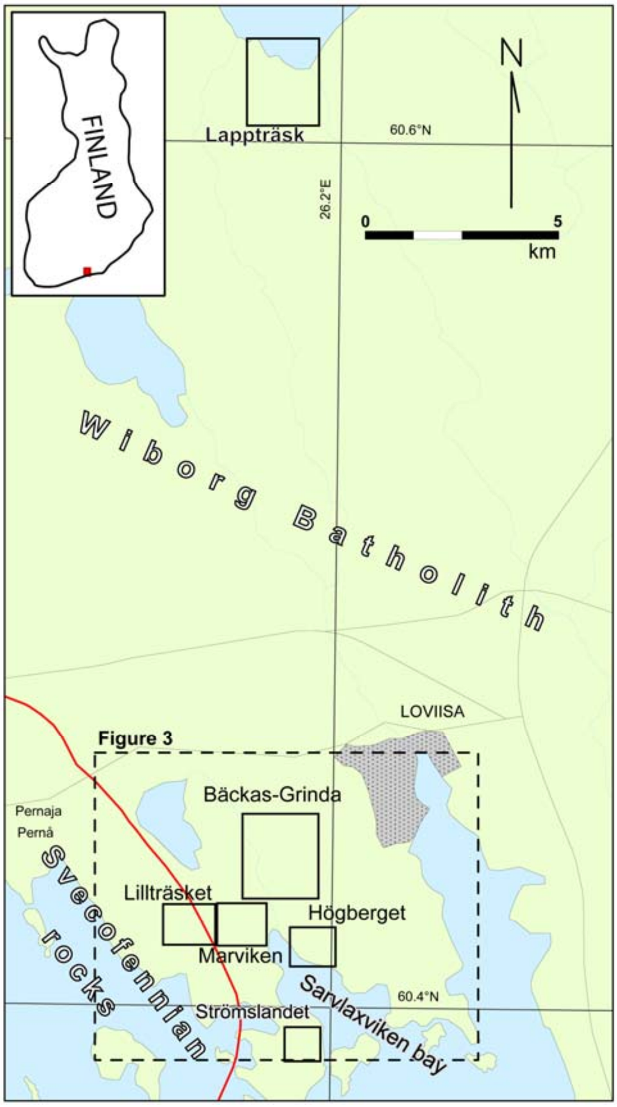

Figure 2. The study areas Bäckas-Grinda, Lillträsket, Marviken, Högberget, and Strömslandet are all located 5 to 10 km southwest of Loviisa town. The Lappträsk area is located 20 km north of Loviisa. Red line marks the boundary between Svecofennian rocks and Wiborg Batholith. Dashed rectangle indicates the position of Figure 3. The background map is from National Land Survey of Finland (2013) and geological boundary from Geological Survey of Finland (2000).

The **Lillträsket** study area is situated on the boundary between Svecofennian crust and the Wiborg Batholith. The bedrock in this area consists of a transition from wiborgites in the east, even-grained rapakivi granites along the batholith border zone into Svecofennian granitoids in the west (García, 2013). In a preliminary assessment, García (2013) distinguished the following lithologies: 1) Svecofennian metamorphic rocks with mineral fabric, 2) fine-medium to coarse-grained granodiorites, quartz, and plagioclase as main mineral components, 3) fine-medium to coarse-grained granites, quartz, plagioclase, and K-feldspar as main mineral components, 4) fine-medium to coarse-grained K-feldspar granitoid with K-feldspar as main mineral component, quartz and plagioclase as minor components, and 5) rapakivi granites with wide range of grain sizes as expressions of unorogenic magmatism in the distribution area of Svecofennian rocks. Svecofennian rocks related to the Lillträsket area are further referred to as granitoids. A complex and wide-spread soil chemistry anomaly has been identified in this area extending from the rapakivi granites in the east into the Svecofennian granitoids. The metals in this soil anomaly are dominated by Fe, Zn, Cd, and In. A Fe-Zn-Cd-bearing greisen zone in an ore boulder discovered in this area is the best indicator of what the source of this soil anomaly could be (Sundblad et al., 2011; E. Nygård, in prep.).

1.3. Geophysical description of the region

The average density of the rapakivi granites in SE Finland (including those in the Wiborg Batholith) is 2,625 kg/m^3, which is about 80 kg/m^3 lower than the surrounding Svecofennian rocks. An extensive Bouguer anomaly low is thus associated with the rapakivi batholiths. A regional high surrounds the low of the batholiths, with a range of values nearly 60 mGal. According to deep seismic sounding results (Elo and Korja, 1993), the crust is 41 km thick in the rapakivi region which is 6 to 20 km thinner than in the west, north, and south.

The magnetic susceptibility frequency histogram of rapakivi granites is distributed into two major components with mean susceptibilities of 165 and 1,305 µSI and three minor components with a log-normal distribution. The first major component (40 % of all measurements) is virtually paramagnetic and the second (60 % of the measurements) is weakly ferromagnetic. Two of the minor components with susceptibilities of 6,000 and 13,500 µSI constitute only 3 % of the samples. The magnetic anomaly values in the rapakivi area are slightly higher than the Svecofennian schist areas, but lower than the values of the metavolcanic belt in the west. The Wiborg Batholith is magnetically a relatively homogenous circular area corresponding to a variance in magnetic field from -250 to +450 nT. Fluctuations in the magnetic field in the main batholith are caused by the more sharply magnetized roof pendants of Svecofennian rocks (Korhonen, 1996). In the western part of the Wiborg Batholith there is a zone of positive regional magnetic anomalies with a well-defined magnetic high of about 400 nT. This anomaly is interpreted as a pipe-like magnetic body with an abnormally strong magnetization (Elo and Korja, 1993).

On the aeromagnetic map by Geological Survey of Finland (Figure 3), illustrating the study area, several features can be identified: 1) the Svecofennian granitoids are expressed by homogeneous magnetic field values, 2) the rapakivi granites in the Wiborg Batholith are expressed by heterogeneous magnetic field values with several highs and lows, 3) for the boundary between the Svecofennian granitoids and the rapakivi granites in the south-western part of the map, a distinction can be made by the transition from heterogenic field values (in the Wiborg Batholith) to homogenous field values (in the Svecofennian granitoids), 4) the regional magnetic high in the western parts of the Wiborg Batholith do not extend to this area, and 5) several local distinct and high magnetic anomalies can be seen throughout the rapakivi area, some of them currently studied by Fernández (in prep.).

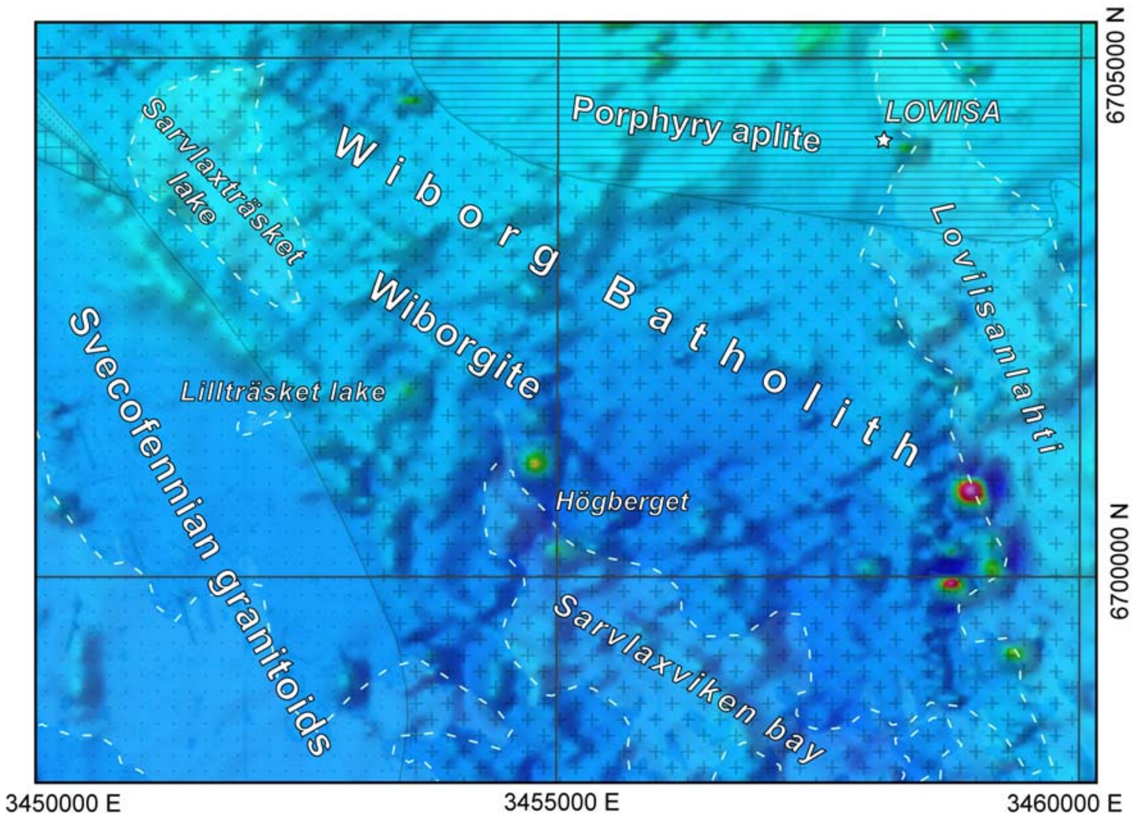

Figure 3. Total intensity low-altitude aeromagnetic map of the study area, mapped in 1 : 20,000 scale. Background values range from 50,600 to 50,700 nT, anomalies reach up to 51,000 nT. The boundary between Svecofennian granitoids and wiborgite is located in the south-western part of the map. Red and yellow colours indicate higher magnetic field values. The map is based on modifications of material from the 1:100,000 Geological map of Finland, Pre-Quaternary rocks, Porvoo district by the Geological Survey of Finland (2000) and the aeromagnetic map of the Geological Survey of Finland (2001).

2. Sampling and methods

2.1. Sampling

Most of the soil samples investigated in this study were obtained from the Practical Course in Ore Prospecting, organized by the University of Turku in 2012 and 2013, when many hundreds of soil samples were collected by numerous three-member student teams. The soil sampling was carried out in order to detect anomaly patterns in the soil chemistry and the magnetic susceptibility. The idea of soil sampling was to detect chemical anomalies in the overburden, where glacial movement could have carried metal-rich rock fragments from mineralized zones in the bedrock into the soil. The chemical anomalies do therefore not necessarily reflect the immediately underlying bedrock, but the bedrock "upstream" in the direction of glacier movement. This technique particularly applies to areas where there are few outcrops and the surficial material dominated by glacial till (Moon et al., 2006). The general glacier movement in the study area was from northwest to southeast (Boulton et al., 2001). Expected sources for the soil anomalies are therefore located northwest of the metal-rich sample sites. The pits were dug about 50 cm in depth and depending on the target area in 20 × 20 m or 100 × 100 m grids. One hundred meter grids were used for identifying possible soil anomalies while 20 m grids were used to define the details of soil anomalies detected by the 100 m grids. Soil material from both 100 m and 20 m grid systems was used from most target areas in this study but from 100 m grids only from the Bäckas-Grinda and Lappträsk target areas. Sample coordinates were obtained from handheld GPS devices. Samples were dried and sieved to fine fraction (< 250 µm). The fine fraction used for the magnetic measurements was about 30-50 grams big, which was enough to fill up 11.148 cm^3 large measuring pot.

2.2. Magnetic susceptibility measurements

The main magnetic property of every substance is the magnetic susceptibility (MS or κ). If a suitable piece of a material under interest is placed in a uniform magnetic field (H) it thereby acquires induced magnetization of M. The magnetic susceptibility is defined as the magnetization acquired per unit field,

$$\kappa = \frac{M}{H}$$

Both H and M are measured in *A/m* (amperes per meter), therefore, κ is dimensionless. If not normalized, MS is called apparent. To obtain what is called the mass susceptibility (χ), κ is divided by density (ρ),

$$\chi = \frac{\kappa}{\rho}$$

and as a result, χ obtains a unit of reciprocal of density, m^3/kg (Evans and Heller, 2003). To use mass-specific susceptibility, MS is divided by the mass of measured sample and the result obtains a unit of m^3/kg. Mass-specific susceptibility is used in present study to describe MS of soil samples.

Rocks and minerals, as well as any other substances, can be divided into three main categories with respect to their magnetic properties. Substances are called **diamagnetic** when the magnetic moments of electrons cancel each other out and the total magnetic moment is nil. When these substances are placed in an external magnetic field, they acquire weak induced magnetization with an opposite direction to that of the inducing field. Some of the most common rock forming minerals (like calcite and dolomite among carbonates as well as quartz, and feldspars among silicates) belong to this category. Their susceptibilities are in the order of -10 µSI. **Paramagnetic** substances also have a total magnetic moment of nil, but when placed in an external magnetic field, a weak induced magnetization is acquired in the same direction as the inducing field. Many silicates belong to this group, in particular pyroxenes, amphiboles, micas, and clay minerals. Their susceptibilities are in the order of 50 … 1000 µSI, but they also have a wide range of variations mainly linked to Fe concentrations in the same minerals. **Ferromagnetic** substances have a strong spontaneous magnetic moment even in the absence of an external magnetic field, this is also called permanent magnetization. Ferromagnetism appears in substances formed of atoms with multiple unpaired electrons in d-orbital. Their magnetic spin moments of electrons are parallel and aligned in the same direction. Sections in crystal lattices with uniform spin moments are called magnetic domains, where the magnetic moment has a certain direction. Ferromagnetism is divided into three sub-divisions. In ferromagnetism itself, all domains have a magnetic moment strictly in the same direction. In antiferromagnetism, the magnetic moments of domains are opposite-directional and are equal in quantity. Domain moments cancel each other out and the resultant magnetic moment is nil. In ferrimagnetism, the magnetic moments are in opposite directions but one domain type is prevalent, thus the resultant magnetic moment is present. Most important members of this group are Fe oxides and sulphides. Their susceptibilities are very variable; ranging from 1000 µSI for hematite up to 10^7 µSI for magnetite. Ferromagnetic minerals are not numerous and are mostly present as accessory minerals in small quantities, but their extremely high susceptibilities tend to mask the effects of other minerals (Lanza and Meloni, 2006).

The magnetic susceptibility is the parameter that most influences the anomalies caused by rock bodies to the Earth's magnetic field, and, therefore, is extremely important in interpreting magnetic surveys and for exploration (Lanza and Meloni, 2006).

The magnetic susceptibility measurements of the crystalline basement were carried out with a Bartington MS3 magnetic susceptibility meter in the summer 2013. Different probes can be used for Bartington MS3 device. In the present case, Bartington MS2D Field Search Loop with MS2 Probe Handle was used. The loop is designed to study approximately 100 mm depth of land surface, its working frequency is 958 kHz and measuring resolution is 2 µSI on 0.1 range (Bartington Instruments Limited, 2013). The first measurement was made in air to eliminate effects of the background magnetic field and the second measurement was made on the bedrock surface. The obtained values are called apparent susceptibility since the measurements on the bedrock outcrops cannot be normalized by any parameter. The susceptibility meter MS3 was operated with a Trimble Nomad personal digital assistant (PDA) with an integrated GPS receiver. The GPS coordinates were thus simultaneously logged during the MS measurements. The measurements at individual locations were very fast (lasting only a few seconds). In order to document lithology changes, notes were written into the PDA.

The magnetic susceptibility measurements of the crystalline basement were carried out on the bedrock outcrops in the Lillträsket and Högberget study areas (see Figure 2). These study areas were chosen since they hold the most interesting mineralization occurrences. The outcrop localities were known from the topographic maps and previous geological mapping work. No particular measuring grid was put up in the landscape since finding the appropriate site for measurement needs some effort and cannot be done at all sites, even on bedrock outcrops. The presence of moss, tree roots, moist etc. disturb the measurements and a site with clean, dry and flat surface is preferred and recommended by Hrouda et al. (2009). Despite some requirements for the measuring sites, hundreds of measurements were made daily. The magnetically anomalous sites were documented more carefully by making several extra measurements. No greater distance than 25 m was left between measuring sites along one bedrock outcrop and at least three measurements were made on very small outcrops. On later assessments, the distribution of measurements was randomly thinned on some sites in order to avoid over-representation of sites where many times more measurements were taken compared to sites overall. Altogether, 1972 MS measurements were made.

The magnetic susceptibility of soil samples was measured with a magnetic susceptibility meter (often referred to as kappameter) SM-100. It is computer controlled and designed to measure the MS with a high sensitivity in small rock samples (Heritage Group Inc., 2005). Each sample was weighed and the MS was measured at least three times, the mean value of the measurements was used during later data analyses. The single measurement cycle time was approximately 15 seconds. The background magnetic disturbance was eliminated by starting and ending the measurement cycle with empty coil. All measurements were made with an operating frequency of 1 kHz and a field intensity of 320 A/m. The mass specific susceptibility (χ) was used in later analyses, thus, the results obtained a unit of m^3/kg or, for easier operating, 10^{-8} m^3/kg since the values were small. Altogether 738 samples were measured and weighed during and after the field courses in 2012 and 2013.

For defining extreme values of the MS, the boxplot method was used, as recommended by Hanesch et al. (2007). They state that the boxplot method reliably detected all previously known metal anomalies in soils of Austria without so-called “false positives”. The method was developed by Tukey (1977) and described in the context of identifying extreme values in geochemical analyses by Reimann et al. (2005). Extreme values are indicated to as *outliers* and *far outliers*. The boxplot is constructed as follows:

1) the data are divided into four equal parts by firstly finding the median and then first and third quartile – these define the central box which therefore contains approximately 50 % of the data, upper and lower ends of the boxes are also called *hinges*;

2) the inner fence is defined as the box extended by 1.5 times the length of the box towards the maximum and the minimum;

3) upper and lower whiskers are then drawn from each end of the box to the farthest observation inside the inner fence. This is defined algebraically, using the upper whisker as an example, as

(i) upper inner fence (*UIF*):

$UIF = upper\ hinge\ (x) + 1.5 \times hinge\ width\ (x)$ and

(ii) $upper\ whisker\ (x) = \max(x[x < UIF])$.

Any value beyond the whiskers are defined as *outliers*, observations beyond the values of the upper hinge plus 3 times the hinge width are defined as the *far outliers* (Reimann et al., 2005).

GPS measurements were made using Finnish KKJ Zone 3 grid system. All tasks related to visualizing spatial data were carried out by using software MapInfo Professional vers.10.5.

3. Results

3.1. Apparent magnetic susceptibility of the crystalline bedrock

In the Lillträsket area, three rock types have been recognized: 1) Svecofennian granitoids, 2) rapakivi granites, and 3) Svecofennian supracrustal rocks (amphibolite and gneiss) occurring as xenoliths in the rapakivi granites. The Svecofennian granitoids have low susceptibilities with a mean value of 40.6 µSI, the rapakivi granite has a medium susceptibility with a mean value of 427.5 µSI, while the supracrustal rocks having the highest susceptibilities, with a mean value of 4,735 µSI (Table 1).

In the Högberget area, two kinds of rapakivi granites are present: 1) wiborgite and 2) an even-grained rapakivi granite. They contrast from each other by moderate susceptibility values for the wiborgite and low values for the even-grained rapakivi granite.

Table 1. Statistical parameters of apparent magnetic susceptibilities of studied rock types in µSI.

	Lillträsket			Högberget	
	Svecofennian granitoids	Rapakivi	Supracrustal rocks	Even-grained rapakivi	Wiborgite
No.	409	117	36	48	987
Mean	40.6	427.5	4735.0	79.9	1386.5
Median	35.0	140.0	1480.0	73.0	843.0
Maximum	462.0	3930.0	30870.0	407.0	65650.0
Minimum	-1.0	3.0	11.0	33.0	26.0
St deviation	31.9	755.8	7941.7	51.3	3493.9

Histograms, depicting the mass susceptibility for each rock type, are shown in Figure 4. The MS distributions of wiborgite, even-grained rapakivi granite, and Svecofennian granitoids are unimodal. The MS distributions of the even-grained rapakivi granite and the Svecofennian granitoids are symmetrical with a few measurements apart from the main population. The wiborgite distribution is asymmetric with a negative skew; a small population of measurements represents very high susceptibility values. The magnetic susceptibilities of the rapakivi granite as well as the supracrustal rocks in the Lillträsket area are very variable without definite distributions and can be called multi-modal.

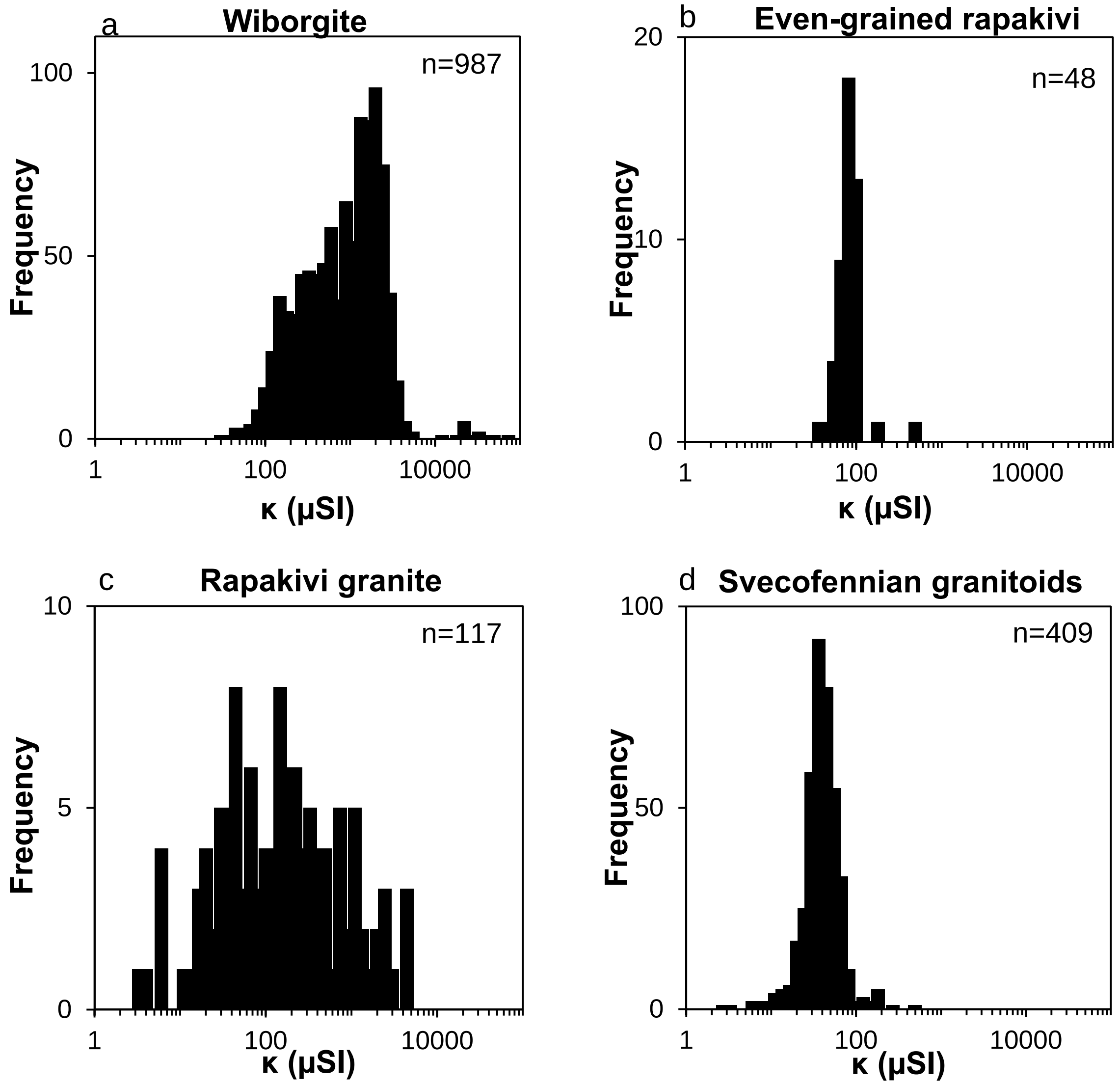

Figure 4. Frequency histograms of the magnetic susceptibilities are characteristic for each rock type: a) wiborgite in the Högberget area, b) even-grained rapakivi granite in the Högberget area, c) even-grained rapakivi in the Lillträsket area, and d) Svecofennian granitoids in the Lillträsket area. The vertical axis indicates the number of measurements for each category; "n" stands for the number of total measurements.

For describing rock magnetism, the Geological Survey of Finland has used the susceptibility value of 2,000 µSI as a cut-off value between para- and ferrimagnetic categories (Airo and Säävuori, 2013). By these means, the Svecofennian granitoids and the rapakivi granites in the Lillträsket area and the even-grained rapakivi granite in the Högberget area are paramagnetic. Wiborgite is mainly paramagnetic with a minor ferrimagnetic component. Supracrustal rocks in the Lillträsket area are ferrimagnetic in 64 % of the measurements.

The spatial distribution of the susceptibility values for the wiborgite in the Högberget area is heterogeneous and scattered (Figure 5). The measurements range from 100 µSI to thousands of µSI and do not form clear populations. An exception is found on the Högberget hill (no. 4 on Figure 5), where low values (from 100 to 1,000 µSI) concentrate. The variable MS values are in compliance with the aeromagnetic data (Figure 3), where the rapakivi area has an irregular surface caused by heterogeneous field values. The even-grained rapakivi granite has low MS values (< 100 µSI), which makes it distinct from the wiborgite.

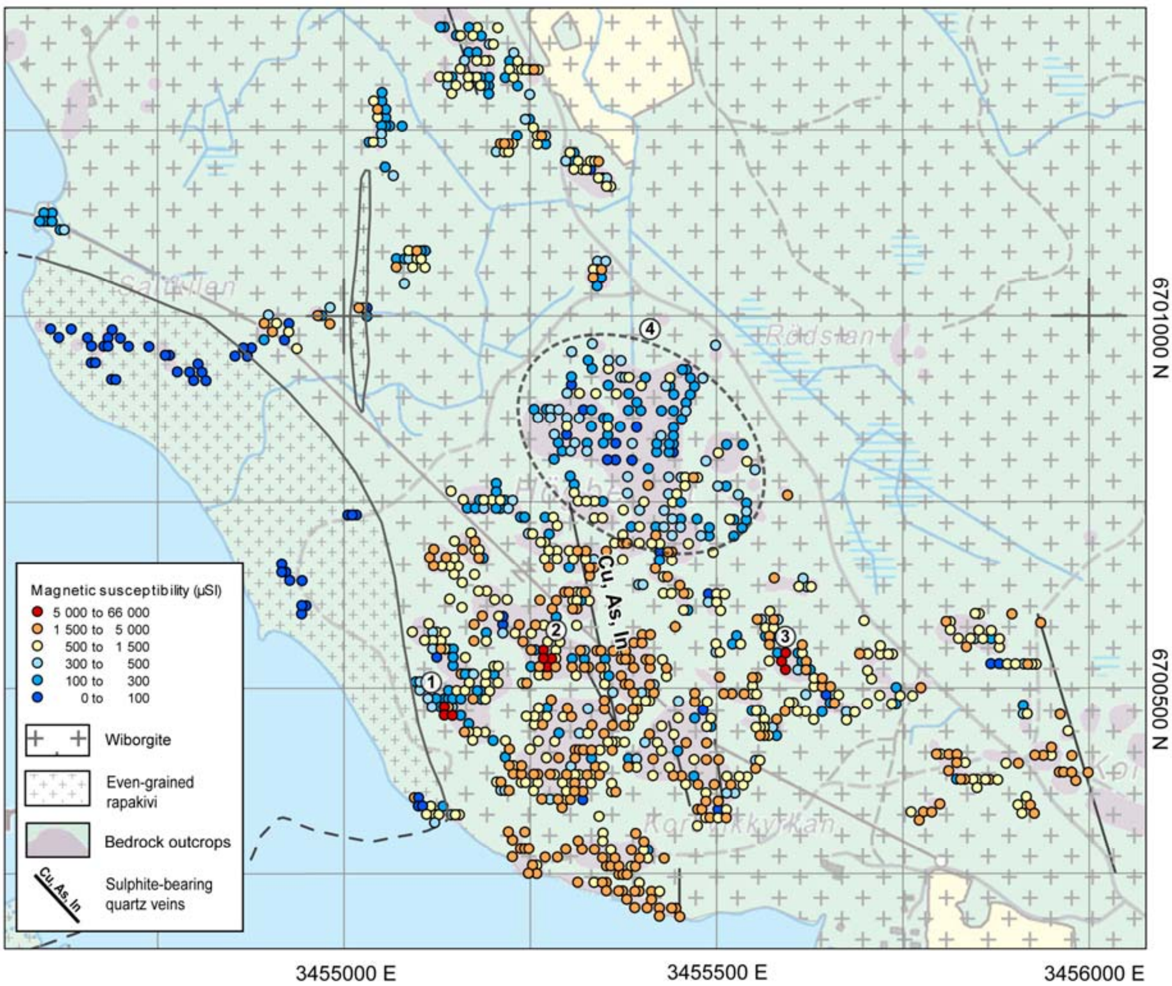

Figure 5. Magnetic susceptibility of the bedrock in the Högberget area. A distinction can be made between wiborgitic and even-grained rapakivi granites. Numbers 1-3 indicate elevated susceptibility values, number 4 indicates the Högberget hill (with a cluster of lower susceptibility values). Geological boundaries after Sundblad et al., pers. comm.

Three small areas, with a highly ferrimagnetic bedrock has been identified close to the gridline 6700500 N, where the susceptibility ranges from 20,000 to 65,000 µSI (marked as 1, 2 and 3 in Figure 5). At one site (3455270 E, 6700544 N in Finnish Grid System KKJ; no. 2 on Figure 5), the susceptibility reaches 65,000 µSI, which is so high that a disturbance on the magnetic compass is noted. These areas correspond to the minor ferrimagnetic category in the histogram in Figure 4a.

A characteristic feature of the Lillträsket area is the boundary between the Svecofennian granitoids and the Wiborg Batholith (Figure 6). Although the range of MS values of the rapakivi granites is wide, moderate values over 500 µSI are common. The Svecofennian granitoids are distinct from the rapakivi granites by low and even MS values (rarely exceeding 100 µSI). In the southern part of the area of Svecofennian granitoids, a NNW-trending line of elevated susceptibility values (115-165 µSI) can be seen (no. 1 in Figure 6).

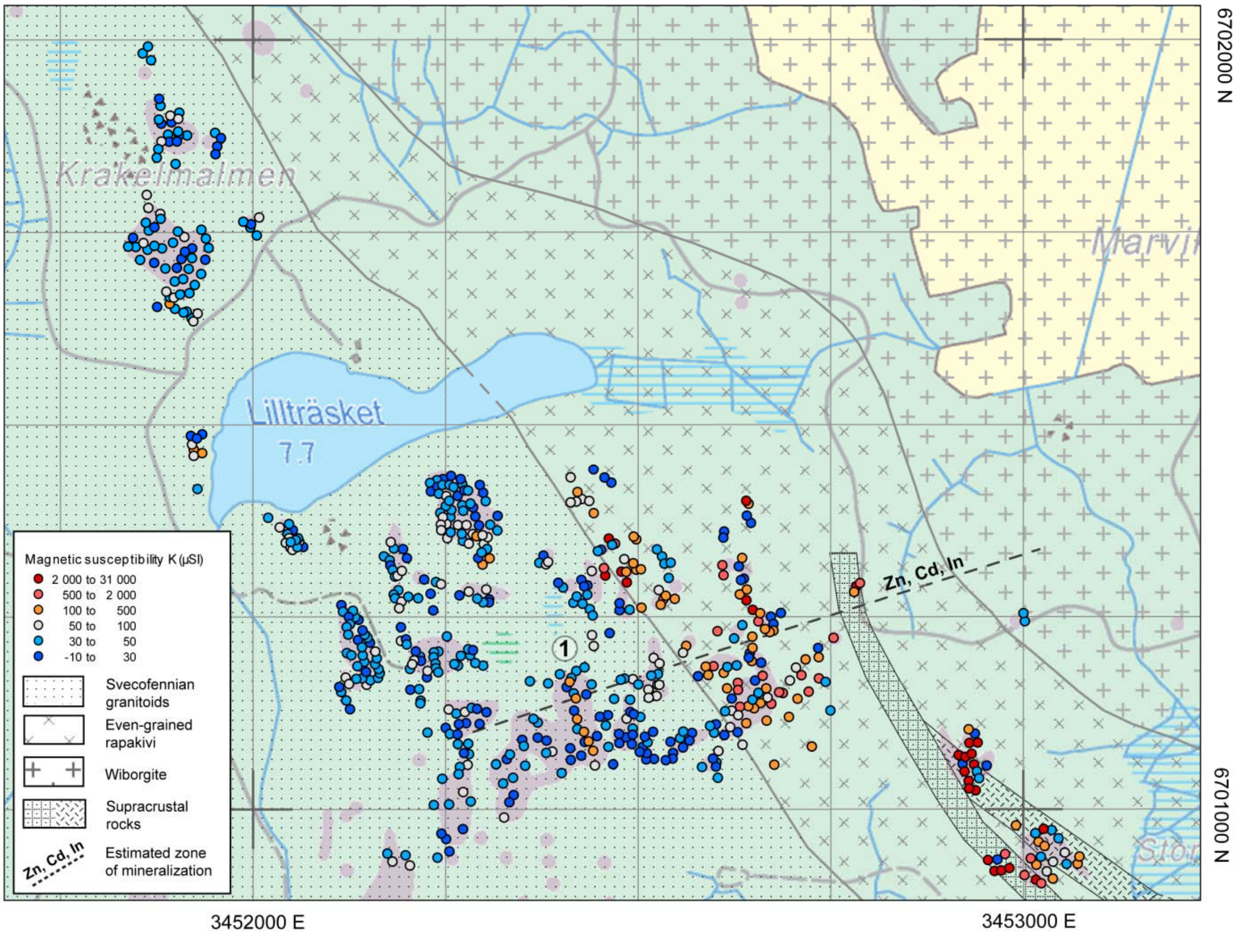

Figure 6. Magnetic susceptibilities of the bedrock in the Lillträsket area. Low susceptibility values represent Svecofennian granitoids, moderate and high values represent rapakivi granites and Svecofennian supracrustal rocks inside rapakivi granites. Number 1 indicates a NNW-trending line of Svecofennian metamorphic rocks (lithologies drawn after Sundblad et al., pers. comm. and García, 2013).

This area corresponds to ~100 m long and a some 20 m narrow zone of Svecofennian metamorphic rocks, recognized by García, (2013). The Svecofennian supracrustal rocks show a wide range of susceptibilities of which the amphibolites have the highest values (1,000-30,000 μSI). This feature makes them very easy to be detected by magnetometric measurements (Fernández, 2014).

3.2. Mass specific susceptibility of soils

In the assessment of magnetic properties of soils, mass-specific susceptibility χ (m^3/kg) is used rather than the unstandardized apparent susceptibility. Most of the soil samples were classified during the field work as light brown to dark reddish-brown till, while a minority of the samples were classified as glaciofluvial sediments. Table 2 lists parameters of the measured samples for the total area as well as for the individual research sites. Typically, the soil susceptibility values are small with a mean of 37×10^{-8} m^3/kg, but exceptionally reach over $2{,}600 \times 10^{-8}$ m^3/kg. The highest maximum values are noted in the Lillträsket, Högberget, and Marviken areas, while the Bäckas-Grinda, Lappträsk, and Strömslandet areas show relatively low values.

Table 2. Distribution parameters of mass specific susceptibility (10^{-8} m^3/kg) for the total area and for individual areas.

Property	Total	Bäckas-Grinda	Högberget	Lappträsk	Lillträsket	Marviken	Strömslandet
No. of samples	738	89	20	72	316	192	49
Minimum	0.1	2.4	4.1	5.1	0.1	0.8	2.0
Maximum	2694.0	94.4	342.8	97.8	2694.0	126.3	79.5
Median	12.2	6.0	25.8	28.4	18.4	8.1	9.0
Mean	37.0	9.0	56.4	32.5	59.9	16.6	18.0
Upper quartile	34.8	8.2	53.3	44.9	51.9	19.7	27.8
Lower quartile	6.3	4.7	13.0	16.2	8.8	4.8	4.4

The distribution of the measurements appears to be log-normal, unimodal and unsymmetrical with a positive skew (Figure 7). The distribution maximum is around $10 \times 10^{-8}$$m^3$/kg. A minority of the samples have significantly higher values than the main population.

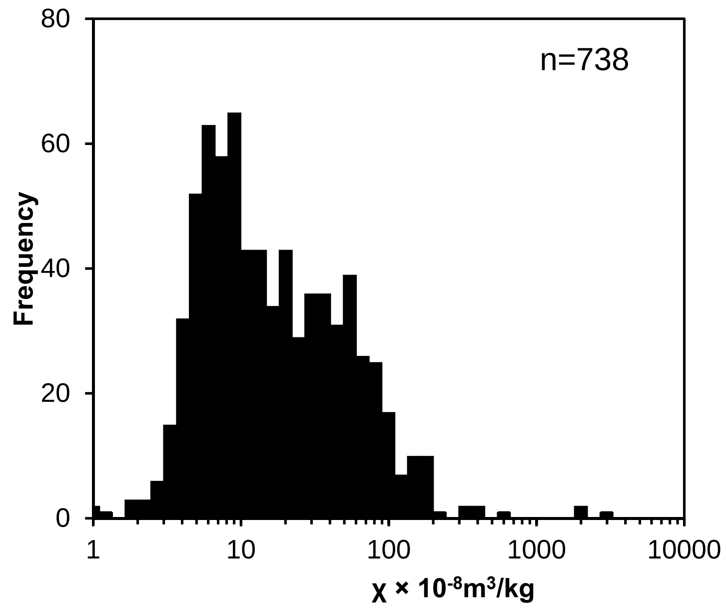

Figure 7. Frequency histogram of mass specific susceptibility given for all samples. The distribution is log-normal, unimodal, and unsymmetrical with a positive skew. The vertical axis indicates the number of measurements in each category; "n" stands for the total number of measurements.

The variability of measurements is visualized and the thresholds of extreme values are defined by the boxplot method (Figure 8). The central line in the box indicates the median of the population, the upper and lower hinges are defined by the upper and lower quartiles, respectively. Samples between the whiskers are considered to be normal or natural in susceptibility. Outliers are samples with values > 1.5 times the box length and far outliers with values > 3 times the box length. All lower whiskers extend to negative values but there are no outlying samples below the lower whiskers. In total, 50 % of the samples fall in the range between 6 and 34×10^{-8} m^3/kg and the upper whisker extends to 77×10^{-8} m^3/kg. Therefore, 77 is the threshold for defining extreme values in all samples. There are 28 samples classified as outliers and 30 samples as far outliers. The highest median values were recorded in the Högberget and Lappträsk areas, although the amount of samples in Högberget, is low and the background values therefore not well defined. The smallest variation in 50 % of the samples is found in the Bäckas-Grinda area, while other areas show somewhat similar variations. Significant populations of outlying samples are observed in the Lillträsket and Marviken areas. A set of outliers is also defined for the Bäckas-Grinda area, but these values are low compared to the total dataset. Other areas host a few outliers.

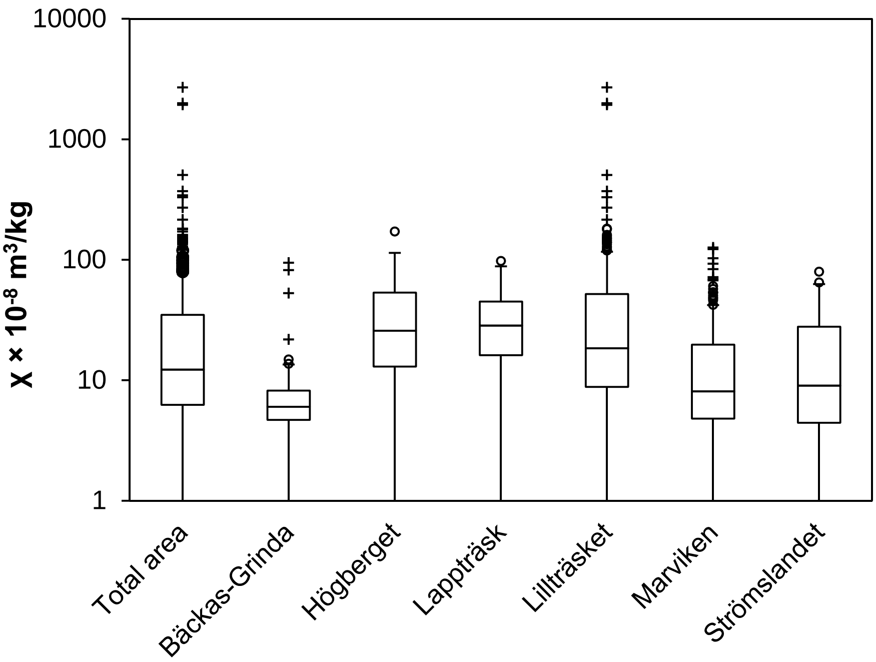

Figure 8. Tukey boxplots of mass susceptibility for the entire population and for individual areas. The central line of the box is the median of the population, while the upper and lower hinges represent the upper and lower quartiles respectively. Outliers are samples with values > 1.5 times the box length (circles) and far outliers with values > 3 times the box length (crosses).

The results are also illustrated in maps (Figures 9 to 11), where the spatial MS variations are shown in relation to the Fe concentrations. The most intense susceptibility anomalies are found in the Lillträsket area (Figure 9). The population of high susceptibility values corresponds to the complex of elevated iron concentrations, yet not all individual high susceptibility values correspond to high iron concentrations and vice versa as indicated with numbers 2 and 3 on Figure 9. The population trends in a NEE direction and is about 700 m long. The susceptibility values obtain a maximum of 2,700 × 10^{-8} m^3/kg and the Fe concentration reaches 17 % in the most anomalous samples. A subset of anomalous values is seen southwest of lake Lillträsket (no. 1 on Figure 9), where slightly higher susceptibility values (60 … 90 × 10^{-8} m^3/kg) occur in a NE-SW trend vs. a background of lower values (6 … 16 × 10^{-8} m^3/kg).

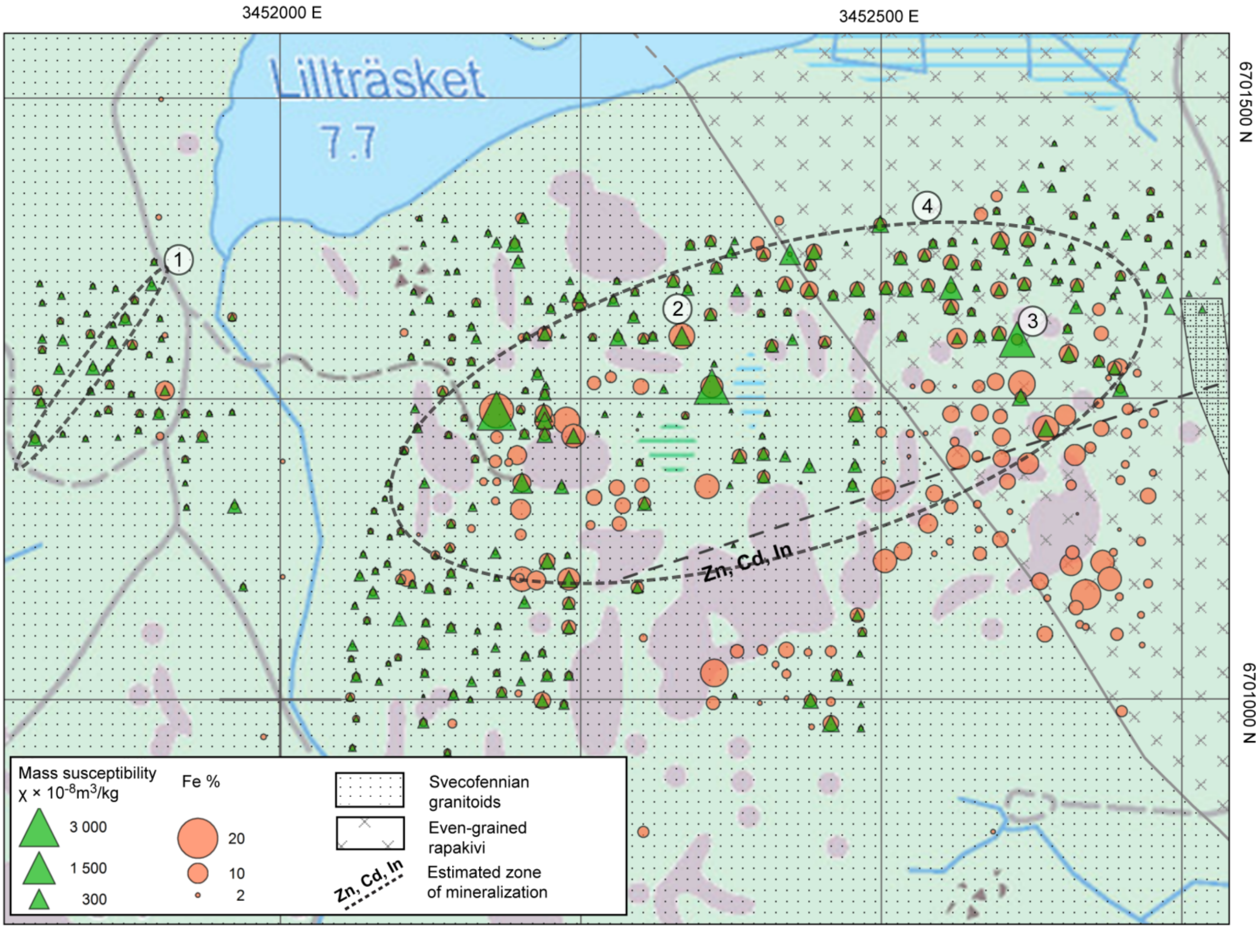

Figure 9. Mass susceptibility compared to Fe concentrations of soil samples in the Lillträsket area. No. 1 indicates a minor NE-trending set of elevated susceptibility values, no. 2 and 3 indicate susceptibility values inconsistent with iron concentration (unexpectedly low for no. 2 and high for no. 3). The population of high values is marked by no. 4 and seen throughout the area with a ENE trend (lithologies drawn after Sundblad et al., pers. comm. and García, 2013).

A potential vein mineralization with Fe, Cd, Zn, and In has been recognized in an area dominated wiborgite, southwest of an horse-shoe shaped even-grained rapakivi stock in the Marviken area (Figure 10). This mineralization was indicated by a soil geochemistry anomaly and an associated magnetic field anomaly already in 2009-2010, before systematic susceptibility measurements were carried out on the soil samples (Sundblad, pers. comm.). Nevertheless, elevated susceptibility values have been recorded for scattered samples collected in 2012 in this area, but they do not form an easily interpretable population. The background values range from 4 to 10 × 10^{-8} m^3/kg, with higher values ranging from 80 to 150 × 10^{-8} m^3/kg. It should be noted that the samples collected in 2009-2010 (for which the susceptibilities not were measured) had significantly higher Fe concentrations than the samples collected in 2012.

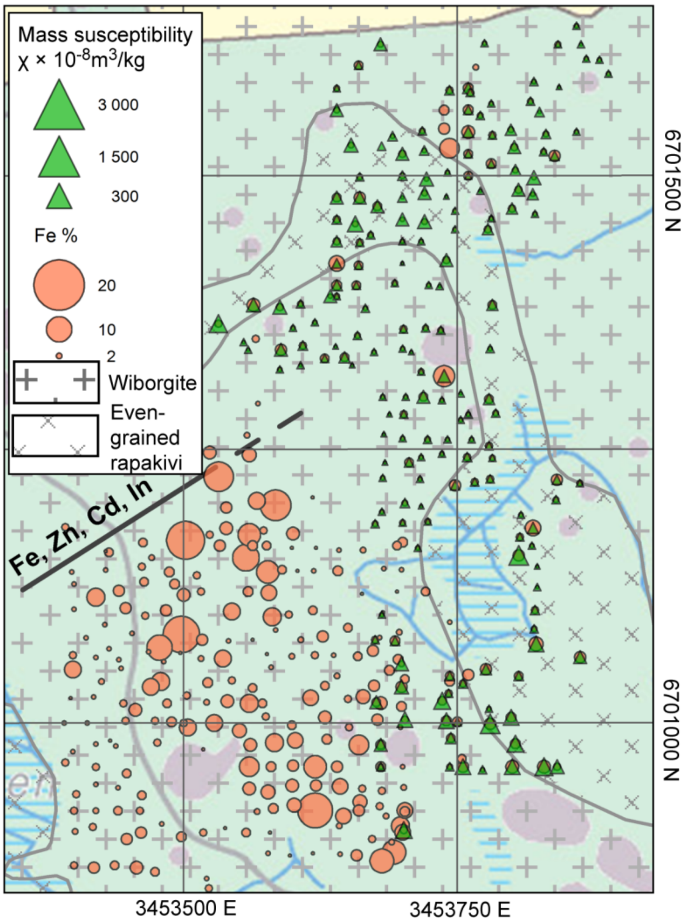

Figure 10. Mass susceptibility compared to Fe concentrations in the soil of Marviken. No clear population of elevated susceptibilities is observed. The black line indicates the assumed vein-type mineralization (lithological boundaries after Sundblad, pers. comm.).

The Lappträsk area is exceptional for its relatively high background MS values compared to other areas (Figure 11). MS distribution shows maximum around 30×10^{-8} m^3/kg, while it is around 10×10^{-8} m^3/kg in the other areas. Occasional high MS values appear in background of low susceptibilities in the Bäckas-Grinda area. The susceptibility distribution shows maximum around 7×10^{-8} m^3/kg, a few samples reach 100×10^{-8} m^3/kg. In the Högberget area, the high susceptibility values are consistent with the high iron concentrations, but the number of samples is relatively small. The values vary from 10 to 400×10^{-8} m^3/kg. The susceptibility in the Strömslandet area is evenly distributed from 5 to 50×10^{-8} m^3/kg. In the Lappträsk and Strömslandet areas, neither chemical data (Sundblad, pers. comm.) nor susceptibility values are anomalous.

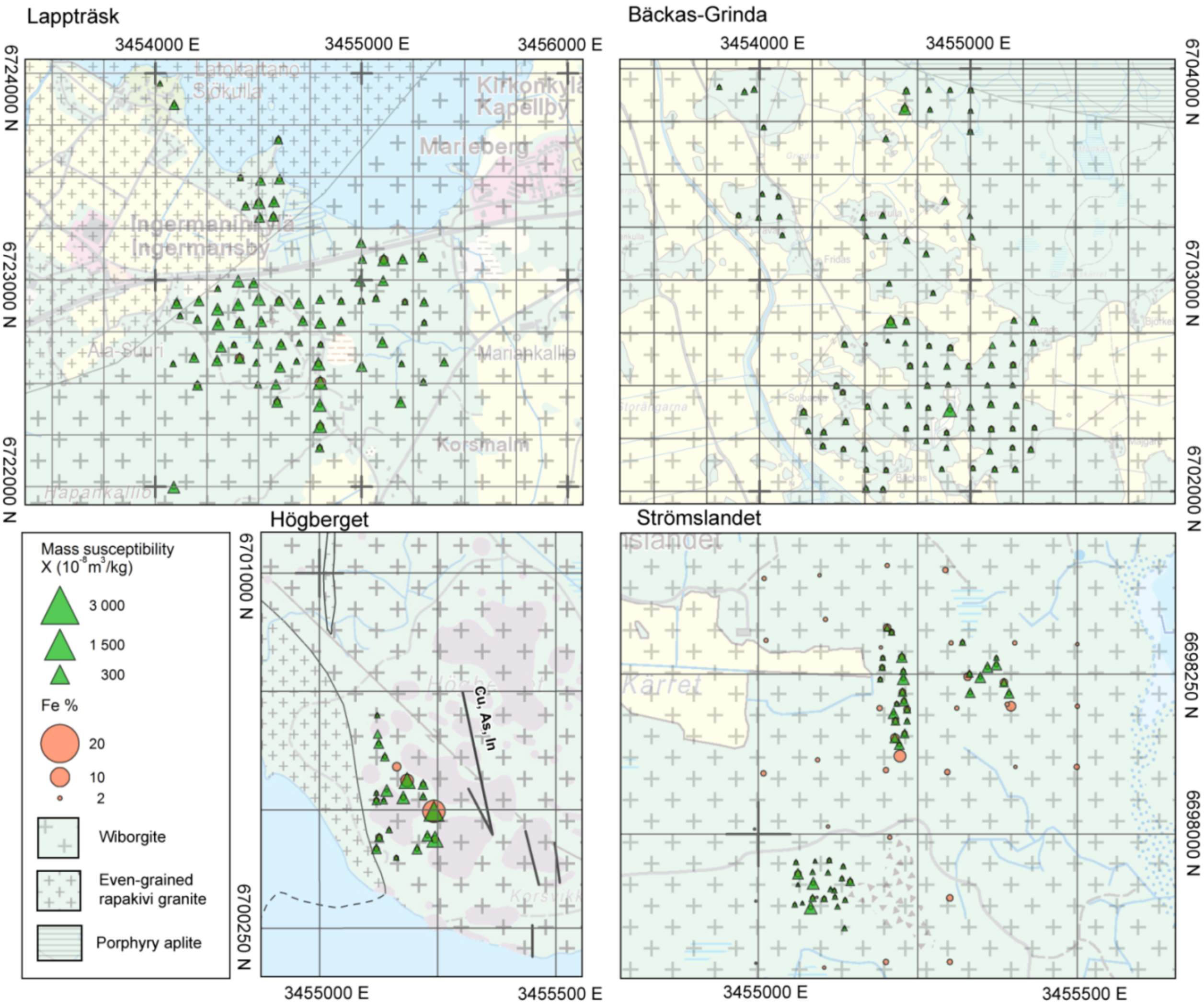

Figure 11. Mass susceptibility in soil compared to Fe concentration in soil in the Lappträsk, Bäckas-Grinda, Högberget, and Strömslandet areas. A relatively higher level of background susceptibilities are noted for the Lappträsk samples. Occasional anomalous susceptibility values occur in the Bäckas-Grinda area. A set of high susceptibility values and Fe concentrations is seen at Högberget (lithological boundaries after Sundblad, pers. comm. and the Geological Survey of Finland, 2000).

4. Discussion

4.1. Apparent magnetic susceptibility of the crystalline bedrock

The magnetic susceptibility of granitic rocks around the world is extremely variable, ranging from 1 µSI to 100,000 µSI. The susceptibility distribution is generally bimodal, with two distinct maxima around 10 to 100 µSI and 1,000 to 10,000 µSI (Aydin et al., 2007).

The investigated wiborgite has similar frequency distribution of susceptibility as has been documented for wiborgite elsewhere in the Wiborg Batholith by Elo and Korja (1993). In both cases, the distribution is log-normal with a negative skew (Figure 12). The distribution maxima are around 1,030 µSI in the histogram presented by Elo and Korja (1993) and around 1100 µSI in this work. Elo and Korja (1993) reported a mean of 1,200 µSI, which is lower than what has been documented in this work (1400 µSI). The histogram by Elo and Korja (1993) does not show the ferrimagnetic component, but Elo and Korja (1993) state that it exists and has a mean value of 13,500 µSI. In the present investigation, the ferrimagnetic component has a mean of 27,000 µSI. Elo and Korja (1993) state that susceptibilities with such amplitudes will create significant aeromagnetic anomalies. This comparison allows the assumption that the wiborgite studied in this work is typical for Wiborg Batholith regarding its magnetic susceptibility. The wiborgite has capability of producing magnetic field anomalies due to its natural magnetic properties.

The investigated Svecofennian granitoids and even-grained rapakivi granites have low susceptibilities (< 100 µSI), which is unusual for granitic rocks. Granites with susceptibilities around 100 µSI are e.g. known in the West Carpathian mountains (Gregorová et al., 2003), though the majority of the susceptibility values is still higher than 100 µSI. It may be suggested that paramagnetic minerals control the susceptibility of the investigated Svecofennian granitoids and the even-grained rapakivi granite. These rocks are not likely to cause magnetic field anomalies.

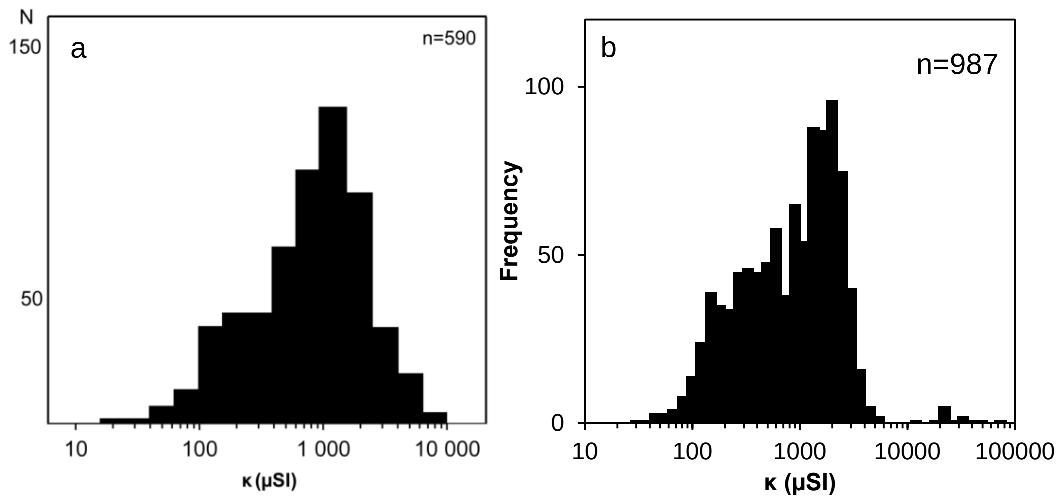

Figure 12. Histograms showing the magnetic susceptibility distribution of wiborgite: a) wiborgite of Wiborg Batholith (Elo and Korja, 1993) and b) wiborgite measured in the present work. The vertical axes show numbers of measurements in each category, „n“ stands for the number of total measurements.

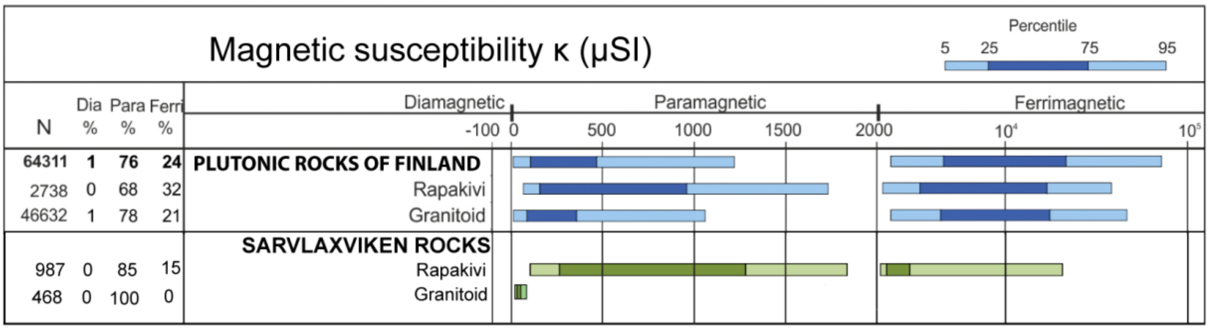

Figure 13. Variability in magnetic susceptibility of Finnish plutonic rock types compared to the rocks studied in this work. The cut-off between the para- and ferromagnetic groups is 2,000 µSI. 90 % of the susceptibility values fall within the range of the blue or green fields and 50 % of the susceptibility values fall within the dark blue or dark green fields. The gap between the ranges is apparent, caused by the division between percentiles (drawn after Airo and Säävuori, 2013).

The variability in the magnetic susceptibility of the measured bedrock was compared to other plutonic rocks in Finland (Figure 13). For that purpose, the susceptibility data were divided into percentiles of 5, 25, 75, and 95. A values of 2,000 µSI was used as a cut-off between para- and ferrimagnetic categories. 90% of the susceptibility values fall within the range of the blue or green fields and 50% of the susceptibility values fall within the dark blue or dark green fields (from 25^{th} to 75^{th} percentile; Airo and Säävuori, 2013). Note that the measurements of the reference material were carried out with laboratory equipment, while the measurements of the material investigated in this contribution was made with field equipment. Rapakivi granites in entire Finland and rapakivi granites studied in this work show a similar variability, except that the data for the rapakivi granites presented in this work show a wider variability within 50 % of the paramagnetic measurements while the variability in the ferrimagnetic category is smaller. The variability of the Svecofennian granitoids in the Lillträsket area is extremely small and the ferrimagnetic category is absent, whereas the overall variability of Finnish granitoids is somewhat similar to rapakivi granites.

Granitic rocks can be divided into two series by the presence of opaque accessory minerals: 1) the magnetite series is characterized by the occurrence of magnetite and 2) the ilmenite series by the occurrence of ilmenite or hemo-ilmenite. Magnetite series granitoids contain 0.1 to 2 vol% magnetite and other accessory minerals include ilmenite, hematite, pyrite, sphene etc. Ilmenite series granites contain less than 0.1 vol% of ilmenite while magnetite is absent, other accessory minerals include pyrrhotite, graphite, muscovite and low ferrous biotite. The occurrence of magnetite or ilmenite is controlled by the oxygen fugacity (Ishihara, 1977). This division is also used in rock magnetic studies, where the boundary of 3000 µSI is used for dividing granitoids between magnetite and ilmenite series (Ishihara et al., 2000). Considering this, the even-grained rapakivi granites and the Svecofennian granitoids can be classified as ilmenite-series granitoids, based on the susceptibility data. For the

Svecofennian granitoids, this is in compliance with the preliminary rock classification by García (2013), where no dark minerals have been detected. For the wiborgite, most measurements do not reach the limit of 3000 µSI and the investigated wiborgite can thus not really be considered to belong to the magnetite series, although magnetite has been reported in wiborgite (Lehtinen et al., 2005). According to Airo and Säävuori (2013), magnetite contents of 0.55 wt% can be expected in rocks with MS of 10,000 µSI. Magnetite could thus also be present in the ferrimagnetic population of wiborgite. Elo and Korja (1993) state that susceptibility of the rapakivi granites increases with increasing amount of mafic and/or ferrimagnetic minerals, the increase of the components are indicated by higher susceptibility values. Moreover, the increase in the amount of ferrimagnetic minerals leads to significantly higher susceptibility values. The populations of ferrimagnetic rocks in the Högberget area, which are marked with numbers 1 to 3 in Figure 5 are thus considered to be in the range of natural magnetic variance of rapakivi granites. As also documented by Elo and Korja (1993) and Karell et al. (2014), the variable magnetic character of the Wiborg Batholith rapakivi granites is due to the occasional presence of ferrimagnetic rocks.

Measurements of the magnetic susceptibility were useful to confirm the lithological boundaries since the neighbouring rock types in the Lillträsket and Högberget areas have contrasting values and susceptibility distributions. The transitions in the character of MS correspond well to the boundaries between the rock types. Even though the susceptibility measurements confirm the lithological boundaries, they do not add any new transitions to those already known from routine geological mapping by visual interpretation. Possible alterations in the bedrock do not apparently cause changes in the magnetic susceptibility. The mineralization types in the study area do probably not affect the presence of ferrimagnetic minerals.

Ground measurements of the bedrock susceptibility also explain the border between Svecofennian granitoids and Wiborg Batholith seen on the total field aeromagnetic map (Figure 3). The unvaried and low MS values of the Svecofennian granitoids create an even magnetic field surface while the heterogeneous MS of the rapakivi granites (except the even-grained rapakivi granite at Högberget) results in an uneven magnetic field surface for the Wiborg Batholith.

The susceptibility data can be used for modelling the shapes of certain magnetic bodies, e.g. the xenoliths of the Svecofennian supracrustal rocks in the marginal zone of the Wiborg Batholith, southeast of Lillträsket. To create more precise model shapes of magnetic bodies in future work, the susceptibilities of the surrounding rock and the composing rock are necessary input parameters.

The understanding of the contrasting magnetic properties of the Svecofennian granitoids and the rapakivi granites can be taken into account while carrying out magnetic field ground measurements. Heterogenic susceptibility values result in varying field values in rapakivi areas, while even field values are expected in the areas of Svecofennian granitoids. Thus, scales for observing magnetic anomalies in Svecofennian granitoids and rapakivi granites should be chosen in correspondence with the rock type under investigation.

4.2. Mass-specific susceptibility of soils

The magnetic susceptibility measurements of the soil samples were used as a complement to chemical analyses of metals. Anomalous sample populations are located in the Lillträsket, Marviken, and Högberget areas, where elevated susceptibility values are in compliance with the geochemical anomalies.

For evaluating the relations between MS and chemical elementary data, a correlation matrix (Appendix 1) was constructed using Pearson's correlation coefficients (r). Due to the circumstance that MS data are distributed rather log-normally, natural logarithms of mass specific susceptibilities were used for calculating r as suggest Hanesch and Scholger (2002). Natural logarithms were also used in the calculations for chemical elements showing log-normal distribution. The strongest correlations are presented in Table 3; correlation coefficients shown are significant at the 0.01 level. Correlations of rare earth elements (REE are defined as lanthanides and Y according to Atkins and Jones, 2008) are given for the sum of REE concentrations, concentrations of Sc were not analysed. Correlation coefficients with indium are absent for sites where In is absent in the soil. Indium enrichments are found at Lillträsket and Högberget. The highest association appears with elementary Fe and is followed by Zn. The Lappträsk area is exceptional for the low correlation with Fe. Of the metals listed in the Table 3, REE, Pb and Be have no significant correlations to the MS in Bäckas-Grinda. Weak correlations with REE and Ga are found in Strömslandet.

Table 3. Strongest correlations between metal concentrations and natural logarithms of mass susceptibilities for the entire area and individual sites; correlation coefficients shown are significant at the 0.01 level. Natural logarithms are also used for elements showing log-normal distribution.

Component	Total	Lillträsket	Lappträsk	Bäckas-Grinda	Marviken	Högberget	Strömslandet
ln(Fe)	0.728	0.754	0.475	0.608	0.703	0.800	0.609
ln(Zn)	0.640	0.561	0.433	0.524	0.597	0.574	0.653
ln(REE)	0.618	0.627	0.422	-0.003	0.504	0.761	0.102
Pb	0.605	0.613	0.438	0.092	0.480	0.668	0.550
ln(Bi)	0.600	0.636	0.455	0.209	0.448	0.631	0.555
In	0.569	0.586				0.733	
Ga	0.535	0.506	0.239	0.367	0.484	0.695	0.270
Be	0.506	0.609	0.417	0.054	0.447	0.723	0.498

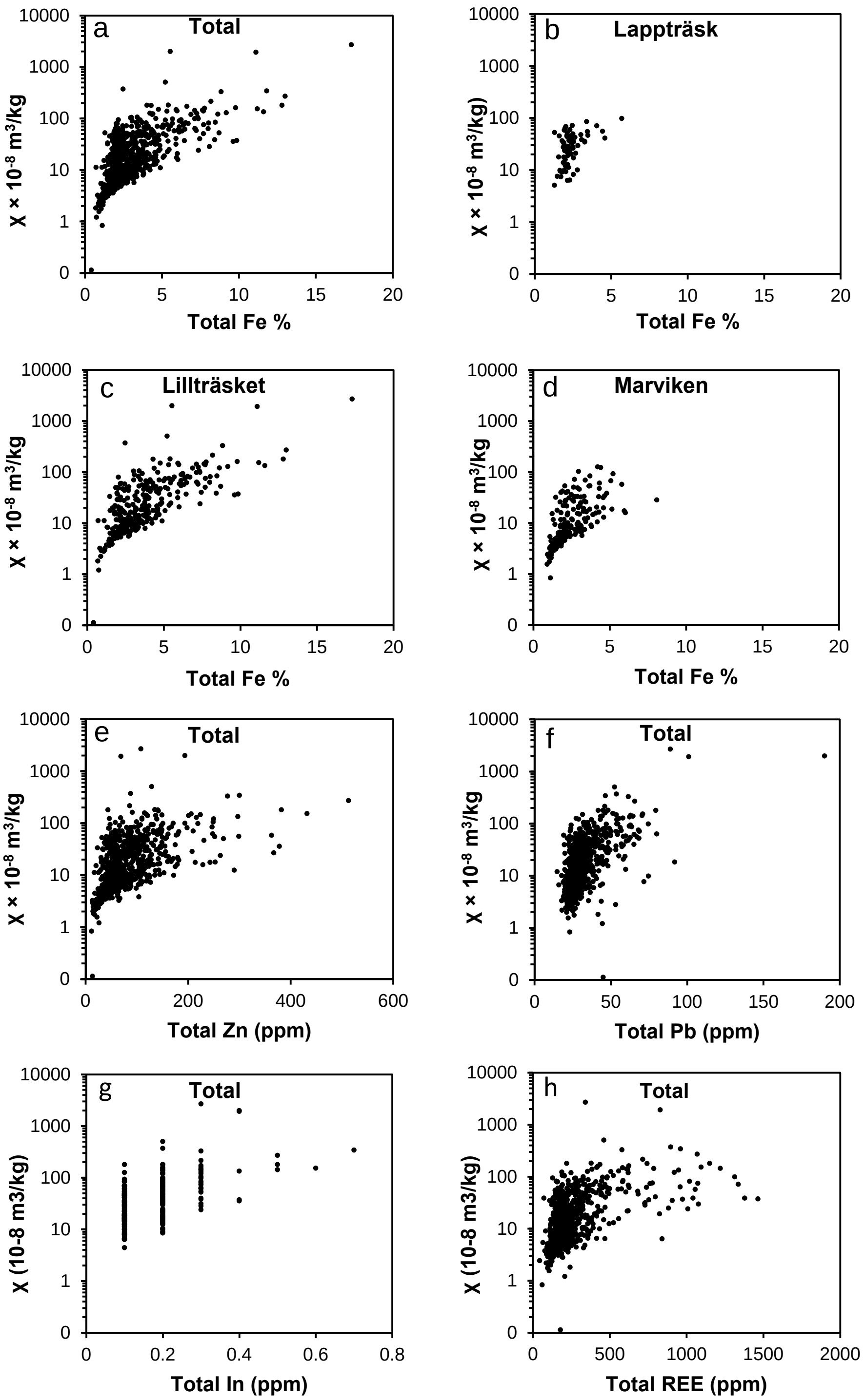

Figure 14. Scatterplots of mass susceptibility vs. concentrations of chemical elements. Plots of Fe are given for different study areas to show the variance in associations.

On scatterplots of Fe and Zn against mass susceptibility, a fan-shaped distribution is present (Figure 14; a, c, d, e). The association between Fe and the susceptibility in the Lappträsk area is weaker than in the Lillträsket and Marviken areas. Iron concentrations and MS values in the Marviken area do not reach so high values as in the Lillträsket area. In scatterplots of other elements with high correspondence, e.g. Pb (Figure 14; f), the distribution is more aggregated and does not branch in many directions. Indium concentrations remain low in all analysed samples and most of the samples do not have any content of indium. However, increase in indium concentrations accompanies increase in MS (Figure 14; g). Increase of REE concentrations is also accompanied with increase in MS (Figure 14; h).

The magnetic susceptibility has the strongest correlation with elementary Fe. Iron in soil environments is represented by many mineral phases: hematite, magnetite, goethite, maghaemite, etc. of which magnetite and maghaemite are strongly ferrimagnetic and usually take most of the account of contributing to magnetic susceptibility of soil when present (Dalan, 1998). Other mineral phases have significantly lower susceptibilities. The fan-shaped distribution on the MS – Fe % scatterplot (Figure 14; a, c, d) – can thus be interpreted as follows: a steep increase in MS in the left part of the fan is the result of magnetite/maghaemite content; other sections where susceptibility increases more steadily are probably related to fewer magnetite/maghaemite grains while other iron mineral phases prevail. The fan-shaped distribution in the Zn diagram (Figure 14, e) could be a result of Zn being closely related to Fe (r=0.72).

The susceptibility is also associated with Zn, Pb, Bi, In, Ga, and Be, which are the elements with strongest correlations. These elements do not appear in so many contrasting mineral phases as Fe, thus the distributions on scatterplots are more aggregated. Relying on molar susceptibilities of common minerals (sulphides, oxides, chlorides etc.) for the above-mentioned elements, they are generally diamagnetic minerals (Haynes, 1999), i.e. have negative susceptibilities. Therefore, the associations with MS likely appear due to a situation that those elements tend to occur together with Fe. Another susceptibility association appears with the rare earth elements, which can be explained by the fact that REE form strongly paramagnetic minerals. In industry, they are used as components in magnets (Haynes, 1999). At the same time, REE also correlate well with Fe (r=0.6 to 0.7). Low correlation coefficients between MS and chemical elements were observed in the Bäckas-Grinda area, which could be due to the low variability of susceptibility measurements compared to other areas. When the susceptibilities do not vary much, there is no correlation to be expected either.

The boxplot method proved to be useful for defining the threshold of extreme MS values. While sorting out the outlying values in a certain area, it has to be decided whether to use local or total dataset. The local dataset includes samples measured in a certain research site while the total dataset includes all measured samples (Figure 8). The decision should be made by the character of each research site. In the Lillträsket area for example, extreme values were defined from the total dataset, while local measurements were not so useful in defining the anomalous area as many high values were excluded. This is due to a relatively big population of samples with high susceptibilities in the area, thus a set of background values is necessary. On the other hand, in the Marviken area, the local dataset was more useful in defining samples with extreme susceptibility values. There are enough samples obtained in the area and not so many anomalous samples; the local dataset is therefore sufficient to provide background values while the total dataset defined only a few outliers. Högberget is an example of an area, where the amount of samples is small and the total dataset is definitely needed to define the background values of the susceptibility. Although extreme values of susceptibility were not recorded in the Lappträsk area, it should be noted that the background values there are relatively higher than in other areas. Thus, when necessary, a local dataset should be more appropriate for defining extreme values in the Lappträsk area.

Outliers are seen in Figure 15 and Figure 16. In the Lillträsket area (Figure 15), extreme values are defined from total samples. Outliers and far outliers are spread consistently with the anomalous population of Fe as described above ("Results"; Figure 9). A minor concentrated set of far outliers is located in the central area (Figure 15, no. 1). Another subset of outliers has a NW-SE trend and is situated in the south-western part of the area; it is supported by fewer measurements (Figure 15, no. 2). This subset is consistent with the geochemical plots for Fe and Zn. A third subset of outliers is situated in the eastern part, immediately along the boundary between the Svecofennian granitoids and the rapakivi granite (Figure 15, no. 3). It has a NW-SE trend and is about 250 m long. It extends by high Fe values further to southeast, where susceptibility is not measured.

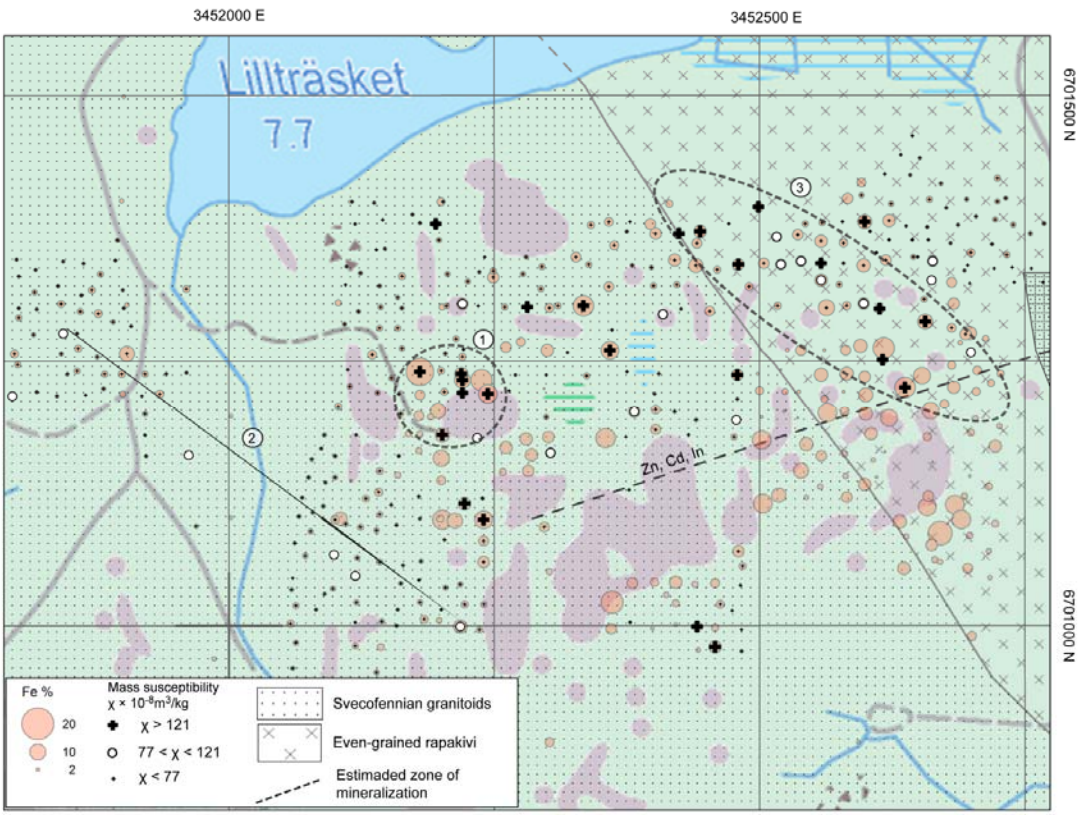

Figure 15. Outliers in the MS observations defined by the boxplot method from total samples in Lillträsket. Numbers indicate the sub-sets of anomalous susceptibilities (lithological boundaries after Sundblad et al., pers. comm).

In the Marviken area (Figure 16), outliers are defined from local samples. A set of anomalous samples is situated SE of the assumed metalliferous vein, it is elongated in NW-SE direction. It is likely that metal source of this population is the metalliferous vein.

Other studied areas do not reveal such populations of outliers in susceptibility. Considering extreme values defined from the total samples, there is a small set of outliers in the Högberget area consisting of three outlying samples. In the Bäckas-Grinda area there are two outlying samples, while there is one in the Strömslandet area and two in the Lappträsk area.

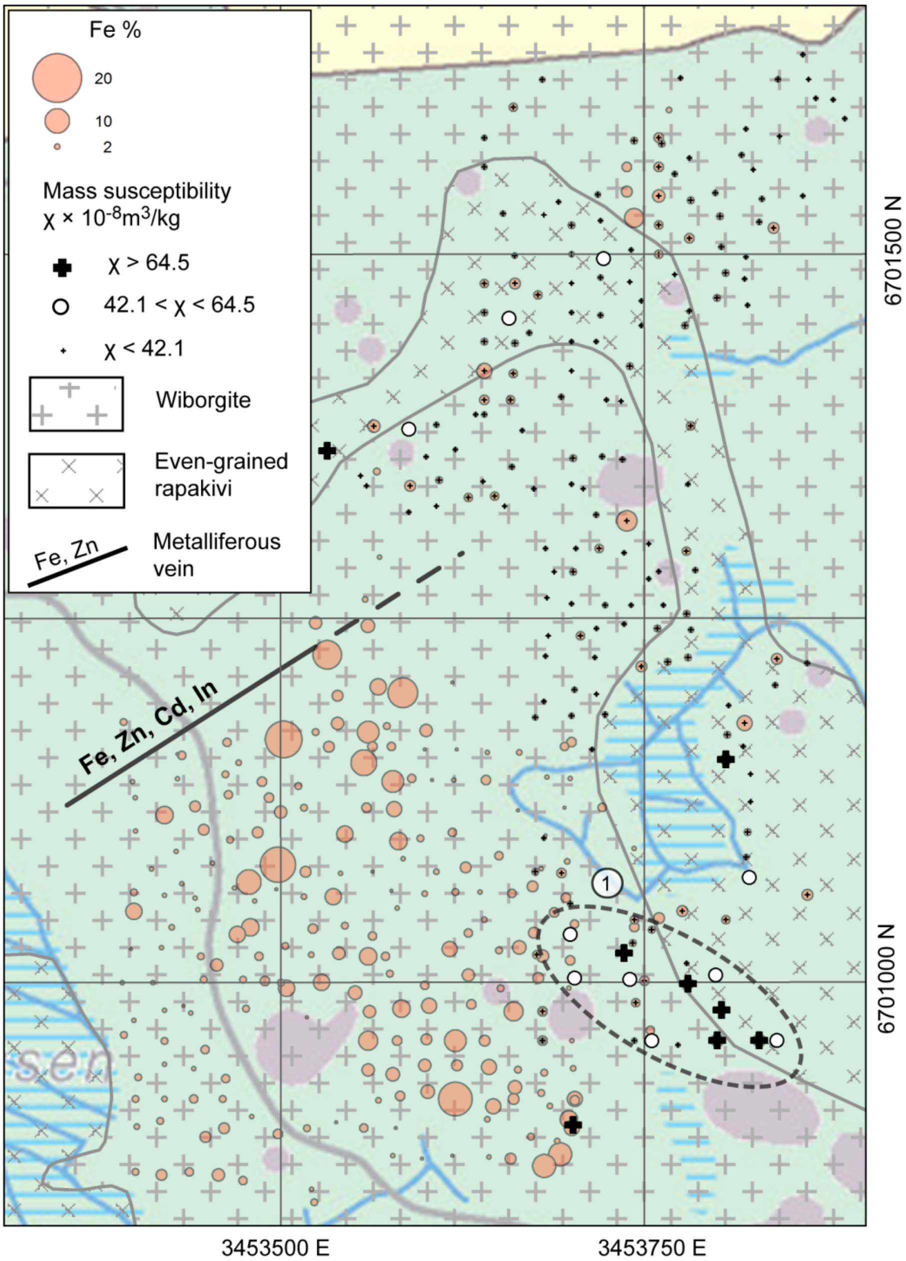

Figure 16. Outliers of susceptibility in the Marviken area defined from local samples by the boxplot method. A population of extreme values of susceptibility is marked with no. 1 (lithological boundaries after Sundblad, pers. comm.).

Populations of samples with anomalous susceptibilities were observed in the Lillträsket, Marviken, and Högberget areas and are consistent with geochemical anomalies in the soil. Three subsets of high susceptibilities in the Marviken and Lillträsket areas (see 2 and 3 on Figure 15 and 1 on Figure 16) have NW-SE trends, which is the same direction as the movement of the former continental glacier (Boulton et al., 2001). The metal contamination could therefore be carried from the source to soil by glacial processes. These anomalies imply that the sources of the metal contaminations could be located NW of the high values.

There could be an effect on the samples where susceptibility values are inconsistently high compared to the Fe concentrations caused by chemical and microbial processes in the soil. When a sample is collected from the C horizon (or below), it should be of the best quality, represent material derived originally from bedrock and only slightly altered by soil-forming processes (Foth, 1990). However, when a sample is collected from the topsoil (and also contains organic matter), it has been under the influence of many soil chemical and biological processes and the original mineralogical composition could be affected. From the perspective of MS, there is a natural tendency for topsoil to accumulate iron minerals. Most common in our climate is the goethite (αFeOOH), while hematite is more prevalent in dry climates. The less common lepidocrocite (γFeOOH) has a tendency to change into the much more magnetic maghaemite when it is dehydrated (Dalan, 1998). Dearing et al. (1996) have proposed a whole secondary ferrimagnetic mineral formation sequence in temperate climate soils, where climate, organisms, drainage, and parent material of soil are the factors of transformations between different mineral phases of iron. They concluded that bacterial Fe reduction causes ferrihydrite ($Fe_2O_3 \times 0.5H_2O$) to transform to magnetite, but the main Fe resource is linked to geological factors, therefore magnetite formation is limited. The iron supply appears to be the main process that controls the formation magnitude of ferrimagnetic minerals. Porsch et al. (2014) demonstrated experimentally, that microbial processes in different soil types led to an increase of MS in the extent of 4 to 11 %, although they also concluded that the increase magnitude depends on the availability of Fe.

Assuming that the soil studied in this work has been under the influence of such processes where magnetite would be produced, it would result in higher susceptibility values. Higher susceptibility values would be obtained, yet the concentration of Fe should still reflect the bedrock chemistry. It could be the situation for the samples where high susceptibility values are recorded, but the iron concentration remains moderate (see no. 2 on Figure 9). To document such occasions, the visual presence of organic matter in the samples was noted during the susceptibility measurements. This shows that on 18 occasions out of 58, i.e. 31 % of the outlying samples, have high contents of organic particles. Every such sample was collected in the Lillträsket area, where anomalous Fe concentrations are recorded; therefore inconsistently high MS values still reflect the area of metallic anomalies and no “false positive” susceptibility anomaly is detected.

Considering the ability for susceptibility measurements to help locating geochemical anomalies, the measurements can thus be used to improve the sampling strategy in the field work. When a population of anomalous MS is detected in the 100 × 100 m sampling, a denser sampling grid could be chosen immediately. At the same time, the results of the chemical analyses will take months and a denser sampling grid would not be done until the next fieldwork session. Another aspect is the capacity of the measuring instrument. If approximately 100 samples are produced during a work day (as was the case in the field courses), the SM-100 instrument was too time demanding to handle so many samples per day. If the SM-100 instrument would be replaced by a hand-held device, like Bartington MS3 (which is also adequately sensitive for these purposes), the measurements could have been done through plastic sample bags. This approach has not yet been tested and would need some comparative evidence to prove if such a system would work.

Conclusions

The magnetic susceptibility of the crystalline bedrock was studied on outcrops in the Lillträsket and Högberget areas. Svecofennian granitoids in the Lillträsket area have low homogenous susceptibility values; rapakivi granites in the Lillträsket area have moderate heterogeneous susceptibility values and Svecofennian supracrustal rocks have highly variable susceptibilities with distinct ferrimagnetic component of high susceptibilities. In the Högberget area, the wiborgite has moderate heterogeneous susceptibility values with a minor ferrimagnetic component of high susceptibilities and the even-grained rapakivi granite has low homogenous susceptibility values. Conclusions of the observations are:

1) all rock types have characteristic MS distributions which make them distinct from neighbouring lithologies on susceptibility maps;
2) the contrasting susceptibility distributions of the Svecofennian granitoids and the rapakivi granites in the Lillträsket area create distinct borders between the lithologies in the total intensity low-altitude aeromagnetic map (Figure 3);
3) the wiborgite and the supracrustal rocks are likely to cause magnetic field anomalies due to the presence of susceptibility values over 10,000 μSI;
4) based on their susceptibility values, the Svecofennian granitoids, the wiborgite, and the even-grained rapakivi granite should belong to the ilmenite-series granites according to the model of Ishihara (1977). Ilmenite (and no magnetite) is thus expected in those rocks, although the wiborgite has a minor ferrimagnetic component, where magnetite could be present;
5) no associations with possible rock alterations or mineralizations have been observed.

The mass-specific susceptibility was measured in 738 soil samples, obtained from five separate sites. The susceptibility values are normally low with a mean of 37×10^{-8} m^3/kg, but exceptional levels (>2000×10^{-8} m^3/kg) were reached. The threshold for defining the extreme susceptibility values was determined by the boxplot method (Tukey, 1977). Extreme susceptibility values are most common in the Lillträsket area, but were also observed in the Marviken and Högberget areas. Concluding statements of the soil studies are:

1) the magnetic susceptibility of soils associates primarily with Fe (i.e. with the numerous mineral phases of iron), but also with Zn, Pb, Bi, In, Ga, Be and, REE;
2) susceptibility measurements of soil samples outline efficiently the metal anomalous areas;
3) soil susceptibility measurements can be used to improve the sampling strategy already during the field work. When an anomalous susceptibility population is detected, the sampling grid could be made denser without awaiting the results of the chemical analyses.

In summary, MS measurements of both bedrock and soil in the Loviisa area have been proven to be an efficient method for the research and exploration project *Polymetallic mineralization associated with anorogenic magmatism in Southern Finland* and is a fast and cheap complement to other methods. Further exploration research in the area should include magnetic methods also in the future.

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Kristalse aluskorra ja pinnase magnetiline vastuvõtlikkus Lõuna-Soomes Loviisa piirkonnas

Johannes Vind

Kokkuvõte

Loviisa piirkonnas uuriti magnetilist vastuvõtlikkust (MV) eesmärgiga tuvastada sealse varasemalt tõestatud (Cook et al., 2011) polümetallilise mineralisatsiooni mõju kristalse aluskorra ja pinnase magnetilistele omadustele. Polümetalliline mineralisatsioon seostub Viiburi plutooni lääneosa rabakivigraniitidega ning seda iseloomustavad kõrged Cu, As, In, Mn, Bi, Sn ja W sisaldused (Cook et al., 2011). Uurimus on panus Krister Sundbladi juhitud Turu Ülikooli projekti *Anorogeense magmatismiga seotud polümetalliline mineralisatsioon Lõuna-Soomes*, mida rahastab K.H. Renlund'i Fond.

Uurimistöö eesmärkideks oli mõõta ja analüüsida

1) pinnaseproovide MV, et (i) leida seoseid MV väärtuste ja keemiliste elementide kontsentratsioonide vahel ja (ii) täiendada proovide kogumise strateegiat välitööde käigus;
2) kristalse aluskorra MV, et (i) mõista seoseid piirkonnas leiduvate kivimite ja nende magnetiliste omaduste vahel ja (ii) pakkuda andmeid magnetiliste kehade modelleerimiseks tulevastes uuringutes.

Pinnaseproovide MV mõõtmised olid täienduseks samade proovide keemilistele analüüsidele. Pinnaseproove koguti selleks, et tuvastada kõrgenenud metallisisaldusega alasid. Mandriliustiku liikumise käigus on aluskorra materjal kandunud üle pinnasesse, mistõttu võiks olla võimalik hinnata, kust pärinevad pinnasest leitud metallid.

Kivimite MV mõõtmised välioludes kasutamiseks mõeldud instrumendiga on kiired ja neid on võimalik teostada säästlikumalt kui laboratoorseid analüüse. Uuringutega saab tuvastada magnetilisi häiringuid, mis on põhjustatud magnetiliste kehade esinemisest, visuaalselt eristamatutest muutustest kivimites või metamorfismi mõjudest. Kivimitel on tihti iseloomulikud MV väärtuste jaotused, mis teeb võimalikuks naabruses paiknevate litoloogiliste üksuste eristamise ning kivimite esialgse klassifitseerimise nende magnetiliste omaduste põhjal.

Kristalse aluskorra uuringute käigus leiti, et

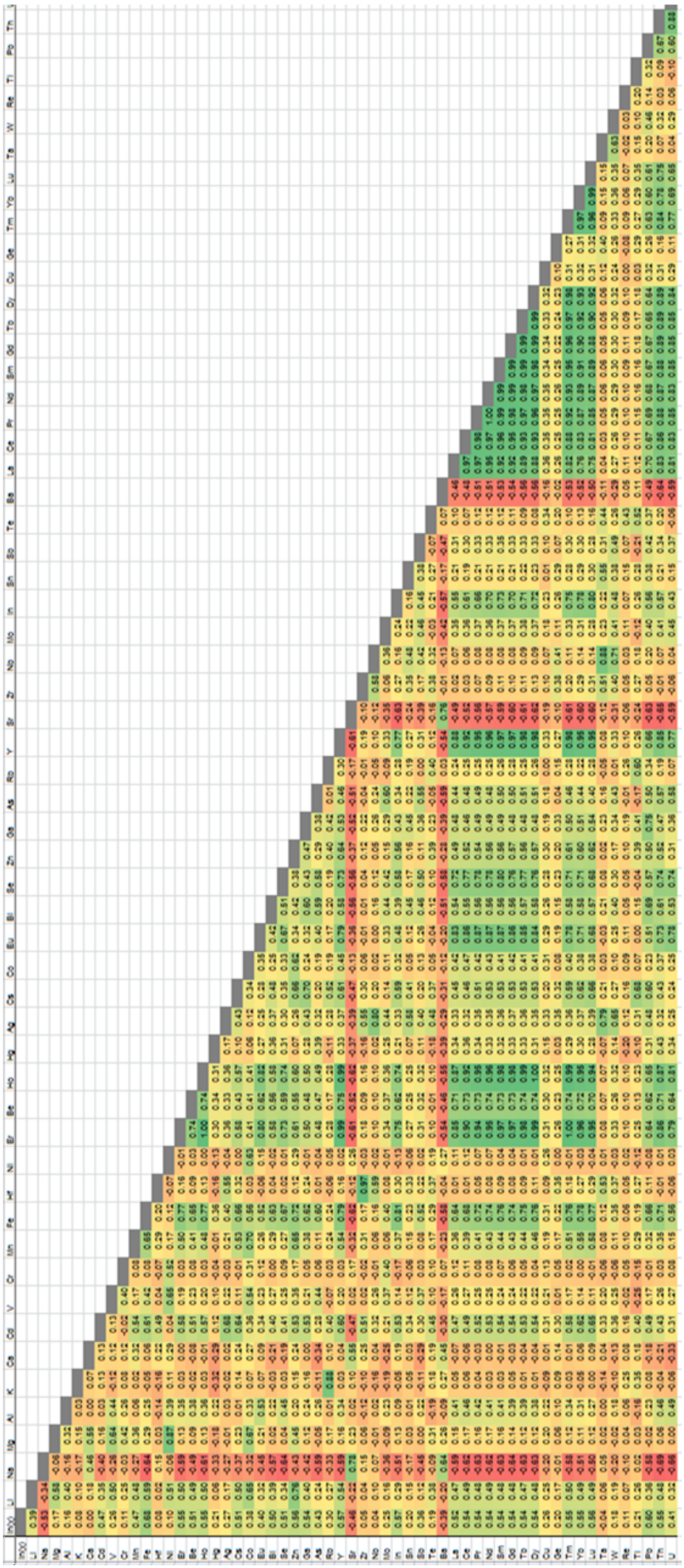
1) kõigil kivimitüüpidel (Svekofenni granitoidid ja metamorfsed kivimid, Viiburi plutooni viburgiit ja võrdteraline rabakivigraniit) on iseloomulikud MV väärtuste jaotused, mis eristavad neid naabruses paiknevatest kivimitest;

2) kontrastsed MV jaotused Svekofenni kivimite ja Viiburi plutooni rabakivide vahel põhjustavad selge kivimitevahelise piiri uuringuala iseloomustaval aeromagnetilisel totaalvälja kaardil;
3) viburgiit ja Svekofenni metamorfsed kivimid võivad põhjustada lokaalseid magnetvälja anomaaliaid, kuna neis esineb MV väärtusi üle 10 000 µSI;
4) Svekofenni granitoidid, viburgiit ja võrdteraline rabakivigraniit klassifitseeruvad Ishihara (1977) järgi kui ilmeniidi-seeria graniidid, niisiis on neis kivimites pigem oodatud ilmeniidi kui magnetiidi esinemine ning
5) seoseid metallilise mineralisatsiooni ja kivimite magnetiliste omaduste vahel ei esine.

Pinnaseproovide mõõtmiste põhjal leiti, et

1) MV väärtused assotseeruvad peamiselt Fe kontsentratsiooniga pinnases (ehk mitmesuguste rauamineraalide esinemisega) ning ka Zn, Pb, Bi, In, Ga, Be ja haruldaste muldmetallidega;
2) MV mõõtmised toovad efektiivselt esile kõrge metallisisaldusega alad;
3) tulemusi saab kasutada täiustamaks välitööde proovimisstrateegiat – leides kogumi kõrgete MV väärtustega proove, võib 100 × 100 m proovimisvõrgu tihendada 20 × 20 m proovimisvõrguks, ootamata keemiliste analüüside tulemusi.

Appendix 1.



Correlation matrix of analyzed elements and natural logarithm of mass susceptibility.

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