



Soil geochemical mapping of manganese in Norrbotten

Delineation of the spatial and statistical distribution of manganese and correlated elements in glacial tills

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Abstract

Information from soil geochemical mapping programmes is useful within a number of different fields including for example mineral exploration and environmental research. The purpose of this thesis was to investigate the relationship between soil metal concentrations and geological factors such as bedrock lithology, structural geology, mineralizations etc. The study used data acquired in association with a nationwide soil geochemical mapping programme conducted by the Geological Survey of Sweden, SGU. These data contained both total element concentrations measured via X-ray fluorescence spectroscopy and acid leached concentrations measured with plasma technique. Basic statistical compilations were made, including classification of element concentrations into percentiles according to SGU standards, calculation of leachability and correlation analyses. Spatial analyses were also done, using GIS-software. The results showed that all investigated elements except zinc had elevated median values for total concentrations in the project area compared to the natural median values. The strongest correlation for total element concentrations was that between iron and cobalt with Spearman $\rho=0.88$. Furthermore, the results of this study indicated that sampling sites superimposing volcanic rocks contained the highest total concentrations of manganese. The results also suggested that manganese content increased with increasing age of the underlying bedrock. The highest median concentration of 0.80 g/kg was found in Archean rocks. Known mineralizations were often reflected in the form of positive element anomalies in the till geochemistry. The obtained results were also consistent with the average composition of the bedrock. No clear connections with any of the other investigated geological factors could be made.

Key Words: geochemical mapping, manganese, GIS, drift prospecting

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1 Introduction

1.1 Geochemical mapping

This study utilizes data obtained from the nationwide soil geochemical mapping programme conducted by the division of Environment and Geochemistry at the Geological Survey of Sweden (SGU). The programme started in 1983, adapting a rather conventional sampling methodology known as C-horizon mapping of glacial tills (Lax 2005). Within the field of mineral exploration this type of method is also known as drift prospecting and it is a favoured technique amongst geological surveys and prospecting companies operating in glaciated shield terrains (McMartin and McClenaghan, 2001).

Till consists of bedrock material that has been eroded, transported and deposited directly by the glacial ice and may therefore, together with boulder tracing and investigations regarding ice-movement direction, serve as a valuable tool in mineral prospecting. Collection of samples in the C-horizon of soils produce material that is principally unaltered by biological processes or anthropogenic sources (McMartin and McClenaghan, 2001). In a Swedish context an exception to the latter can be found in the area around the Falun copper mine in central Sweden where centuries of extensive mining has resulted in elevated levels of copper and lead deep into the soil horizon (Ek et al. 2001). Apart from that one example, Sweden can generally be said to be well suited for till sampling as the soil type is widely distributed across the country, covering about 75% of the bedrock (Fredén 1994). It is therefore not surprising that Sweden, as well as the rest of Fennoscandia, have been the target for extensive investigations. Till geochemical surveys have so far covered practically all of Fennoscandia and the bulk of scientific papers published on the subject in the recent decade relates to surveys conducted in either Fennoscandia or Canada (e.g. Andersson et al. 2014; Gustavsson et al. 1994; Koljonen 1992; Levson 2001; Parent et al. 1996; Shilts 1993) (McClenaghan et al. 2000).

There are many ways of designing a till geochemical survey and there are several aspects that have to be taken into account when doing so. The most important and expensive component when collecting data is sampling. Considerations have to be made regarding sample density, sample depth and sample method. Sample density can vary greatly depending on the scale of the survey. At a reconnaissance phase, it usually lies within the range of one sample per 100-500 km². Late-stage mineral exploration may on the other hand involve as much as 1-100 samples per km². The scale of the survey also effects the choice of sampling depth. In reconnaissance or regional scale studies samples are usually taken at relatively shallow depths (0.5-1.0 m) so that they may reflect a broader source area. Sampling in more detailed studies are done further down in the soil profile so that they may better reflect the composition of the bedrock directly underlying the sampling site. The type of terrain in the study area, i.e. forested or permafrost, must also be taken into account when deciding what sample depth that is appropriate. The last choice to be made regarding sampling is what type of method to use. There are several methods that can be chosen depending on the thickness of the drift cover, available funds and, most importantly, aim of the study. These methods involve different types of equipment, which are used to collect the samples, and include shovels, drills and even excavators. Drills are typically used in areas covered by thicker drift so that the vertical soil profile can be determined, alternatively, when there is a different type of sediment layer covering the till layer. When designing a geochemical survey consideration also have to be made regarding laboratory methods. The appropriate size fraction and analytical methods are dependent on the character and composition of the potential ore body as well as economic factors (McMartin and McClenaghan 2001).

The Swedish soil geochemical mapping programme was initially developed with the purpose of supporting mineral prospecting activities. It should, however, be pointed out that data from the programme only show a general picture of the underlying bedrock and are intended to provide a general background levels for element concentrations. Even though the primary

application area for the mapping programme was focused towards mineral exploration, the data have shown to be useful in several other fields such as environmental- and medical research, municipal planning, forestry and discoveries of contaminated land (Lax 2005; SGU 2015). Similar development can be seen in many geochemical mapping programmes across the world, evolving from having mineral prospecting as the only purpose to involving several other fields of interests as well (Garret, et al., 2008)

As a field of science progresses the need for standardized methods and units of measurement often becomes evident. This is commonly easier to achieve in basic sciences, where experiments are done under very idealized conditions, than in applied sciences. In exploration geochemistry, which has to deal with the complexity of the earth's crust, it has proven to be especially challenging to introduce standard methods and units of measurement. But the broadening application base for geochemical data has further come to emphasise the importance of global standardisation in geochemistry. It is particularly the increased demand for data concerning natural background levels of element concentrations which has driven the process of standardisation forward. National regulatory agencies and similar organizations require this kind of data in order to set up guideline values for chemical substances in the environment. Datasets including a wide range of elements have previously been sparse and restricted to a few national programs. The reason for this is that most previously existing geochemical datasets derive from exploration investigations which often are aimed at a small group of elements which are of economic interest, such as Cu, Pb, Zn, Co, Ni or Sn. Darnley (1995) compared eighteen different regional-scale mapping programs situated on six different continents and ascertained that only three elements were common to all the programs. One positive effect that the standardization process has had on exploration geochemistry is that it has become easier to detect metallogenic similarities between regions (Darnley 1997). As a result of the rapid technological development seen in recent time the advancements within geochemical mapping have also come to involve new computer-based applications such as geographical information systems (GIS) technology (Carranza 2009)

1.2 Manganese as a focus element of this study

This study is focused on manganese and elements that are known to correlate with it, e.g. iron, magnesium and titanium. For a long time it has been known that manganese plays an important role in many geochemical contexts. For example, manganese- and iron hydroxides together with reactive particulate carbon seem to be the main regulators for metal sorption in both soil and fresh-water sediments (Jenne 1968). Manganese- and iron oxides act as scavengers for several heavy metals. This may generate metal anomalies in otherwise non-mineralized areas (Chao and Theobald 1976). It is well-known from previous studies that secondary processes may cause disturbance of the geochemical distribution pattern of manganese (Ladenberger et al. 2012). But if utilized in the right way, the potential for manganese- and iron oxides to act as a valuable prospecting tool have also been recognized (e.g. Chao and Theobald, 1976; Nowlan, 1976). Furthermore manganese oxides are vital in several types of geochemical barriers (Smith and Huyck 1999).

For industrial purposes, manganese has a wide area of application including manufacturing of dry cell batteries, plant fertilizers, animal feed and brick colorant, but the bulk of the manganese produced is used in association with steel production. In 2014, an estimated total of 18 million metric tons of manganese were produced in the world's mines (Corathers 2015). Manganese is the twelfth most abundant element in the earth's crust comprising about 0.1% of the total weight (Emsley 2001). Substantial deposits of manganese are found in the form of so-called deep-sea nodules on the ocean floor. So far, these resources have not been successfully mined but lately the interest in prospecting them has increased (Abramowski & Stoyanova 2012). Land-based manganese resources are unevenly distributed and mainly concentrated to a few countries. The majority, 75%, is located in South Africa, which also is the leading nation considering annual production. Other large resources are found in countries such as the Ukraine, Australia, Brazil, India and China (Corathers 2015). In Sweden

manganese ores have previously been mined in the Långban and Nyberget deposits, both of which are situated in the Filipstad district in the central part of the country (NMAB 1981). Nevertheless, significant amounts of manganese are still being extracted from Swedish bedrock in association with iron mining. Of the approximately 27 million metric tons of iron concentrate that were produced in Sweden in 2013 about 15 million had a manganese content exceeding 1 percent (SGU 2014).

1.3 Scope and limitations

1.3.1 Scope

The purpose of this thesis is to delineate the distribution of element concentrations for manganese and correlating elements in the till geochemistry of the project area both statistically and spatially (in map form). The aim is then to relate the obtained results into a context of other geological data.

The main question posed in the thesis is: How do soil metal concentrations relate to the following geological parameters:

- i) Structural geology
- ii) Bedrock lithology
- iii) Mineralizations
- iv) Metamorphic alterations
- v) Geophysics
- vi) Quaternary geology

1.3.2 Limitations

The relationship between soil metal concentrations and the geological parameters mentioned above are investigated at a regional scale, not considering more local variations in geology. The reason for this is that the study area is relatively large and if all small-scale geological properties were taken into account it would demand a considerably more extensive study, far beyond the scope of this thesis. Results from this study can instead be used to point out specific areas of interest, for example concerning mineral explorations or environmental studies. In which more detailed investigations then can be conducted.

2 Theory

2.1 Regional geology

2.1.1 Tectonics and structure

Tectonic setting and evolution

The study area is located in the northern part of Norrbotten County, above the Arctic Circle. The county is in turn situated in the northwestern part of the Fennoscandian shield where Archean rocks in the northeast meet Proterozoic ones in the southwest (fig. 1) (Bergman, Kübler and Martinsson 2001). The bedrock evolved as a result of a complex series of geodynamic events including both compressional and extensional processes, with related accretion, magmatism and sedimentation (Weihered, et al., 2005). This part of the shield was affected by three major orogenies during the Archean-Paleoproterozoic namely, the Samian (3.5-3.0 Ga), Lopian (2.9-2.6 Ga) and the Svekokarelian (1.96-1.75 Ga). Younger orogenies occurred in the western and southwestern parts of the shield, e.g. the Caledonian orogeny (0.5-0.4 Ga) which has affected the area in the westernmost part of the study area (Bergman, Kübler and Martinsson 2001).

Structural formations and trends

Two major ductile shear zones passes directly through the study area namely, the Karesuando-Arjeplog-deformation zone (KADZ) and the Kiruna-Naimakka deformation zone (KNDZ) (Fig. 1). The former constitutes one of the largest deformation zones in Sweden. Its northern part stretches from west of Gällivare up to Karesuando in the north. It is built up of many individual shear zones, ranging in character from ductile to brittle-ductile. The total width of the shear zone system can at places be up to 8 kilometres, displaying a varying degree of strain intensity. The Kiruna-Naimakka deformation zone stretches from Kiruna in the south to Naimakka in the north, with a continuation into Finland. It is composed of a protruding belt of anastomosing¹ shear zones which is almost parallel to the Karesuando-Arjeplog-deformation zone and also shows the same shear sense. There are also two major shear zones located in the vicinity of the study area: The Nautanen deformation zone (NDZ), which passes through the Gällivare area; and the Pajala Shear zone (PSZ) which extends through the eastern part of the county passing the border into Finland near Huuki (Fig. 1) (Bergman, Kübler and Martinsson 2001).

The general structural trend in northern Norrbotten is about NNE to NNW. An example of this is the area surrounding the shear zone which passes through Lainio where a weakly defined NNW-SSE striking pattern has been generated by the shear zone. But there are also areas in the region that can exhibit different structural patterns. For instance in the well investigated Kiruna area where the structural orientation is roughly N-S (Bergman, Kübler and Martinsson 2001). Figure 2 shows small- scale deformations in the region surrounding the study area, east of the Caledonian orogen.

¹ “A branching and reconnecting netlike pattern similar to the veins of a leaf” (Eggleton, 2001).

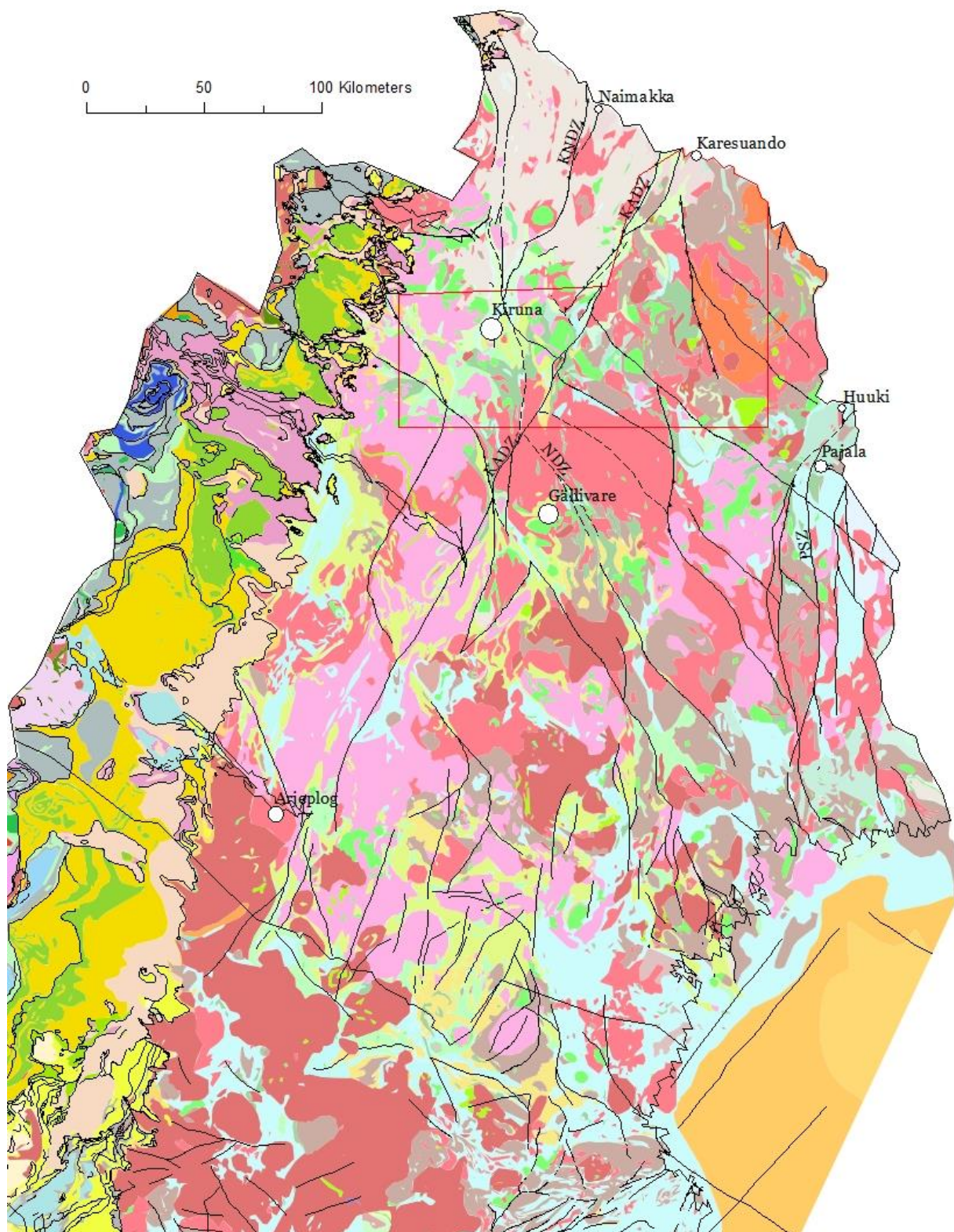


Figure 1. Large-scale deformations. KADZ = Karesuando-Arjeplog-deformation zone, KNDZ = Kiruna-Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala Shear zone. Red solid line marks the project area. © SGU

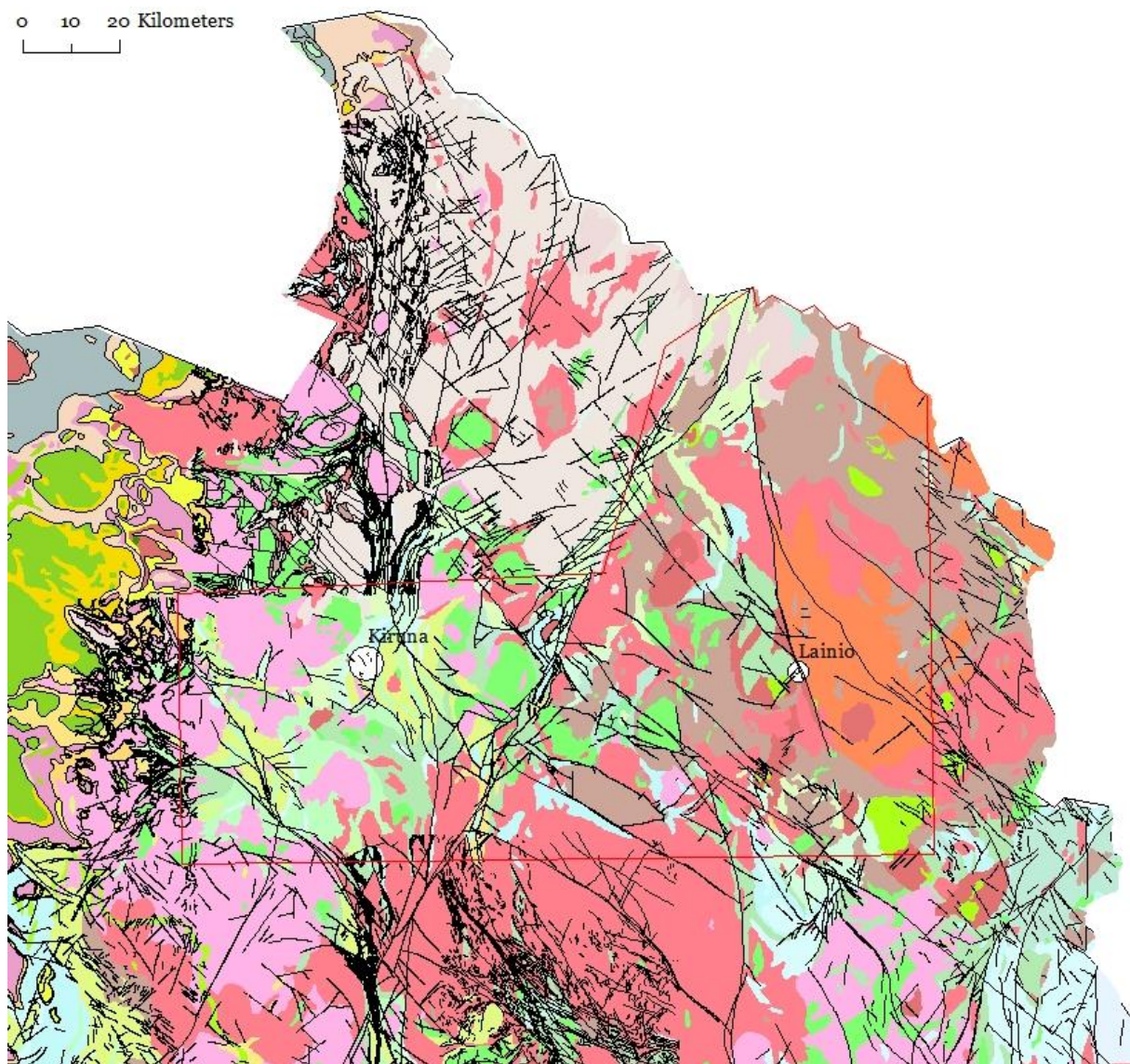


Figure 2. Small-scale deformations. Red solid line marks the project area. © SGU

2.1.2 Geophysics

The magnetic anomaly map (Figure 3) reflects the miscellaneous character of the bedrock in the region and some of the major lithological properties can be distinguished. In the Kiruna area, irregular magnetic banding related to supracrustal rocks can clearly be seen. Tendency to banding can also be seen in the Archean rocks in the northernmost part of the county, in this case exhibiting a more elongated structure. A sharp magnetic field gradient can be seen along the northern part of the Karesuando-Arjeplog-deformation zone (Figure 3). The KADZ also roughly constitutes the border between less dense rocks to west and denser ones in the east (Figure 4). In an area between Muonionalusta, Karesuando and Lannavaara there is a large positive gravity anomaly (Fig. 4), probably associated with high density mafic rocks at depth (Bergman, Kübler and Martinsson 2001).

2.1.3 Metamorphic alterations

Bergman, Kübler och Martinsson (2001) categorizes the Proterozoic rocks in northern Norrbotten into three different groups based on their metamorphic grade: High, medium and low. The Archean rocks have been excluded from this classification as it was considered that there wasn't enough data available to make such distinctions. Generally speaking, the Archean rocks underwent high-grade metamorphism even though medium-grade rocks may occur locally.

The only rocks, within the study area, classified as low-grade are located in two partly separated, approximately 50 kilometers long, belts. They extend from Kiruna up along the KNDZ and another, large-scale, N-S striking, deformation zone, respectively (Figure 1). In these rocks, primary structures are well preserved. High-grade metamorphic rocks are present in the northeast, roughly coextensive with the gravity high area mentioned in the previous section. Smaller zones containing high-grade rocks occur in the south-central parts of the study area around Svapavaara and Vittangi. The rest of the area is built up by rocks that has either undergone medium-grade metamorphism or, alternatively, intrusive rocks that at a regional scale can be regarded as essentially unmetamorphosed (Bergman, Kübler and Martinsson 2001; see printed map illustrating the distribution of different metamorphic grades, *Ba 56:2, Metamorphic, structural, and isotope age map*).

Hydrothermally altered (metasomatic) rocks can be reflected in the till geochemistry in the form of specific element anomalies that differs depending on the type of alteration. These anomalies are often oriented along the direction of ice-movement. Hydrothermal alterations are often associated with ore deposits. As such, alterations often constitute an efficient instrument for mineral prospecting (Ladenberger et al. 2012).

Sodium alterations in the form of spilitization, albitization and scapolitization are frequent throughout the county. These probably originate from dissolution of evaporate deposits in association with the regional metamorphism; something that probably have caused the large chlorine anomalies that are common all across Norrbotten (Ladenberger et al. 2012). Other types of alteration that can be found in the county include formation of skarn, potassium feldspar, sericite, tourmaline and epidote. Many of the alteration products are spatially connected to shear zones (Bergman, Kübler and Martinsson 2001).

2.1.4 Mineralizations

Northern Norrbotten constitutes one of the major ore provinces of Sweden. There are four metallogenic areas that entirely, or to a large extent, lie within the study area: The Kiruna, Vittangi, Lannavaara and Viscaria-Sauttusvaara metallogenic areas (Figure 7). Of these, the latter is categorized as a base metal area while the other three are ferrous. There are also two ferrous metallogenic areas that are only partially included within the perimeters of the study area; namely, the Pajala and Tärendö areas (Eilu, 2012).

Kiruna area

The Kiruna metallogenic area contains some copper deposits, such as the Rakkurijärvi and Tjårrojåkka deposits, but mainly the area hosts apatite-iron ores. Some major deposits that fall into this category are the Luossavaara, Nukutus and Tuolluvaara deposits. However, the Kirunavaara deposit is by far the most important. Containing a total amount of about two billion metric tons of iron-ore (previously produced and projected remaining reserves), with an iron content of 60%, it constitutes the only world-class deposit in Sweden (Eilu 2012). Apatite-iron ores are also referred to as Kiruna type ores (Geijer 1931). When investigating these types of ores in Sweden and in South America, Nyström and Henriques (1994) found that they typically were low in titanium content and relatively rich in vanadium.

Vittangi area

The Vittangi metallogenic area contains iron deposits in the form of apatite-iron and skarn-iron ores. The former type is mainly located in the northern and eastern parts of the area while the latter type is mostly found in the western and southwestern parts. The largest skarn deposit in the area is Vathanvaara. Of the apatite-iron deposits, Leveäniemi is the most significant and it also constitutes the third largest iron deposit in the county. The area also contains some minor copper-cobalt deposits, one example being Kiskamavaara (Eilu 2012).

Lannavaara area

Sattavaara, Kevus and Teltaja are three iron ores located around Lannavaara. They are all enriched in manganese. The two latter in fact have a rather unique composition that is not to

be found anywhere else in the region (Frietsch 1985). The northern part of the Lannavaara metallogenic area is poorly explored so far but is known to host some minor iron ores. Nearby the Kevus and Teltaja deposits there is also a zinc-lead deposit named Huornaisenvuoma (Eilu 2012). It has an ore zone that is enriched in several elements, including three of the elements investigated in this study, namely; iron, zinc, copper and manganese (Bergman, Kübler and Martinsson 2001).

Viscaria-Sautusvaara area

The Viscaria-Sautusvaara metallogenic area hosts a number of Iron and copper deposits. Examples of iron ores within the area include the Sautusvaara and Tjavelk deposits. The Viscaria deposit, situated about four kilometers west of Kiruna, was mined for copper and zinc between 1992 and 1997 and there are currently serious plans to resurrect the mine. Pahtohavare is another copper deposit in the area (Eilu 2012) which was mined for copper and gold from 1990 to 1997 (Bergman, Kübler and Martinsson 2001).

2.1.5 Surficial geology

The eastern part of the project area is characterized by peat- and wetlands with soil layers that are generally more extensive than in the western parts, where exposed bedrock increases in occurrence closer to the mountain belt (Figure 5). The landscape tends to slope in a southeastern direction towards the coast. Ice-melting had probably started in the north and then continued towards west. The general direction of ice-movement in the project area is directed towards NE-NNE (Figure 9). The entire area is located above the high post-glacial shoreline. From a morphological perspective many different glacial landforms can be found in the area, for example drumlins and Veiki moraine (Lagerbäck, 1988; Ladenberger et al. 2012). The northern part of a large-scale, lobe formed, collection of Veiki moraines, termed the Lainio arc, passes through the north-eastern part of the project area (Figure 6) (Hättestrand 1998).

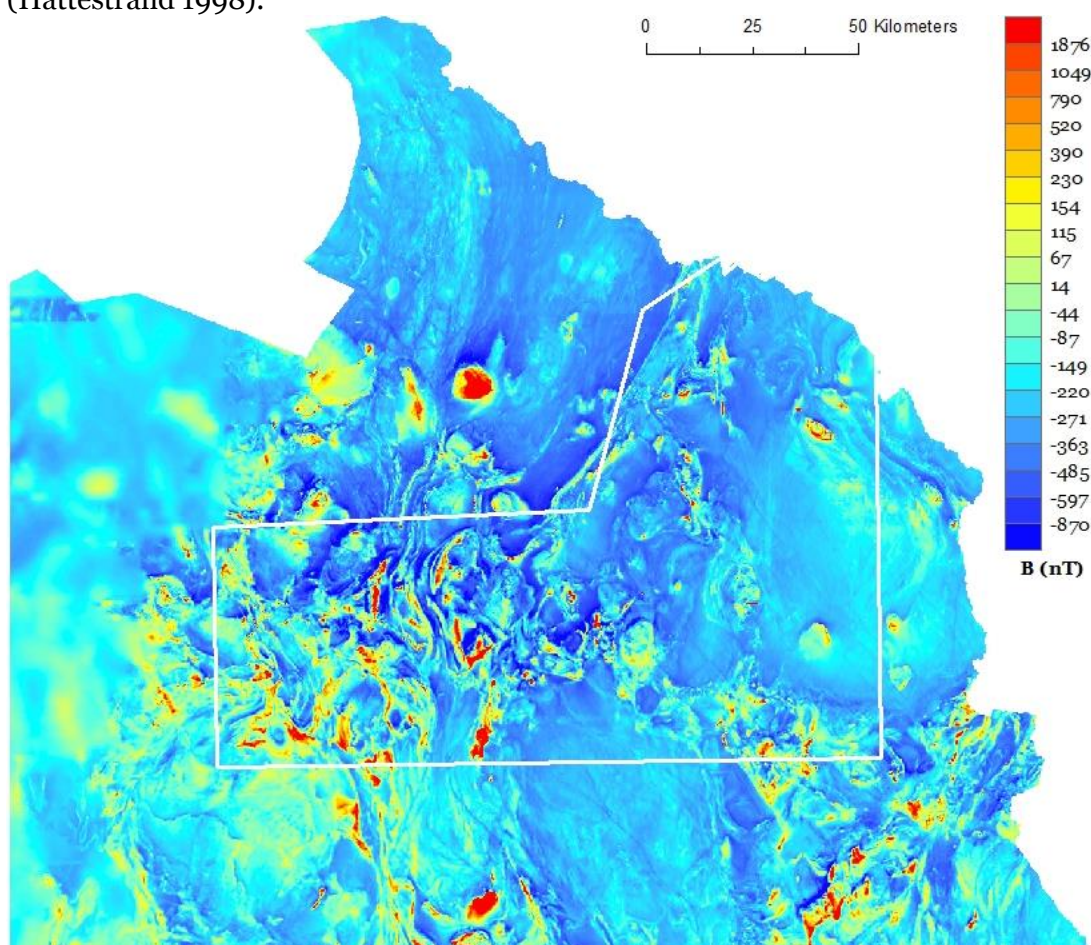


Figure 3. Magnetic anomaly map. White solid line marks the project area. © SGU.

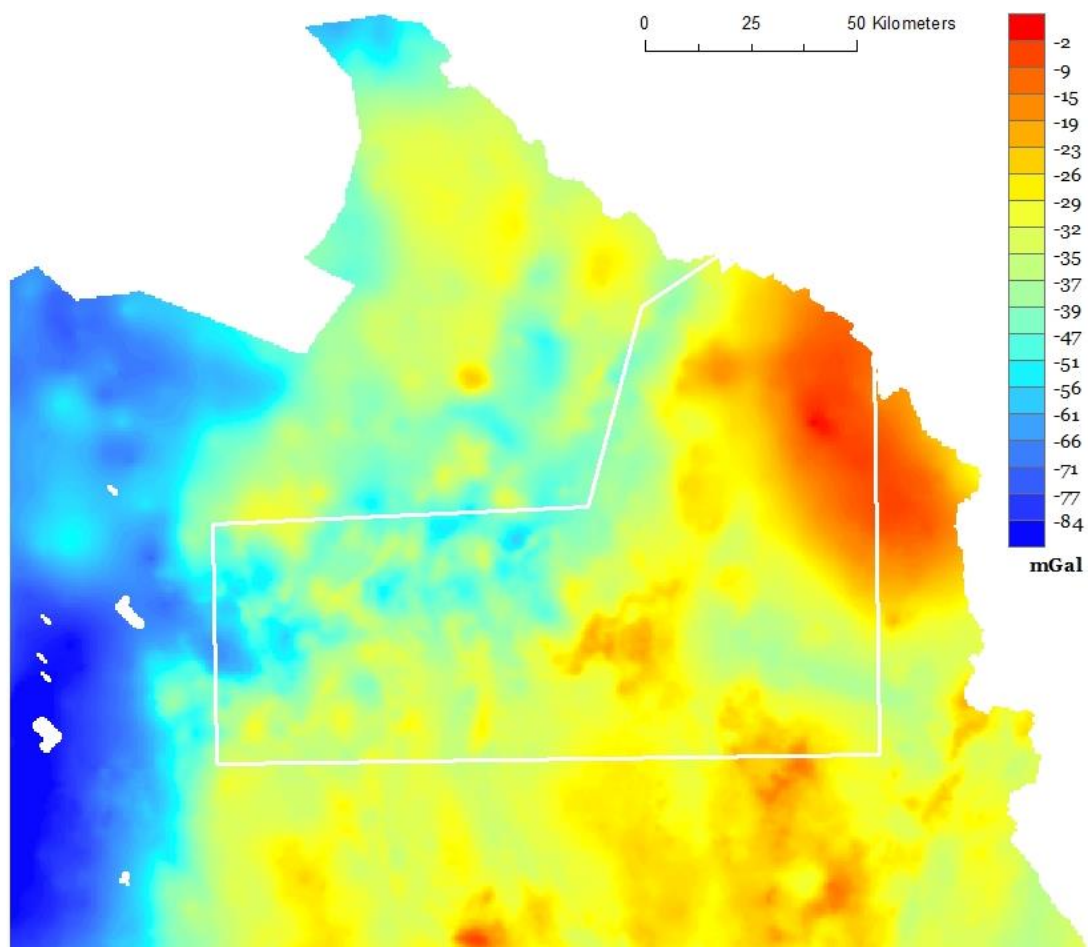


Figure 4. Regional Bouguer anomaly map. White solid line marks the project area. © SGU.

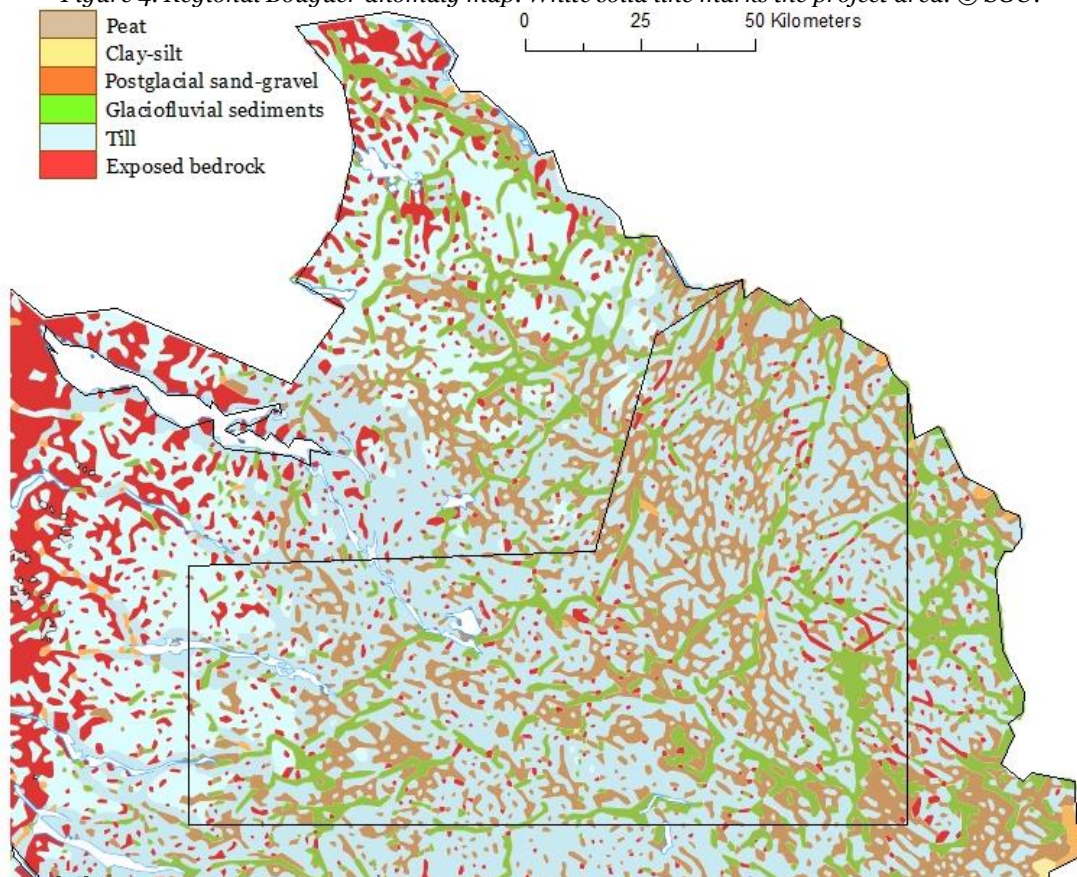


Figure 5. Simplified Quaternary map. Black solid line marks the project area. © SGU.

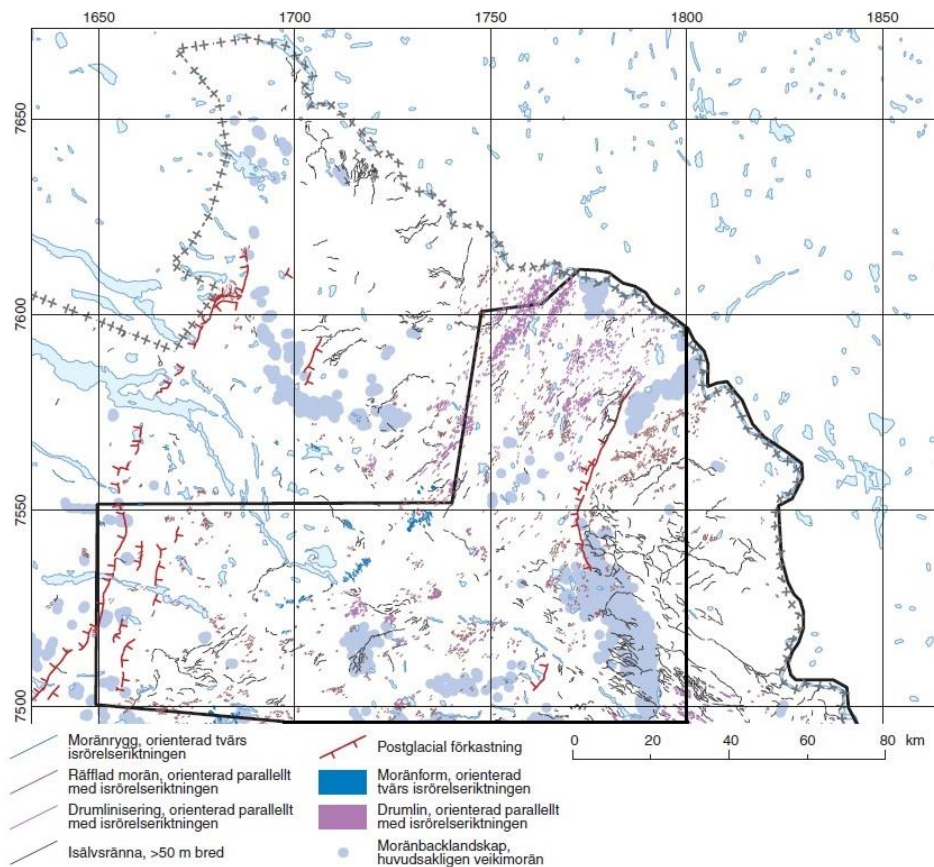


Figure 6. Geomorphological map. Black solid line marks the project area. Modified from (Ladenberger, et al., 2012). © SGU.

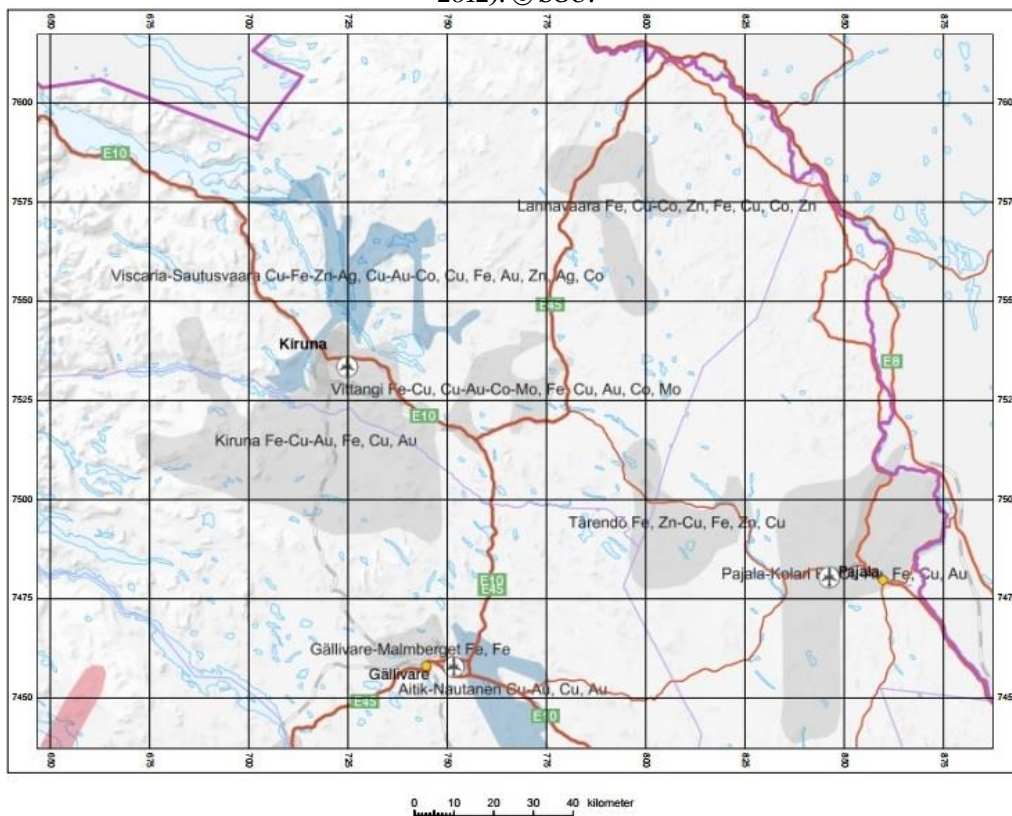


Figure 7. Metallogenic areas. Blue=base metals; Grey=Fe. Generated from SGU's "Kartvisaren" (<http://apps.sgu.se/kartvisare>). Coordinates in Sweref99™. © SGU.

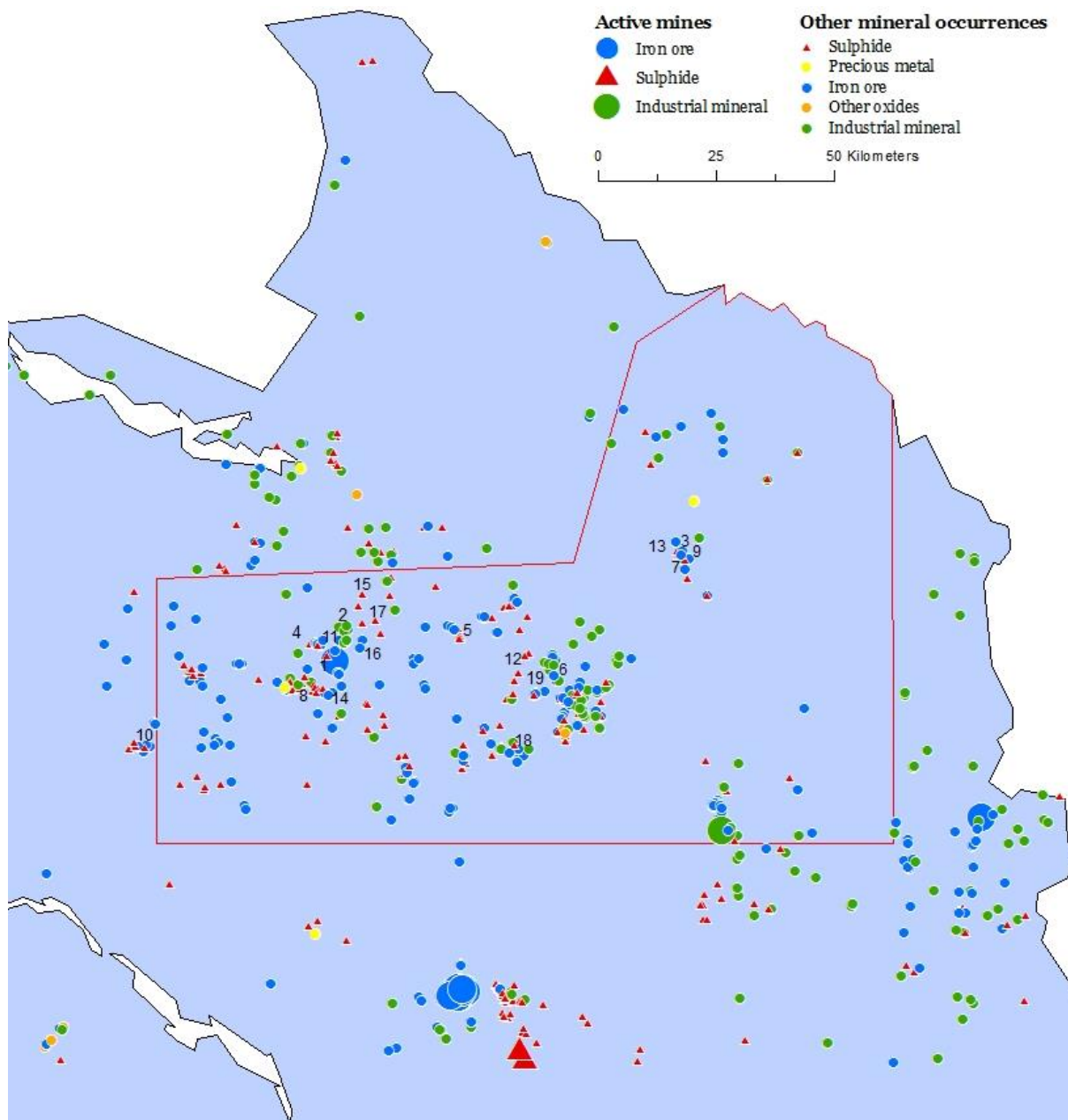


Figure 8. Mines and mineralisations. Mineralisations referred to in the text are marked with a number. This number is found in Table 1. Red solid line marks the project area. © SGU.

Table 1. Mineralisations mentioned in text. These are marked in figure 8. Coordinates in national grid RT90.

No	Name	N-coordinate	E-coordinate	Commodity
1	Kirunavaara	7533150	1684600	Fe; apatite;
2	Nukutus	7540500	1687000	Fe; apatite;
3	Kevus	7558498	1757259	Fe; Mn; pyrite; Co;
4	Viscaria	7536770	1681100	Cu; Zn; Ag; Fe-sulphides;
5	Sautusvaara	7538600	1711380	Fe-sulphides;
6	Vathanvaara	7532477	1730814	pyrite; Fe;
7	Huornaisenvuoma III Zn	7555850	1757800	Zn;
8	Pahtohavare Central	7528109	1680291	Cu; Au;

9	Teltaja	7554959	1759814	Fe; Mn;
10	Tjärrojåkka	7514980	1642800	Fe; Cu; apatite;
11	Luossavaara	7537750	1685600	Fe; apatite;
12	Kiskamavaara	7534380	1725040	Cu; Co;
13	Sattavaara Fe	7556750	1758500	Fe; Mn;
14	Rakkurijärvi Fe	7525950	1683250	Fe; pyrite;
15	Kurravaara Nya	7547363	1690602	Cu;
16	Tuolluvaara	7535850	1689880	Fe; apatite;
17	Nukutus	7540660	1687020	apatite;
18	Leveäniemi	7513700	1721600	Fe; apatite; REE; kaolinite;
19	Vathanvaara	7532505	1730037	Fe; Skarn

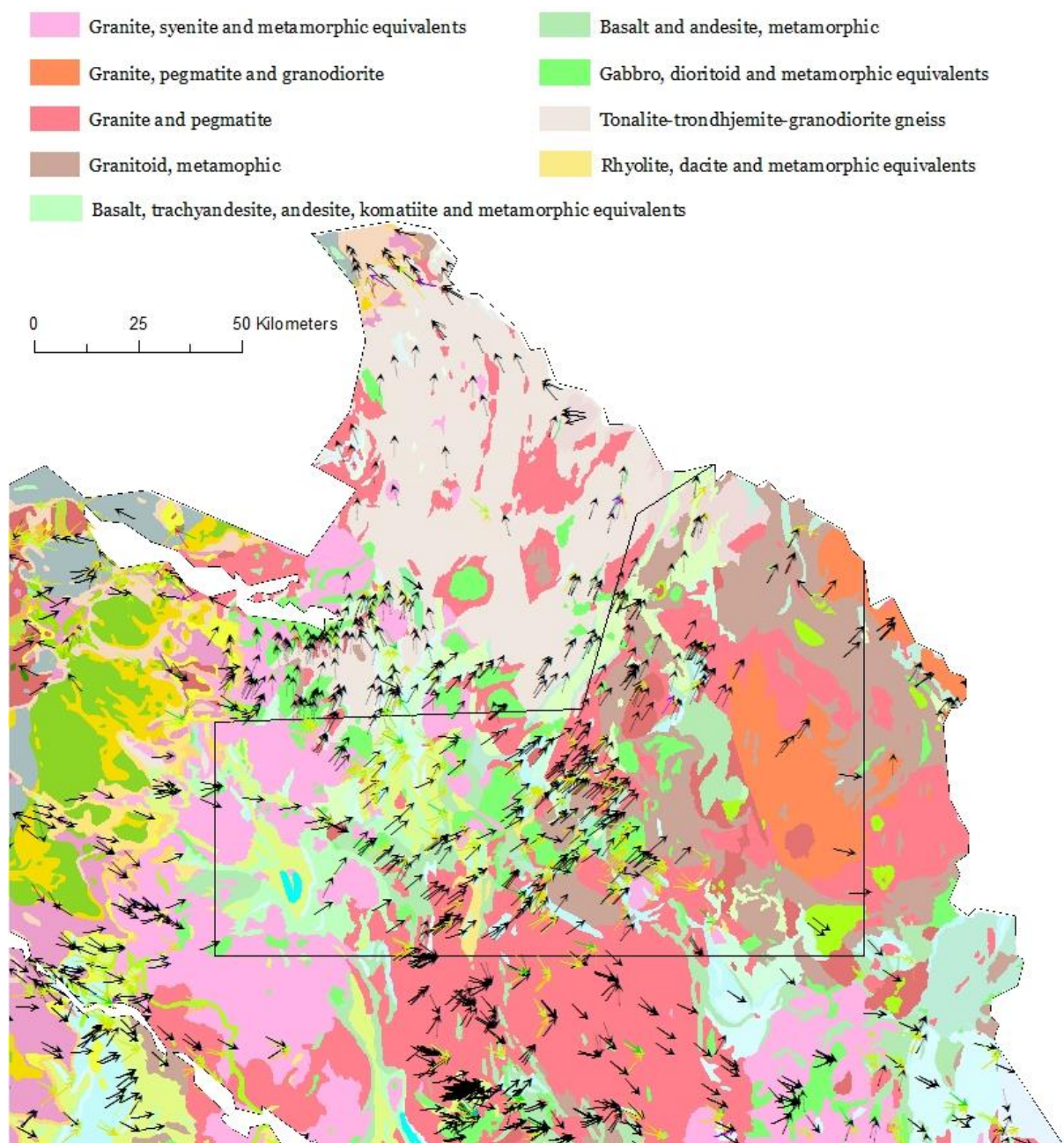


Figure 9. Bedrock lithology and ice-movement directions. Black solid line marks the project area. © SGU.

2.2 Geochemical surveys

2.2.1 What are the geochemical databases available?

Geochemical mapping programme at SGU started in early 80's and it was originally based on total concentration data and aqua regia digestion results. SGU database was merged with NSG (the State Mining Property Commission) database which carried out a regional scale mapping programme in the 80's and early 90's. NSG mapping was entirely dedicated towards mineral exploration and covered an area of 130 000 km². The database was further extended to include samples collected by Terra Mining AB, STC-Minerals and SGU. The resulting database had a coverage of 190 000 km² and included 12 700 till samples. The methods used were essentially the same as those used in SGUs soil mapping programme but for some elements there are levelling problems due to analytical differences between the two data sets. Subsequently the methodology using nitric acid digestion was applied as a routine technique and aqua regia digestion together with XRF method became complementary ones. In this study, the results from mapping campaign in years 2000-2007 are presented (Ladenberger et al. 2012). Furthermore, the region is included in large, European scale, geochemical surveys such as the "*Geochemical Mapping of Agricultural and Grazing land Soils*" (GEMAS) and the "Geochemical Atlas of Europe". These studies slightly differ from SGUs soil mapping programme in terms of aim, sampling media and techniques etc. (for details see Reimann et al. 2014 and Andersson et al. 2014).

2.2.2 What determines soil geochemistry?

Soil composition is controlled by factors such as parent material, climate, vegetation, organisms, topography and time (Jenny 1941). Till C-horizon composition is mainly determined by the composition of the underlying bedrock and is largely unaffected by the soil-forming processes active in the upper soil layers (Ladenberger et al. 2012). Exceptions include labile minerals such as sulphides and carbonates which are unstable above the water table. The decomposition and redistribution of these minerals may have great influence on mineral prospecting as many of them constitute glacially dispersed ore minerals. It is therefore important that sampling is done well below the leached B-horizon, where trace metal concentrations remains relatively unaltered (McMartin and McClenaghan 2001).

Experience has shown that geochemical distribution patterns in regional and reconnaissance scale surveys conducted in shield terrain are often spatially connected to large scale structural features of the bedrock and the enhanced mobility and ore forming processes associated with such zones of crustal weakness (Gustavsson et al. 1994). Other factors that govern the geochemistry, as well as the provenance, of till deposits are glacial dispersal processes (which in turn of course can be structurally controlled) including the transport, erosion and deposition by glacial ice. Unlike non-glaciated terrains, glaciated ones have only been exposed to weathering since the last deglaciation, which in the study area occurred sometime after 10 500 years ago in the study region according to Lindén (2006). Therefore sediments in these two types of terrains differ from one another in terms of composition, structure and texture caused by glacial dispersal processes and weathering. In glaciated areas the sediments mainly consists of crushed, unweathered bedrock detritus (McMartin and McClenaghan 2001). Rock fragments are eroded as they are transported by the moving glacial ice but different rocks have different resistance capability. The transport distance, till type and source material may affect texture (Ladenberger et al. 2012). To some degree, the texture might impact the till geochemistry. For example, clay minerals in the clay-size fraction (2 µm) have large reaction areas, high ion-exchange capacities and lattice structures that readily accept new cations, and may thus easily attract different elements, such as from previously mentioned sulphides and carbonates, causing accumulation of such elements in this size fraction during weathering (Shilts 1995). Generally, there is a negative correlation between the grain size and the metal content of sediments. In other words, metal content increases as the grain size decreases (Maslennikova, Larin and Larina 2012). As mentioned above, the texture can be influenced by till type. There are three main types of till: Lodgement till, melt-out till and flow till. Lodgement till, which has been deposited at the bottom of a

moving glacier, exhibits quite different properties than the other two types mentioned. Generally, it is homogenous in terms of texture and composition, lacks structures and has not been transported very far. Melt-out till might on the other hand be quite heterogeneous and, as it can have been transported on top of a moving glacier, it may be deposited far from its source. In terms of geochemical interpretation possibilities, flow till is rather similar to melt-out till (Ladenberger et al. 2012). The concentration of till material that has been transported englacially (i.e. within the ice) decreases linearly with distance whereas material transported at the bottom of an ice bed is associated with an exponential decay curve (Klassen 2001). Studies suggests that the transport distances of till in Sweden normally aren't longer than about 2-3 km. Boulder tracing associated with Ni mineralizations in Norrbotten indicated transport distances in the interval of 0.5-3.0 km in most cases (Sohlenius, Lax and Ladenberger 2009). However, the interpretations of geochemical dispersal patterns are complicated by so-called palimpsest dispersal trains, i.e. residual traces from earlier ice-movements (Parent, Paradis and Dorion 1996). A study in Finland has shown that preglacial, polycyclic sediments may, at some places, constitute significant proportions of till and can influence till geochemical attributes (Lintinen 1995). Other factors that may influence till geochemical element patterns include: thin soil covers, high deposition of sulphur or other airborne contaminants and also high precipitation (Andersson 2006).

2.2.3 Interpreting geochemical data

Many of the factors discussed in the previous section, complex soil formation processes, differences in transport distances etc., may of course cause difficulties when it comes to interpreting till geochemical data. Despite these difficulties, till geochemical mapping is often superior to alternative testing methods when it comes to gaining an insight regarding the general characteristics of the bedrock. Methods such as drill core sampling are often very expensive and may be misleading due to inhomogeneity issues. Till sampling is generally less expensive and the results can be seen as an aggregate sample of the source rock (Ladenberger et al. 2012).

By analyzing till geochemical element patterns, it is possible to get a sense for the mineral composition of the underlying bedrock. In this study the elements are investigated for both total and acid leached concentrations. Only looking at total concentrations, element anomalies can often be interpreted as many different minerals. By including acid leached concentrations it is also possible to get an indication of how hard the elements are bound to the mineral, i.e. its susceptibility to weathering. A specific example of this can be high levels of potassium in some till samples. In nature this element, almost exclusively, occurs in potassium feldspar and biotite. But because biotite is more susceptible to weathering, it means that a sample containing biotite will render higher acid leached concentrations of the element than a sample containing potassium feldspar. Investigations of the ratio between certain elements may also be an instrument for learning something about the mineralogical content. The elements calcium and strontium can be used to exemplify this: both elements have similar ion ratios and may thus easily substitute with one another. But in magmatic rocks the element ratios are affected by the fractional crystallisation of the melt. In the early stages of crystallization, the proportion of calcium is higher and strontium is lower, while the opposite is true for latter stages. This causes calcium to dominate in the minerals such as Ca-rich plagioclase (anorthite), apatite and pyroxene, which crystallise early from the melt (Ladenberger et al. 2012).

2.2.3 SGU's sampling and analytical methods

The data that are the basis of this study originate from SGU's soil geochemical mapping programme. In the sections below, the methods used by the SGU to obtain these data are summarized, all according to Ladenberger et al. (2012).

Sampling

With the aid of topographical maps, a grid of testing sites is created so that they may be as evenly distributed as possible. The sampling sites are preferably placed in a square angle with

regards to documented ice-movement directions at an interval of about 2.5 km, equivalent to about 15 samples per 100 km². Some considerations are made regarding the placement of previous test sites included in the NSG-SGAB database so that a potential merger of data will render the best possible degree of coverage. Apart from that, test sites are placed prejudicially, without consideration to factors such as mineralizations or bedrock types.

In the field, samples are collected from hand-dug pits at a depth of about 0.6-1.2 m. In that way it is possible to get down into the C-horizons of soils where material generally is not affected by soil forming processes active in the overlying layers. Making it more likely that samples will reflect the element concentrations of the underlying bedrock. The samples should weigh about 0.8 kg and be of the type sandy or sandy-silty till. The exact locations of the test sites are decided after local conditions have been considered. If the test site for some reason is unfit, for example due to moist or plant roots extending deep into the ground, it can be repositioned somewhat.

Sample preparation

The samples are vacuum-dried and thereafter they are sieved so that the fine fraction (< 0.063 mm) is separated. This fraction is used because, unlike coarser fractions, it almost exclusively contains monomineral grains, which are desirable because they render results that are more representative and easier to reproduce. Another advantage is that the fine fraction does not have to be grinded, which might cause contamination of the samples.

Analytical methods

The total element concentrations were obtained using X-ray fluorescence spectroscopy (XRF). The acid leached concentrations were obtained through digestion of the samples with either nitric acid (7M HNO₃) or aqua regia, whereafter the solution is analyzed with plasma technique (ICP-MS). SGU also determines the acidity (pH values) of the samples, although this is not considered in this study.

Quality control

In order to assure the quality and reliability of the samples, internal and external quality control routines are used, including investigations of both analytical and sampling variances. The latter is investigated through the examination of replicate samples collected in the field. Sampling variances includes differences that may arise due to small-scale inhomogeneity in till composition. An internal standard is used to determine the analytical variance. Altogether, about 10% of the analyses conducted serve as some kind of control sample.

3 Material and Methods

3.1 Material and project area

The material in this study consists of data obtained in association with SGU's nationwide soil geochemical mapping programme. These data show both total element concentrations, measured via XRF, as well as acid leached concentrations, measured with ICP-MS, from about 1000 soil samples. The sampling sites are located in northern Norrbotten within the map areas 29J Kiruna, 29K Vittangi, 29L Lainio and 30L Lannavaara (Figure 10).

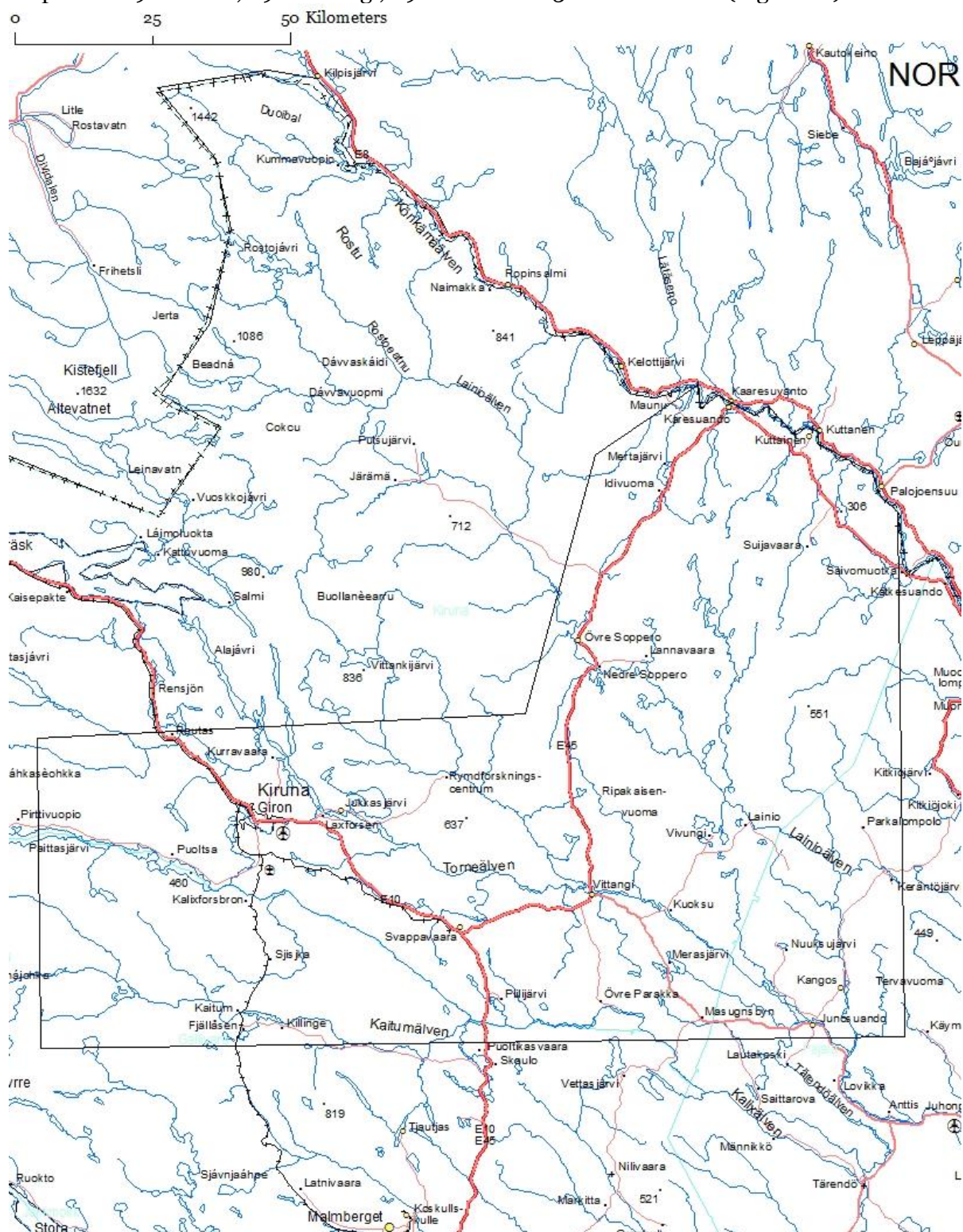


Figure 10. Overview map of the project area.

3.2 Statistics

The total and acid leached concentrations of the elements were divided into percentiles in accordance with how SGU perform their nation-wide soil geochemical mapping programme. This made it possible to compare element levels in the project area with the country as a whole (Appendix, table 1). Consequently, the data were divided into the following limits: The 10th, 30th, 50th, 70th, 90th, 95th and 99th percentile. These limits indicate how large share of the analytical values that fall below a certain percentage. For example, the 30th percentile, p30, means that 30 percent of the values are lower than p30 while 70 percent are higher. Hence, median value is given by the 50th percentile, p50. The units used were: g/kg for the major elements (Fe, Mg, Mn and Ti) and mg/kg for the minor elements (Co, Zn, V). The major elements are presented in oxide form as Fe₂O₃, MgO, MnO and TiO₂. Relative standard deviations were also calculated for each of the elements. In order to make comparisons between the project area and the rest of the country easier, the percentile values of the former were divided with the corresponding ones for the latter.

Leachability, i.e. how large share of total element concentration that dissolves after addition of nitric acid (7M HNO₃), was calculated as follows: $e_{\text{ICPMS}}/e_{\text{XRF}} \times 100$, where e is element concentration. The variable was studied both statistically and spatially (in map form, see below). For the statistical calculation the median value, p50, was used. For the spatial analyses the leachability was calculated separately for each sample.

Spearman rank correlations were used to investigate how strong the correlations were between the total and acid leached concentrations of the elements. The method is defined as Pearson coefficients for the ranking order of the variables. Geochemical information consists of data that are not normally distributed, which makes it well-suited for Spearman correlations. Also, the method is relatively insensitive to extreme values. The correlation coefficient, ρ , can vary between -1 and +1 where the former specifies a perfect negative linear relationship and the latter a corresponding positive one. In this report values of ρ in the interval 0.6-0.7 are considered to be relatively strong and values exceeding 0.7 are considered as strong. The significance level, α , was set to 0.01.

In order to relate the obtained analytical values for manganese to the lithology of the project area, the software ESRI ArcGIS 10.2 was used. SGU provided shapefiles containing information about the bedrock distribution in the region. Coordinates for the sampling sites were spatially joined with the bedrock layer, from which the attribute values thereby could be related to samplings sites based on what rock unit the respective site was overlaying. The acquired data were then compiled in boxplots based on bedrock type and age, respectively. Bedrock type was arranged into six categories of the most frequent occurring rock types. Age distribution was divided into the following four categories: Archean (>2.5 Ga), early Paleoproterozoic (2.4-1.96 Ga), Older Svecokarelian (1.96-1.86) and younger Svecokarelian (1.88-1.66).

Excel 2013 was used to conduct the calculations of percentiles, standard deviations and leachability. The software was also used to sort data concerning the relationship between till geochemistry and lithology, obtained according to the description above of so-called “data mining” in ArcGIS, and then compiling these data into boxplots. Statistica 12 was used in the making of correlation analyses and associated scatterplots.

3.3 Spatial distribution maps

Maps illustrating the spatial distribution of total- and acid leached concentrations as well as leachability in the project area were produced using the extension spatial analyst in ArcGIS. The software uses an interpolation technique called IDW (Inverse Distance Weighted). This technique converts the values of the sampling sites into a regular network of cells (raster) that are then assigned linearly weighted average values that decrease with increasing distance. As such, the values are mathematically calculated estimations, which should be

regarded when interpreting the results. It also follows that surfaces covered by soils other than till are included in the maps. The map colour schemes are divided into classes based on the previously mentioned percentile classes of the project area. Analytical values lower than the 10th percentile and higher than the 90th are defined as negative and positive anomalies respectively. Maps showing total element concentrations are presented in the results part and the maps showing acid leached concentrations and leachability are placed in Appendix b.

4 Results

4.1 Background levels of elements in till

Median values (50th percentile) for the total element concentrations in the project area are elevated compared to the country as a whole, except for zinc that shows slightly lower values (Table 4). Of the major elements investigated, magnesium shows the highest percentage elevation; and of the minor elements, vanadium does (Table 4). In both cases the median values for total concentrations are over two times as high in the project area than in the country (Table 4). The same comparison made for acid leached concentrations shows that the project area has lower median values for zinc as well as manganese; higher ones for cobalt, magnesium and vanadium; while iron has exactly the same value in both cases (Table 4). The ratios shown in Table 4 are generally lower for the total concentrations compared to acid leached concentrations for all investigated elements except cobalt, for which the ratio of the median values in both cases are about 1.5. In both total and acid leached concentrations zinc has the highest standard deviation (Table 3). For all elements, the standard deviations for acid leached concentrations are larger than the corresponding values for total concentrations (Table 3).

Table 2. Total element concentrations in the project area. $n=1156$. Percentile classes p10–p99, where p50=median value. Median values for the country as a whole are listed in the row “Natural median” (see table 1 Appendix). A. Total concentrations. B. Leached concentrations.

A.

Total concentrations, analyzed with X-ray fluorescence.

	Co (mg/kg)	Fe ₂ O ₃ (g/kg)	MgO (g/kg)	MnO (g/kg)	TiO ₂ (g/kg)	V (mg/kg)	Zn (mg/kg)
min	10	30	14	0.39	5.4	61	23
p10	20	45	20	0.60	7.6	108	32
p30	26	53	24	0.68	8.6	123	38
p50	30	59	27	0.74	9.3	133	42
p70	34	64	30	0.80	10.0	146	49
p90	39	71	36	0.92	11.1	163	63
p95	43	76	40	1.01	11.7	173	74
p99	53	88	52	1.25	14.0	199	118
max	80	114	82	2.75	23.8	318	197
Natural median	20	37	13	0.60	7.4	58	50

B.

Nitric acid (7M HNO₃) leached concentrations, analyzed with ICP-MS.

	Co (mg/kg)	Fe ₂ O ₃ (g/kg)	MgO (g/kg)	MnO (g/kg)	TiO ₂ (g/kg)	V (mg/kg)	Zn (mg/kg)
min	2.1	4	1.2	0.05	0.32	9	1
p10	4.6	11	4.3	0.13	1.02	16	10
p30	6.5	15	6.1	0.17	1.3	22	14
p50	8.0	17	7.3	0.21	1.52	26	17
p70	9.4	20	8.6	0.25	1.76	31	21
p90	12.6	27	11.9	0.35	2.22	41	32
p95	14.8	31	15.1	0.42	2.60	47	41
p99	20.8	42	21.3	0.71	4.06	70	72
max	37.9	105	62.3	2.19	10.92	195	119

Natural median	5	17	5	0.23	1.2	20	29
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Table 3. Relative standard deviation for element data. Total concentrations. B. Leached concentrations.

A.

Co	Fe	Mg	Mn	Ti	V	Zn
27%	18%	26%	20%	17%	17%	38%

B.

Co	Fe	Mg	Mn	Ti	V	Zn
44%	41%	50%	55%	42%	44%	63%

Table 4. Ratio (%) for element concentrations in the project area (Table 2) divided by the corresponding values for the country as a whole (Appendix, table 1). Median values (50th percentile) are marked in yellow. A Total concentrations. B. Leached concentrations.

A.

	Co	Fe ₂ O ₃	MgO	MnO	TiO ₂	V	Zn
p10	154	180	286	150	146	300	107
p30	153	171	240	136	132	256	93
p50	150	159	208	123	126	229	84
p70	148	145	188	114	120	206	80
p90	134	129	171	102	116	165	78
p95	139	129	174	101	114	160	80
p99	133	119	163	78	120	133	87

B.

	Co	Fe ₂ O ₃	MgO	MnO	TiO ₂	V	Zn
p10	230	122	215	108	170	160	77
p30	163	107	153	94	130	147	70
p50	160	100	146	91	127	130	59
p70	134	87	123	78	126	119	51
p90	126	82	119	66	117	111	52
p95	123	76	137	55	124	121	53
p99	122	75	125	59	145	121	65

4.2 Leachability

Figure 11 illustrates the median values of the leachability (%) for the analyzed elements. With a leachability of 39%, zinc shows the highest levels and titanium the lowest with 16% closely followed by vanadium at 19%. The other elements show a quite similar leachability, all in the interval of 27-29%.

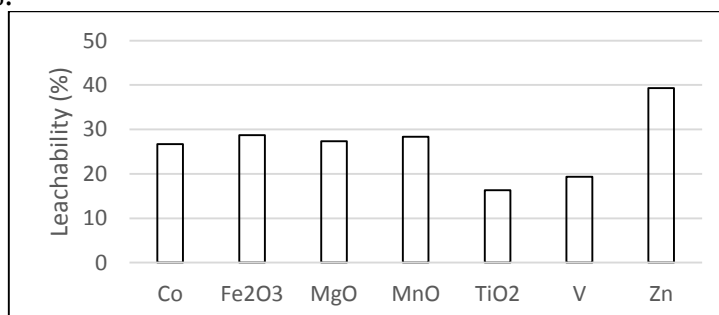


Figure 11. Leachability of analyzed elements.

4.2 Correlations

4.2.1 Total concentrations

Table 5 and Figure 12 show the correlations between total element concentrations of the investigated elements in the project area. The strongest correlation of all possible element combinations is that between iron and cobalt with $\rho=0.88$. The only correlation that doesn't reach the significance level of $\alpha = 0.01$ is the combination cobalt-titanium with a p-value of around 0.5. The combination is also the only one with a negative correlation coefficient, $\rho=-0.02$. The only other element combination that is not zero is that of iron and titanium with a p-value of 0.002192 which, however, is over the significance level.

Table 5. Correlation coefficients (Spearman ρ) for the total concentrations of the investigated elements.

Element	Co	Fe	Mg	Mn	Ti	V
Fe	0.88					
Mg	0.28	0.28				
Mn	0.49	0.53	0.50			
Ti	-0.02	0.09	0.59	0.57		
V	0.41	0.48	0.77	0.64	0.74	
Zn	0.20	0.24	0.53	0.70	0.73	0.56

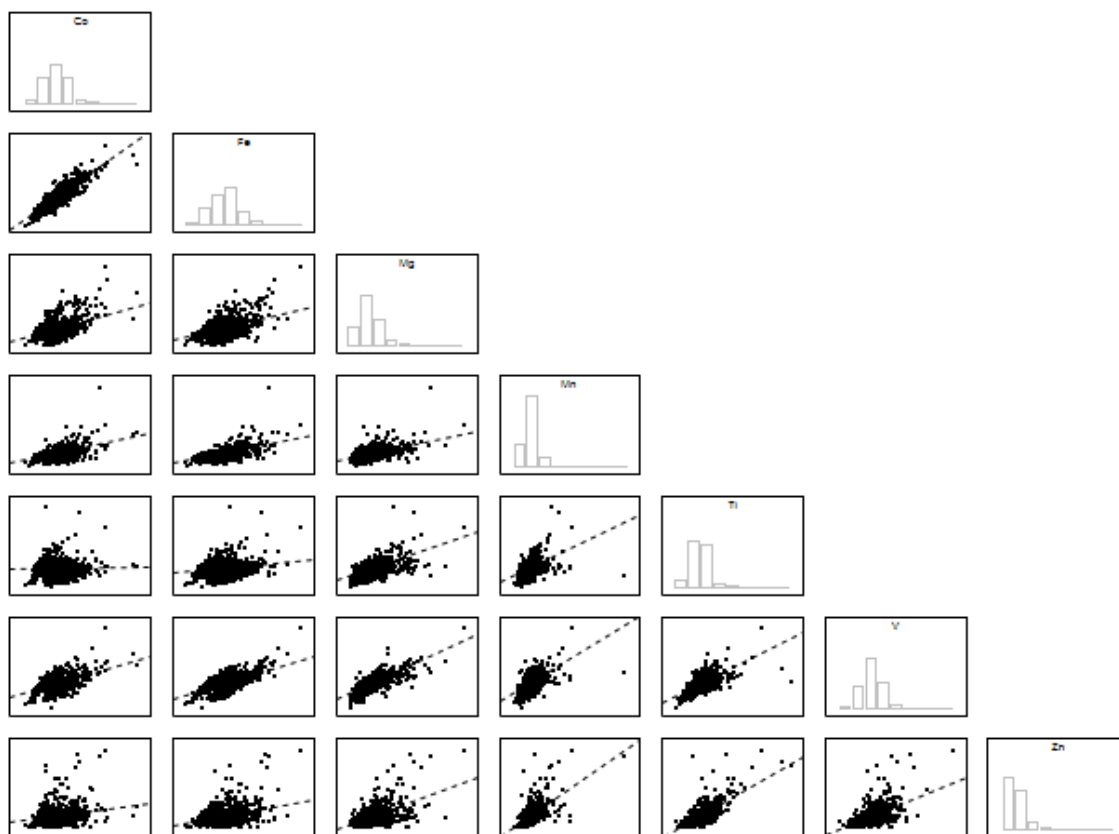


Figure 12. Scatterplot matrix of correlations for the total concentrations. Element pairings follows the same order as in Table 5.

4.2.2 Acid leached concentrations

Table 6 and Figure 13 show the correlation between the acid leached (HNO₃) concentrations of the investigated elements in the project area. All element combinations have a p-value of zero. Correlations are generally higher than the corresponding values for total concentrations. The strongest correlations are shown by the two combinations iron-titanium and iron-vanadium, for both of which the correlation analysis rendered $\rho=0.91$. An almost as

strong correlation is that between titanium and vanadium with a corresponding value of 0.90. The weakest combination is that of cobalt and zinc with $\rho=0.42$.

Table 6. Correlation coefficients (Spearman ρ) for the acid leached concentrations of the investigated elements.

Element	Co	Fe	Mg	Mn	Ti	V
Fe	0.73					
Mg	0.79	0.86				
Mn	0.71	0.71	0.79			
Ti	0.69	0.91	0.85	0.67		
V	0.70	0.91	0.81	0.58	0.90	
Zn	0.42	0.68	0.66	0.69	0.68	0.60

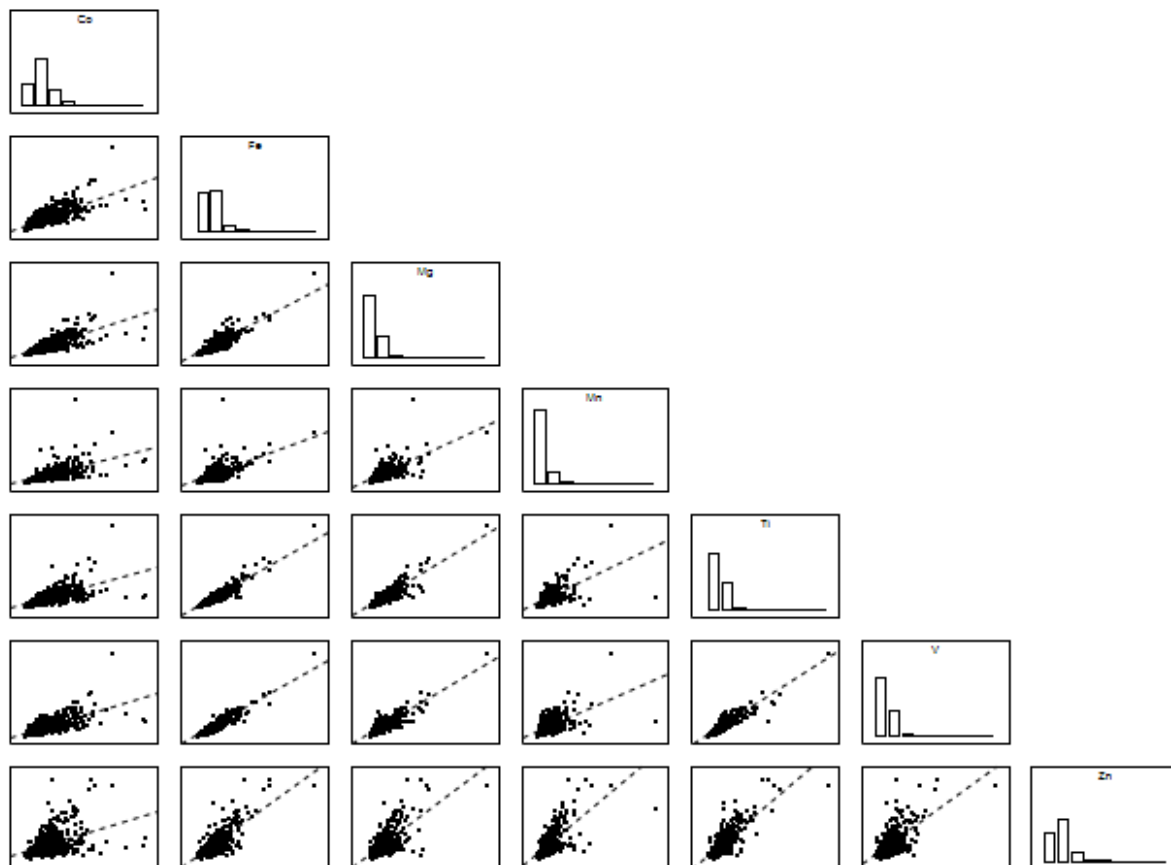


Figure 13. Scatterplot matrix of correlations for the acid leached concentrations. Element pairings follows the same order as in Table 6.

4.3 Manganese in relation to lithology

4.3.1 Bedrock composition

Figure 14 shows the relationships between the total concentrations of manganese in till and the lithology of the underlying bedrock. The lowest median concentration is found in the group of ultramafic, mafic and intermediate intrusive rocks with a value of 0.7 g/kg. A slightly higher median value of 0.73 g/kg is found in the group of felsic intrusive rocks. Thereafter, in order of size for the median values, follows the two groups mica-rich metamorphic rocks and quartz-feldspar-rich sedimentary rocks², both of which has a median value of 0.75 g/kg. The highest median value of 0.82 g/kg is found in the group of felsic volcanic rocks closely followed by the group of ultramafic, mafic and intermediate volcanic rocks with a median value of 0.81 g/kg. The latter group shows the highest standard

² An extreme value of 2.75 g/kg was removed from this group.

deviation, 0.2 g/kg. The second highest standard deviation, 1.6 g/kg, is found in the group of felsic volcanic rocks. All the other groups have corresponding values of around 0.1 g/kg (Figure 14). It should be noted that the number of testing points are relatively low in the two groups quartz-feldspar- and mica-rich rocks, 28 and 35, respectively (Table 7).

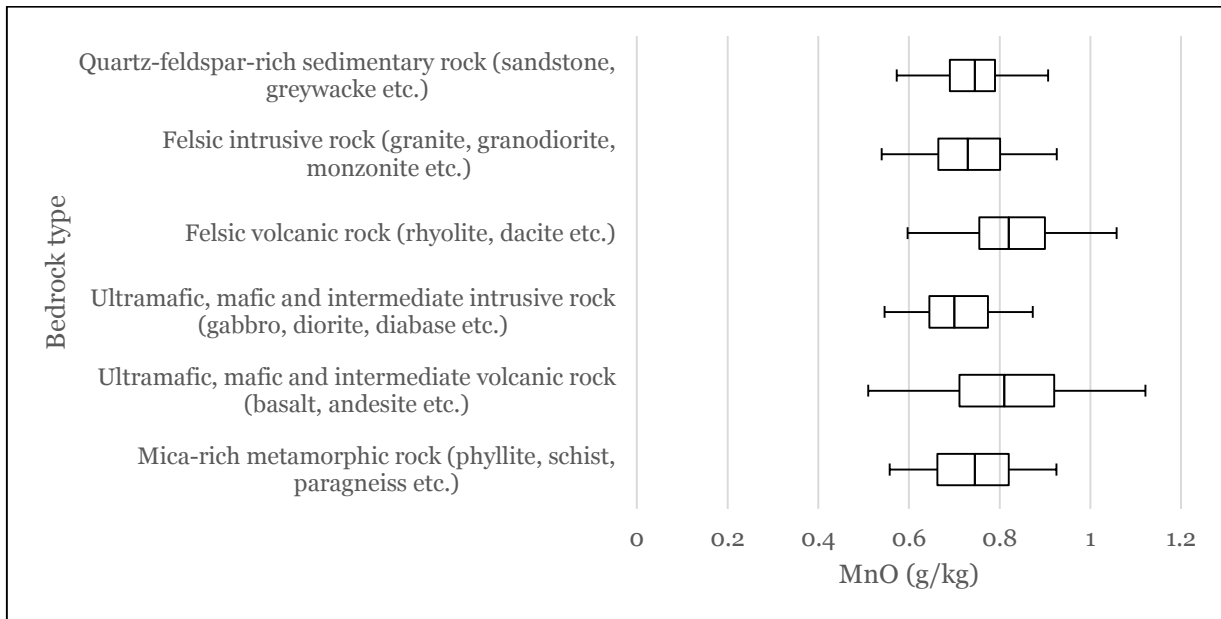


Figure 14. Relationship between the manganese content in till and the lithology of the underlying bedrock. Lines in the middle of the boxes show median values, whiskers are one standard deviation long.

Table 7. Number of sampling points included in each rock group.

Rock type	Number of sampling points
Mica-rich metamorphic rock (phyllite, schist, paragneiss etc.)	35
Ultramafic, mafic and intermediate volcanic rock (basalt, andesite etc.)	151
Ultramafic, mafic and intermediate intrusive rock (gabbro, diorite, diabase etc.)	212
Felsic volcanic rock (rhyolite, dacite etc.)	88
Felsic intrusive rock (granite, granodiorite, monzonite etc.)	594
Quartz-feldspar-rich sedimentary rock (sandstone, greywacke etc.)	28

4.3.2 Bedrock age

In Figure 15 the total concentrations of manganese in till are related to the age of the bedrock underlying the sampling sites. From this it is made clear that the median concentration of manganese increases with increasing age of the groups. Hence, the lowest median values, 0.73 and 0.74 g/kg, are found in the groups of younger and older Svecokarelian rocks respectively. The group of Paleoproterozoic rocks³ has the second highest median value, 0.78 g/kg. Finally, the highest median value, 0.80 g/kg, is that of the Archean rocks. However, this group only consists of 18 samples, compared to 148 for Paleoproterozoic rocks, and over 400 for the two remaining groups (Table 8). Standard deviations for the respective groups, in order of increasing age, are as follows: 0.12, 0.13, 0.21 and 0.16 g/kg (Figure 15).

³ An extreme value of 2.75 g/kg was removed from this group.

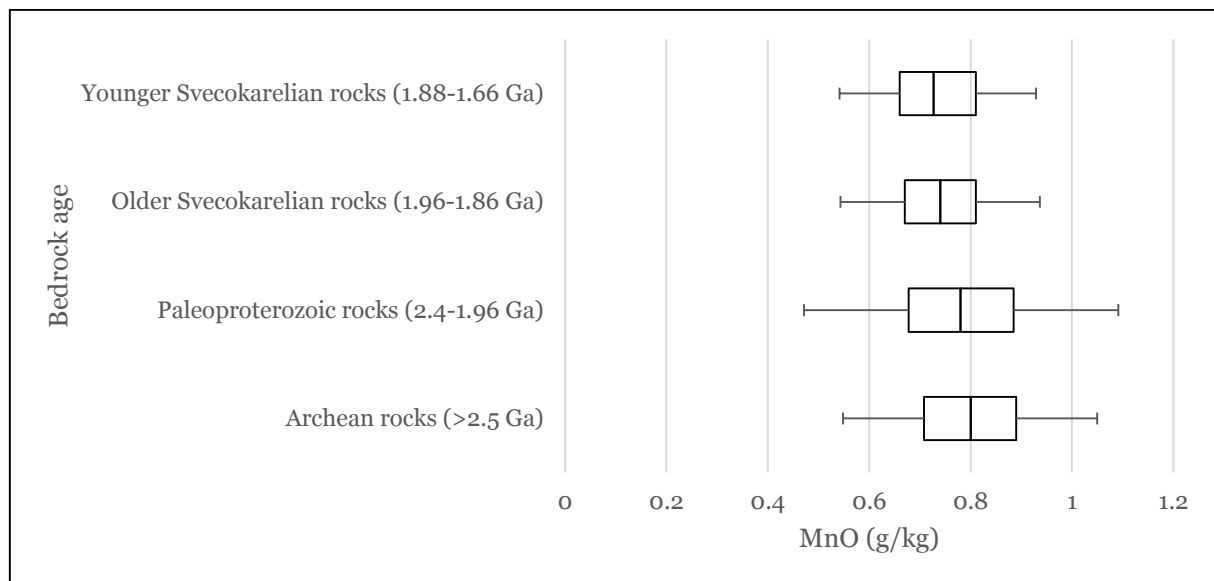


Figure 15. Relationship between the manganese content in till and age of the underlying bedrock. Lines in the middle of the boxes show median values, whiskers are one standard deviation long.

Table 8. Number of sampling points included in each age group.

Bedrock age	Number of sampling points
Younger Svecokarelian rocks (1.88-1.66 Ga)	402
Older Svecokarelian rocks (1.96-1.86 Ga)	433
Paleoproterozoic rocks (2.4-1.96 Ga)	147
Archean rocks (>2.5 Ga)	17

4.4 Geochemical anomaly maps

The results from the spatial analyses for the total concentrations of the investigated elements are shown in the maps below (Figure 16–Figure 22). Maps showing acid leached concentrations and leachability are found in Appendix b. As most of the elements show significantly elevated concentrations compared to the rest of the country, the map colour schemes are divided into classes based on the percentile classes of the project area (Table 1). This is preferable when interpreting data, compared to using percentile classes based on the whole country. The latter would, for many elements, practically have rendered the whole area as one positive anomaly. For example, iron has a median value of 59 g/kg for the project area (Table 2), which is exactly equivalent to the 95th percentile value for the country (Appendix, table 1). The interpretations of these results are placed in the discussion section.

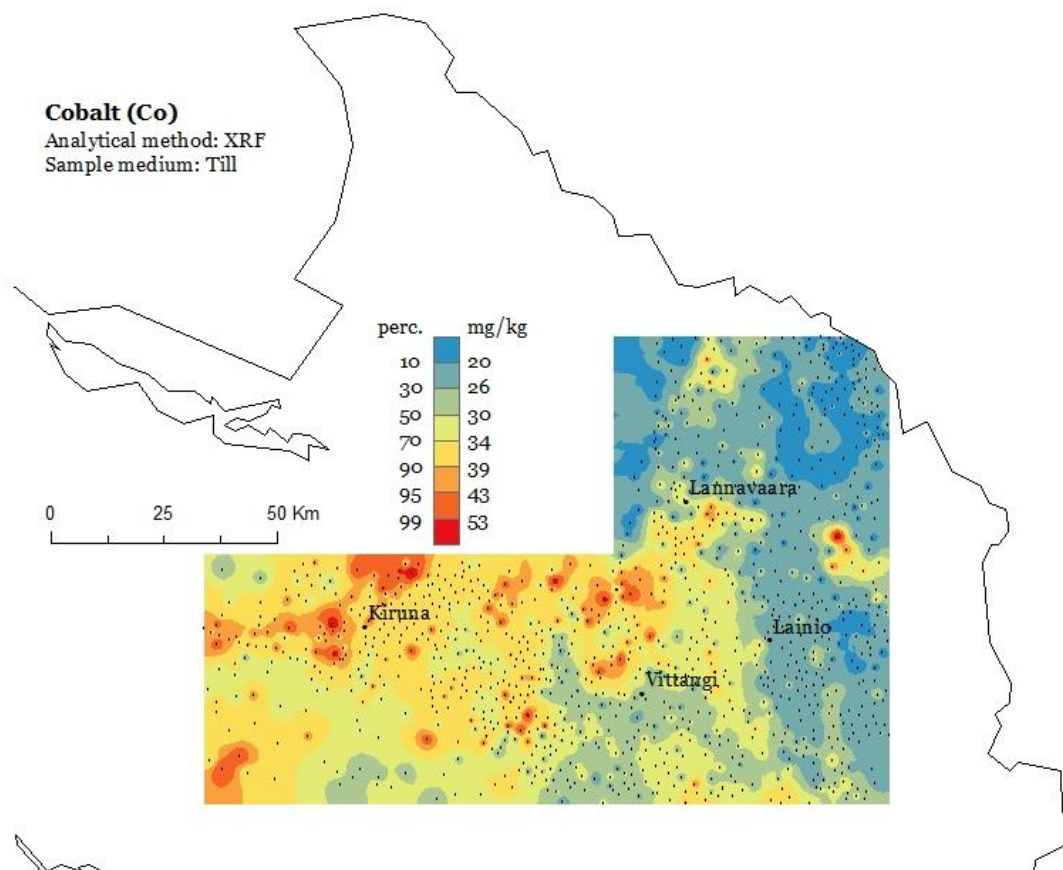


Figure 16. Map showing the spatial distribution of total concentrations for cobalt within the project area.

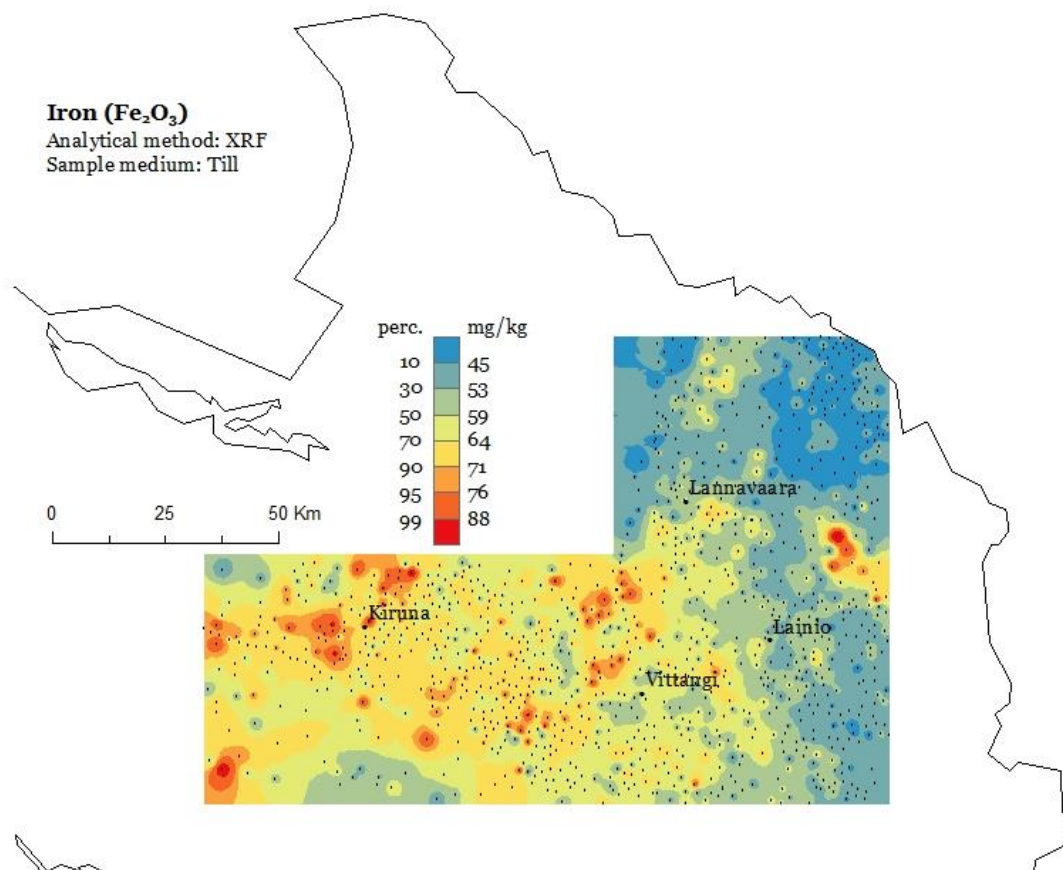


Figure 17. Map showing the spatial distribution of total concentrations for iron within the project area.

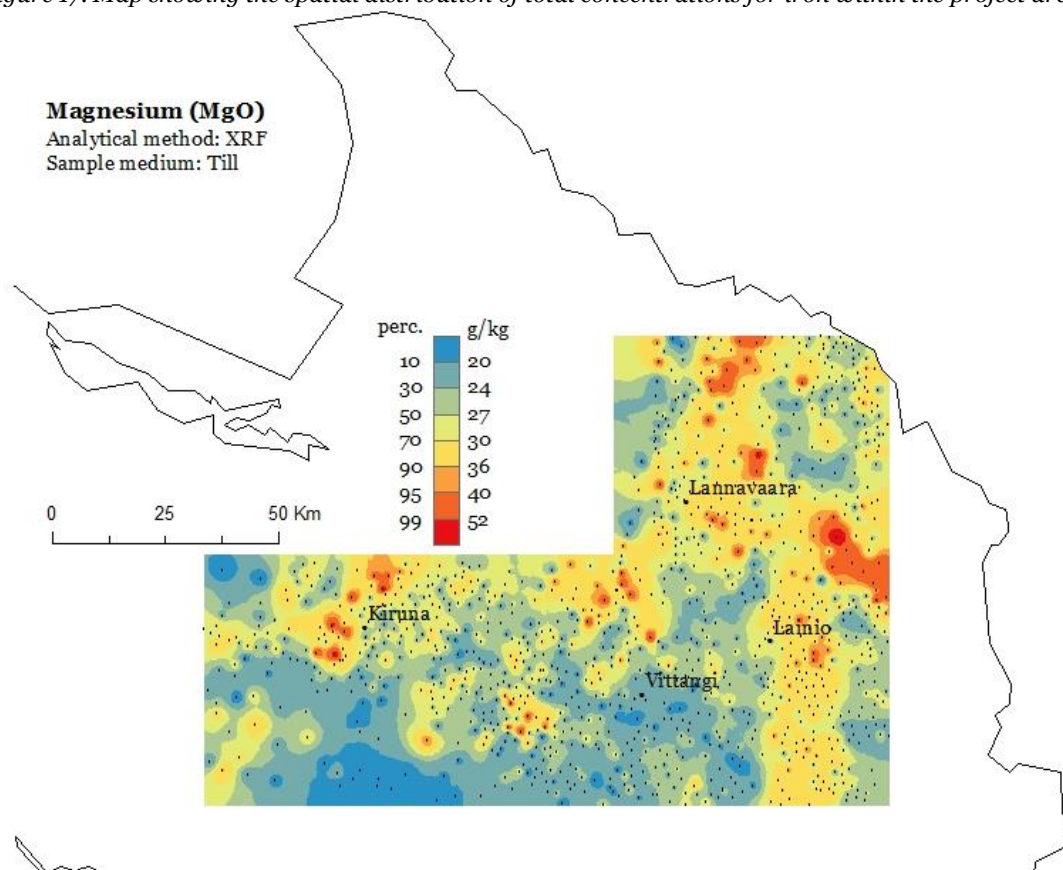


Figure 18. Map showing the spatial distribution of total concentrations for magnesium within the project area.

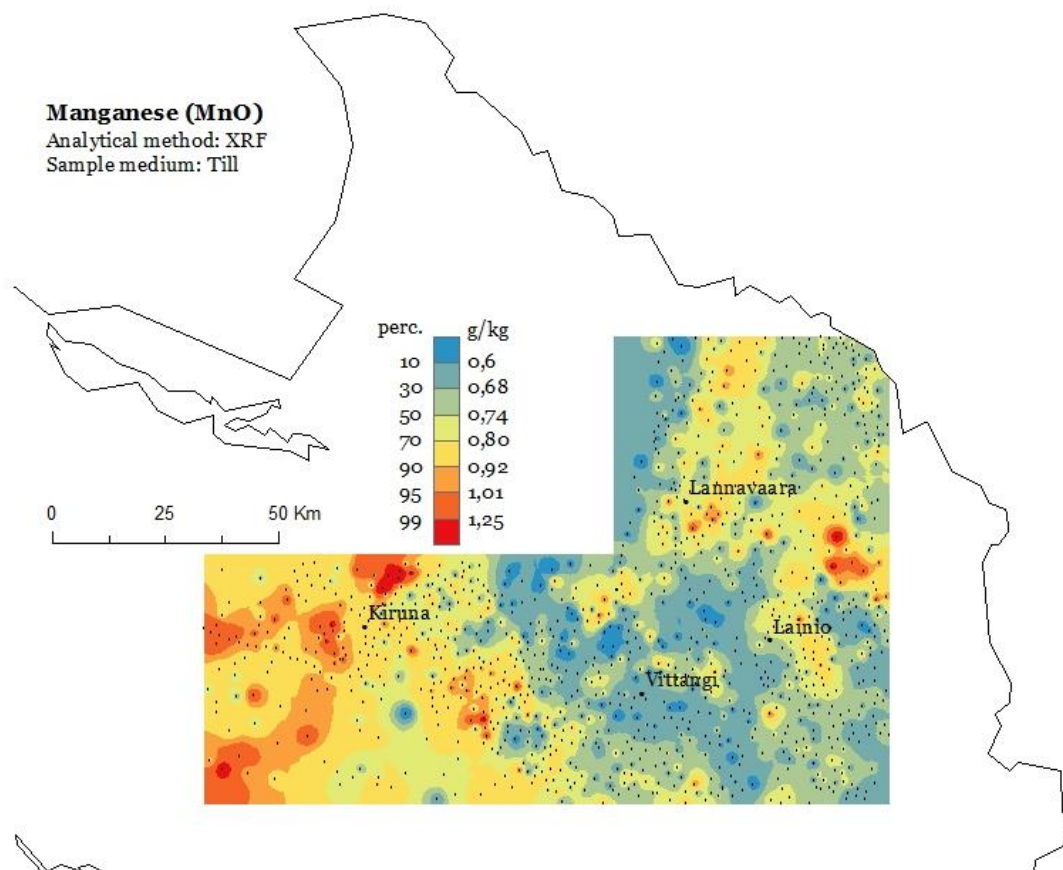


Figure 19. Map showing the spatial distribution of total concentrations for manganese within the project area.

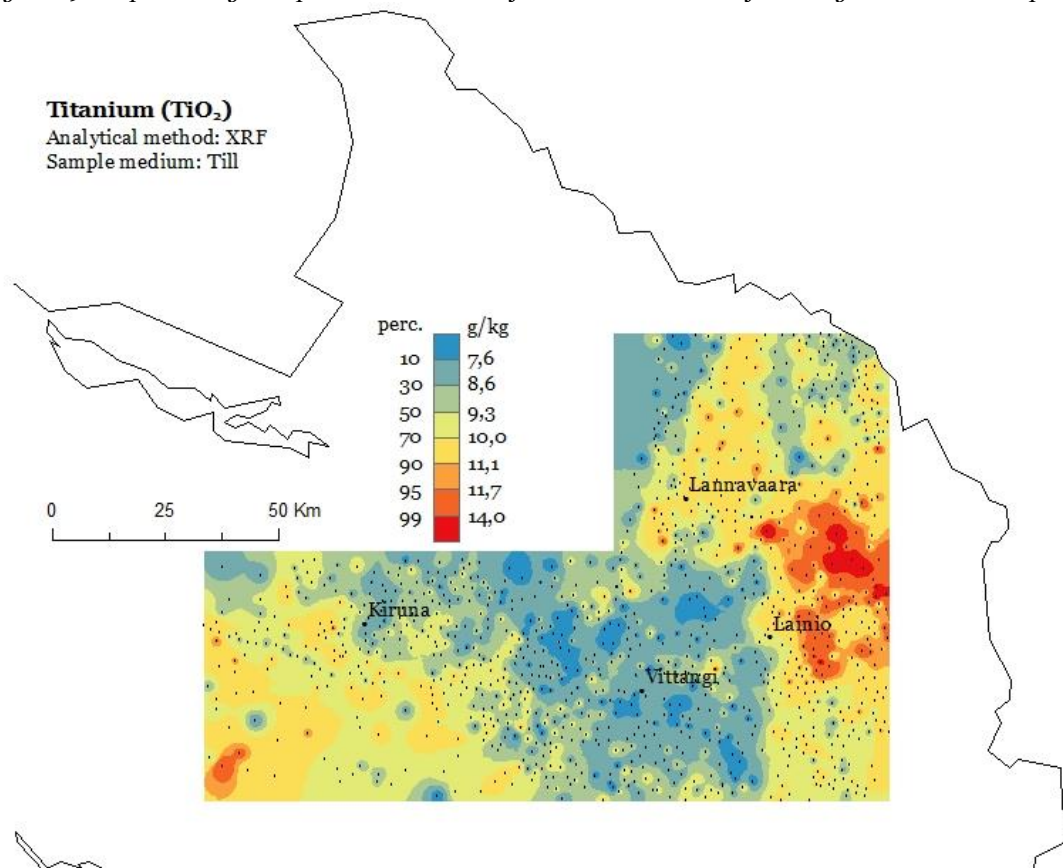


Figure 20. Map showing the spatial distribution of total concentrations for titanium within the project area.

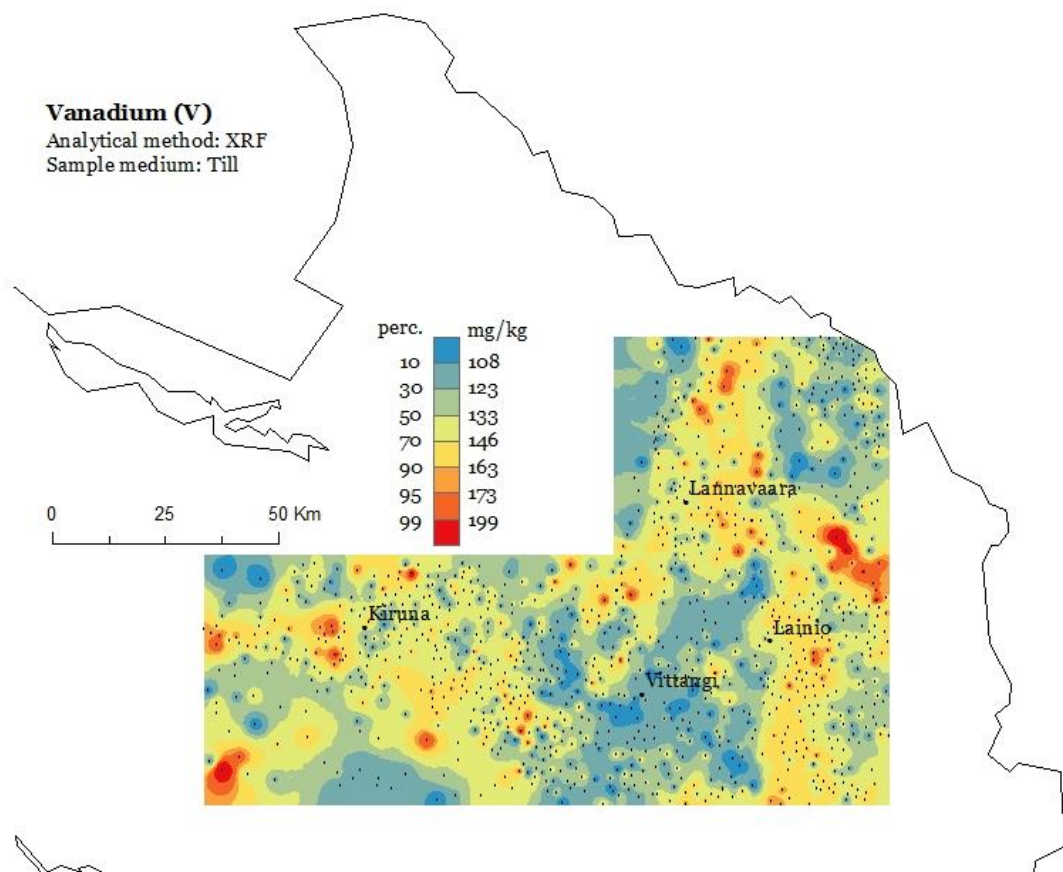


Figure 21. Map showing the spatial distribution of total concentrations for vanadium within the project area.

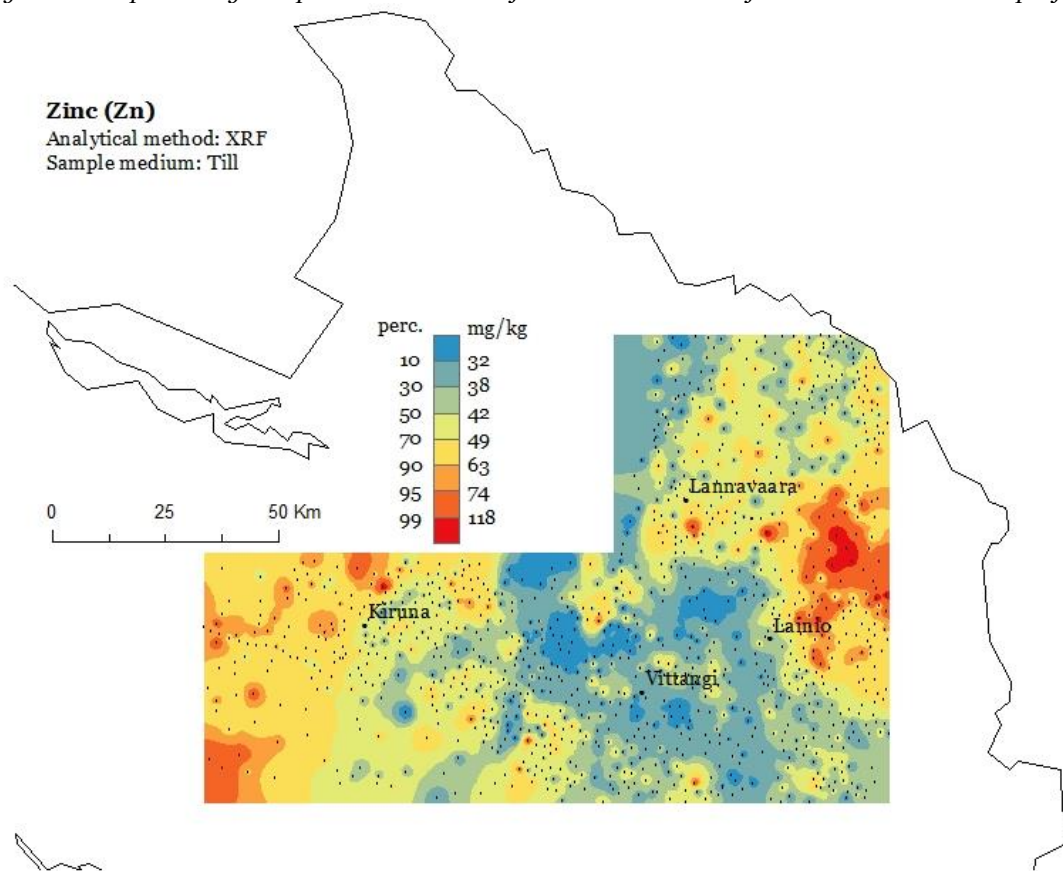


Figure 22. Map showing the spatial distribution of total concentrations for zinc within the project area.

5. Discussion

5.1 Geochemistry of the project area – Occurrence and distribution of the elements in till

In the following sections the results from the statistical and spatial analyses are interpreted and related to the results from SGU's national database on till geochemistry (Appendix, table 1). Correlation coefficients, ρ , in the interval 0.6-0.7 are interpreted to be relatively high and values exceeding 0.7 are interpreted as high. The mineralizations discussed refer to data from the SGU database on mineralizations (Figure 8) and includes prospects.

5.1.1 Cobalt

The median levels for the total and acid leached concentrations of cobalt in the project area are 30 and 8 mg/kg respectively. Both levels are elevated compared to the rest of the country. It follows that the leachability is 27%, which is quite similar to the corresponding value for the whole country, 25%.

Cobalt concentrations are elevated in the areas around Kiruna and north of Vittangi, while the levels are generally lower in the eastern and northernmost parts of the project area. An exception being a smaller area north-east of Lainio that shows elevated cobalt levels. There are a total of 14 mineralizations known to carry cobalt within the project area. All of which are associated with high levels of cobalt in the surrounding till.

Total concentrations of cobalt show a high correlation with iron ($\rho=0.88$), while the correlation with the rest of the elements are relatively low. Acid leached concentrations are on the other hand relatively high or high for all elements except zinc.

5.1.2 Iron

Not surprisingly, because the area hosts a number of significant iron deposits, the median total concentration for iron in the project area (59 g/kg) is elevated compared to the rest of the country. The corresponding value for the acid leached concentrations is the same in the project area as it is for the country, namely 17 g/kg. Thereby follows that the leachability for iron in the studied area is 29%, which is significantly lower than the corresponding value of 46 % seen in the country as a whole.

Elevated total concentrations of iron roughly coincide with the extent of the iron mineralized areas. These are also areas that are generally characterized by positive magnetic anomalies. There are also a few sampling sites north-east of Lainio with high iron levels. For the acid leached concentrations this is the largest area containing positive anomalies.

Iron shows a correlation with cobalt for the total concentrations. For the acid leached concentrations iron shows a relatively strong correlation with zinc and high correlations with the rest of the elements - highest for titanium and zinc, $\rho=0.91$.

5.1.3 Magnesium

Of all major elements investigated, magnesium is the one that shows the highest values in terms of the median value for the total concentrations, when comparing the project area to the country. With a median value of 27 g/kg it is over two times as high as the corresponding value for the country of 13 g/kg. The median value for the acid leached concentrations is also elevated, 7.3 g/kg in the project compared to 5 g/kg in the country. The leachability in the project area thus becomes 27%, compared to 38% in the whole country.

There are four magnesium silicate mineralizations located in the vicinity of Kiruna. All of them are associated with positive anomalies in the surrounding tills. Positive anomalies are also found around Svappavaara and Lannavaara, north of Vittangi, north-east of Lainio and in the northernmost part of the project area.

Magnesium shows a high correlation with vanadium for total concentrations. For the acid leached concentrations the correlation is high for all elements except zinc.

5.1.4 Manganese

The median value for the total concentrations of manganese in the project area is 0.74 g/kg, which is higher than in the rest of the country (0.60 g/kg). The median value for the acid leached concentrations is, on the other hand, lower than in the rest of the country with a value 0.21 g/kg versus 0.23 g/kg. This means that the leachability is 28%, compared to 38% for the rest of the country.

Positive manganese anomalies within the project area are mostly found in the areas north and west of Kiruna. The by far highest manganese concentration measured comes from a sample taken in the vicinity of the Kurravaara copper mineralization just north of Kiruna. The sample has total and acid leached concentrations of 2.75 and 2.19 g/kg respectively. This amounts to a leachability of almost 80%. Manganese levels are elevated around the manganese bearing mineralizations Kevus, Teltaja and Sattavaara. A few samples showing positive anomalies are found just north-east, i.e. in the direction of ice movement, of the mineralizations. There are also a few positive anomalies located in areas south-east of Kiruna and north-east of Lainio. The former area hosts both copper sulphide- as well as apatite-iron deposits. Lower levels of manganese are found in the central parts of the study area. The total correlations are relatively high for vanadium and zinc, while the acid leached concentrations are high or relatively so for all investigated elements except vanadium.

When investigating the relationship between the manganese content in tills and the underlying bedrock, the expected result would have been to see an elevated manganese content in silica poor rocks. However, this was not the case. Although the second highest median value of 0.81 g/kg could be seen in the group of ultramafic, mafic and intermediate volcanic rocks, a slightly but not significantly higher value of 0.82 g/kg was found the group of felsic volcanic rocks. The lowest median value, 0.70 g/kg, was actually found in the ultramafic, mafic and intermediate intrusive rocks. Furthermore the manganese content seemed to increase with increasing age of the rock groups. But the reliability of these results can of course be discussed – The fore mentioned results, regarding composition of the bedrock compared to the till geochemistry, might suggest that investigations regarding the relationship between lithology and till geochemistry should be accompanied by analyses of ice-movement direction and distance.

5.1.5 Titanium

The median values for total and acid leached concentrations of titanium in the project area are 9.3 and 1.52 g/kg respectively. These are both elevated compared to the rest of the country. The leachability for titanium is the lowest of all investigated elements, 16% but this is actually the same value as for the whole country.

Almost all positive anomalies for titanium total concentrations are found north-east of Lainio. A total of four mineralizations within the project area are known to carry titanium. Three are located around Svappavaara and one about 20 km ENE of Kiruna, all of which are iron oxide mineralizations. They are actually not very clearly reflected in the till geochemistry, being situated in the transition zone between somewhat elevated total concentrations in the south-western parts of the project area and low concentrations in the central parts.

The total concentrations of titanium show a high correlation with vanadium and zinc. The acid leached concentrations show a relatively high correlation with cobalt, manganese and zinc; and strongly with the rest, i.e. magnesium, iron and vanadium.

5.1.6 Vanadium

Vanadium levels are significantly elevated within the project area. The median total concentration of 133 mg/kg is well above the 95th percentile limit for the country, which is 108 mg/kg. Acid leached concentrations are also elevated but not to the same extent. For the country the leachability for vanadium is 34%, while the corresponding value for the project area is only just over half of that, 19%.

Positive anomalies for total concentrations of vanadium are scattered across the project area. The largest area containing positive anomalies is located north-east of Lainio. There are three iron oxide mineralizations located between Vittangi and Svappavaara that carry vanadium.

Vanadium shows a high correlation with magnesium and titanium for the total concentrations. The correlations for the acid leached concentrations are also high for the previously mentioned combinations as well as for the combination vanadium-iron. A relatively high correlation can also be seen between the acid leached concentrations of vanadium and cobalt.

5.1.7 Zinc

Zinc is the only investigated element that is typically enriched in high silica content rocks (Appendix, table 2). It is therefore not unexpected to find that zinc is the only investigated element that, compared to the country, shows lower concentrations. The median values for total and acid leached concentrations in the project area are 42 and 17 mg/kg respectively. This also means that zinc has the highest leachability of all elements, 39%. But this is still lower than the 58% leachability seen in the country as a whole.

Generally, elevated total concentrations for zinc are found in the north-eastern and south-western parts of the project area while levels tend to be lower in the central parts. A large area containing positive anomalies is located north-east of Lainio. A total of 18 zinc mineralizations are found within the project area and they are often associated with elevated zinc levels in the surrounding tills.

Zinc total concentrations show the highest correlation with manganese and titanium with correlation coefficients of 0.70 and 0.73, respectively. The acid leached concentrations are relatively high for all elements except cobalt.

5.2 Conclusions and suggestions for further studies

The element concentrations in till have generally shown to be elevated in the project area compared to the rest of the country. This is consistent with the bedrock composition of the area that, in contrast to the rest of Sweden, contains a high proportion of low silica content rocks, which are normally enriched in the investigated elements. Mineralizations are also typically well reflected in the till geochemistry in the form of elevated element concentrations. In many cases positive anomalies are found downstream the direction of ice movement from mineralizations.

The acid leached concentrations for all investigated elements show spatial distribution patterns that are roughly similar to the corresponding ones for total concentrations. The spatial distribution for the leachability of the elements show generally scattered patterns. A common feature for all elements is that leachability is elevated east to north-east of Lainio. Cobalt and titanium show leachability levels in the project that are approximately the same as in the rest of the country. While the rest of the investigated elements show lower levels of leachability, especially iron and zinc.

Gustavsson (1994) suggested that geochemical distribution patterns in regional and reconnaissance scale studies often are spatially connected to large-scale structural features of the bedrock. It is not possible to clearly determine whether or not such a relationship exists

within the project area of this study. To properly study this relationship would probably require till geochemical data from a larger area. Take, for example, the positive anomalies seen for many elements just NNE of Kiruna. These anomalies could very well be connected to the KNDZ, whose southernmost part is situated in that area. But to determine whether or not this is a continuous trend would of course require geochemical data from an area extending further northward along the deformation zone.

When it comes to the relationship between element distribution patterns in the till geochemistry and geophysical anomalies, no clear connection can be seen. Other than the obvious one that magnetic anomalies are associated with areas abundant in magnetic elements, such as iron; and these are areas that also show elevated concentrations for those elements in the till geochemistry. However, the gravity-high area in the north-eastern part of the project area might be an example of where geophysical and geochemical anomalies may be connected somehow (see discussion in the last paragraph).

The other geological parameters mentioned in the initial question formulation, metamorphic alterations and surficial geology, do not really exhibit large scale features that are possible to relate to the till geochemistry of the investigated elements. Both factors are undoubtedly intimately connected with till geochemistry, but when looking at regional scale geological features, as this study does, no such connections have been interpreted for the elements considered. But once again there might be an exception (see discussion on the Lainio arc below).

All investigated elements show positive anomalies for both total and acid leached concentrations in an area north-east of Lainio. There are no known mineralizations in this area and the bedrock is granitic in composition. Because the elements investigated normally are not elevated in these types of rocks, the positive anomalies seen in this area become hard to explain. As previously mentioned (see section on geophysics), this area is characterized by a gravity high that is probably caused by mafic rocks at depth (Bergman, Kübler and Martinsson 2001). It is possible that these rocks are mixed with the overlying rocks and that this may be the source of the geochemical anomalies seen. Another theory could be that they are caused by the scavenging properties of manganese and iron oxides, which have been known to create heavy metal anomalies in otherwise non-mineralized areas (Chao and Theobald 1976). A third theory could be that the anomalies in some way are related to the Lainio arc, which has been associated with geochemical anomalies (Ladenberger et al. 2012). This is of course speculation and it would perhaps be warranted to conduct more detailed studies in this area in order to elucidate what is causing the observed anomalies.

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I would like to express my sincere gratitude to my supervisor Prof. Richard Bindler, who has supported me throughout my B.Sc. thesis with his patience, motivation and expertise. I would also like to thank my advisors at the Survey, especially Dr. Anna Ladenberger and also Dr. Madelen Andersson for providing the necessary data for this study as well as encouragement and constructive, insightful comments on my work.

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Appendix A - Statistics

Natural background levels

Natural background levels in the C-horizon of till based on data from SGU's geochemical mapping in Sweden, from Ladenberger et al. 2012:

Appendix, table 1. Natural background levels and pH in the C-horizon of till <0.063 mm. Data from SGU's geochemical mapping in Sweden. Percentile classes p10–p99, where p50=median value. A. Total concentrations. B. Nitric acid leached concentrations.

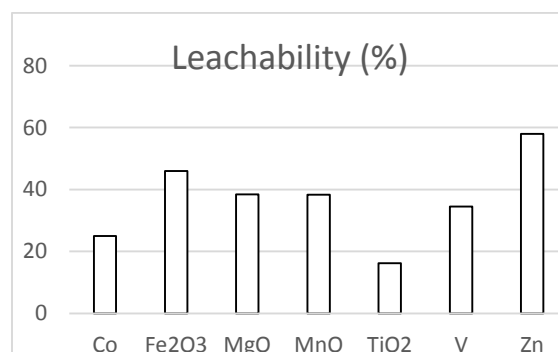
A. Total concentrations, analyzed with X-ray fluorescence.

	Co (mg/kg)	Fe ₂ O ₃ (g/kg)	MgO (g/kg)	MnO (g/kg)	TiO ₂ (g/kg)	V (mg/kg)	Zn (mg/kg)
p10	13	25	7	0.40	5.2	36	30
p30	17	31	10	0.50	6.5	48	41
p50	20	37	13	0.60	7.4	58	50
p70	23	44	16	0.70	8.3	71	61
p90	29	55	21	0.90	9.6	99	81
p95	31	59	23	1.00	10.3	108	92
p99	40	74	32	1.6	11.7	150	135

B. Nitric acid (7M HNO₃) leached concentrations, analyzed with ICP-MS.

	Co (mg/kg)	Fe ₂ O ₃ (g/kg)	MgO (g/kg)	MnO (g/kg)	TiO ₂ (g/kg)	V (mg/kg)	Zn (mg/kg)
p10	2	9	2	0.12	0.6	10	13
p30	4	14	4	0.18	1.0	15	20
p50	5	17	5	0.23	1.2	20	29
p70	7	23	7	0.32	1.4	26	41
p90	10	33	10	0.53	1.9	37	61
p95	12	41	11	0.76	2.1	39	78
p99	17	56	17	1.21	2.8	58	111

Leachability



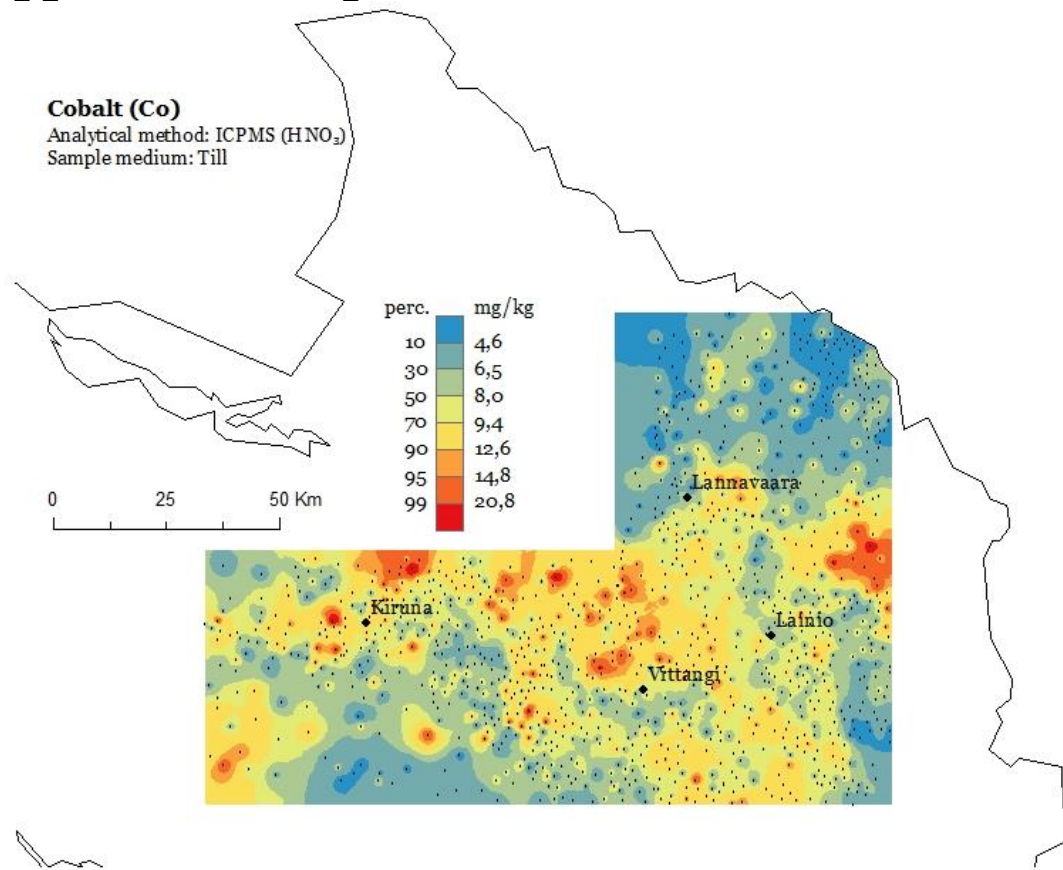
Appendix, figure 1. Leachability of the investigated elements for the country. Based on data from SGU's geochemical mapping in Sweden (i.e Appendix table 1 and 2).

Rock types and associated elements

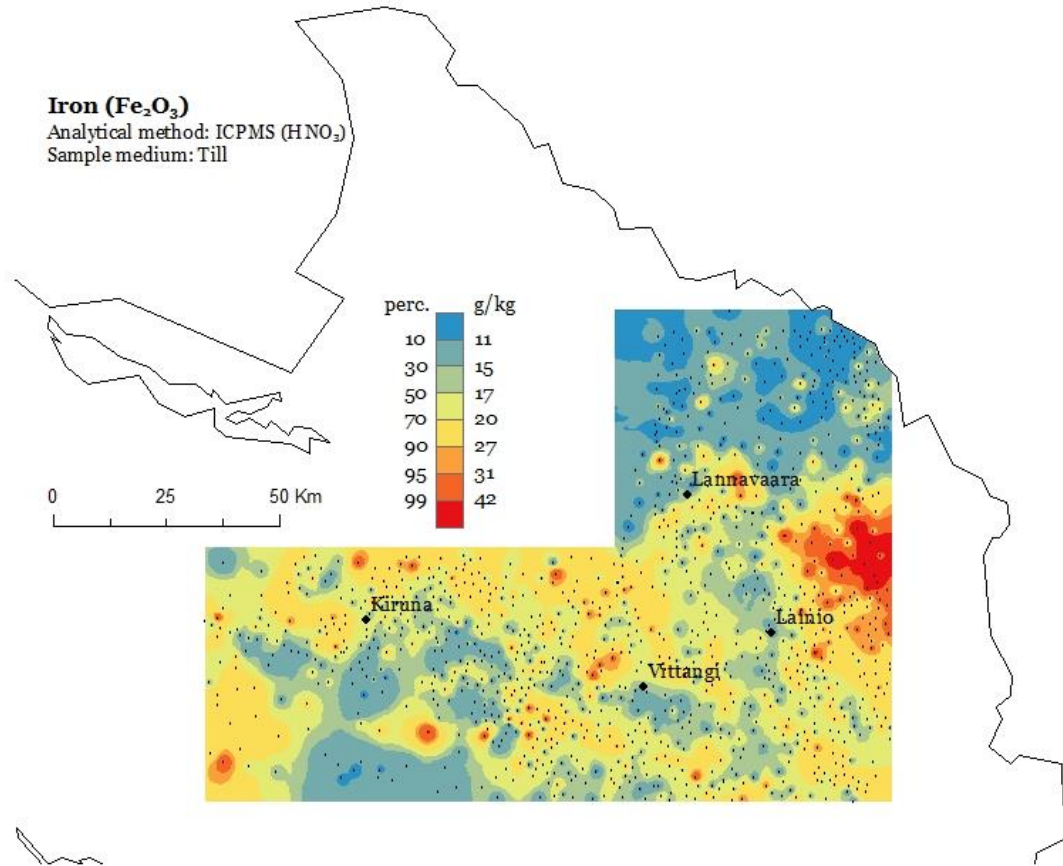
Appendix, table 2. Rock types and associated elements. Based on (Ladenberger, et al., 2012).

Granites	Au, Ba, Be, Bi, Cl, K, La, Mo, Pb, Rb, Sn, Th, Tl, U, W, Y, Zr
Felsic volcanic rocks (ryolites, andesites etc.)	Ag, As, Cd, Cu, Hg, Pb, Se, Zn
Mafic rocks (gabbros, basalts etc.)	Ca, Fe, Mg, Mn, P, Ag, Cd, Co, Cr, Cu, Ni, S, Sr, Ti, V, Zn
Shales	Al, Ag, As, Au, Ba, Bi, Cd, Cl, Co, Cu, La, Li, Mo, Ni, Pb, Rb, S, Sb, Sn, Se, Th, Tl, U, W, Y, Zn

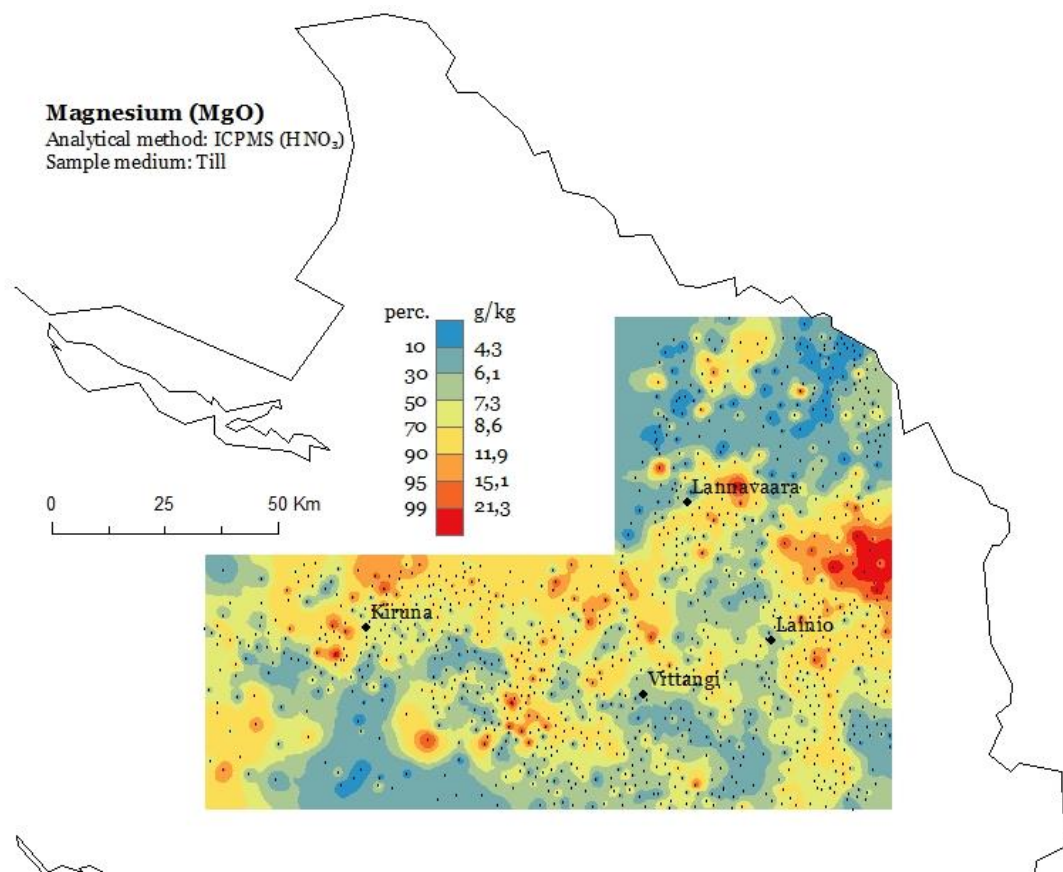
Appendix B - Maps



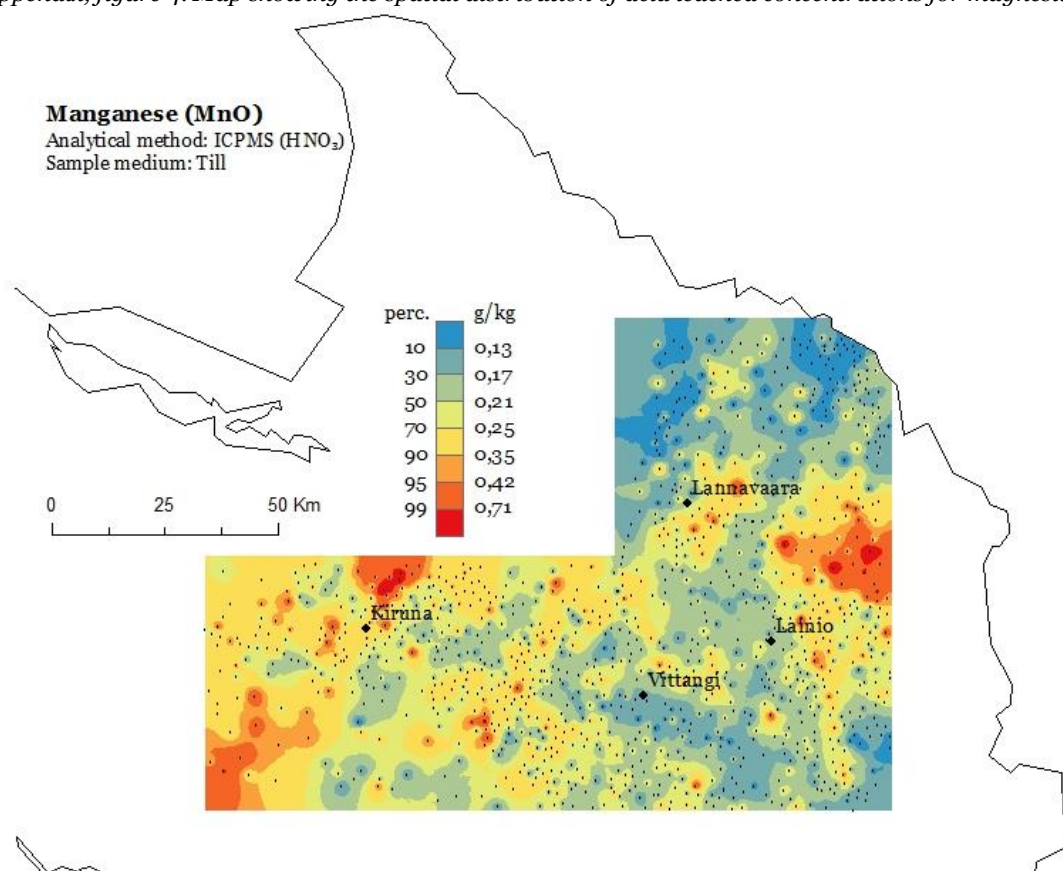
Appendix, figure 2. Map showing the spatial distribution of acid leached concentrations for cobalt.



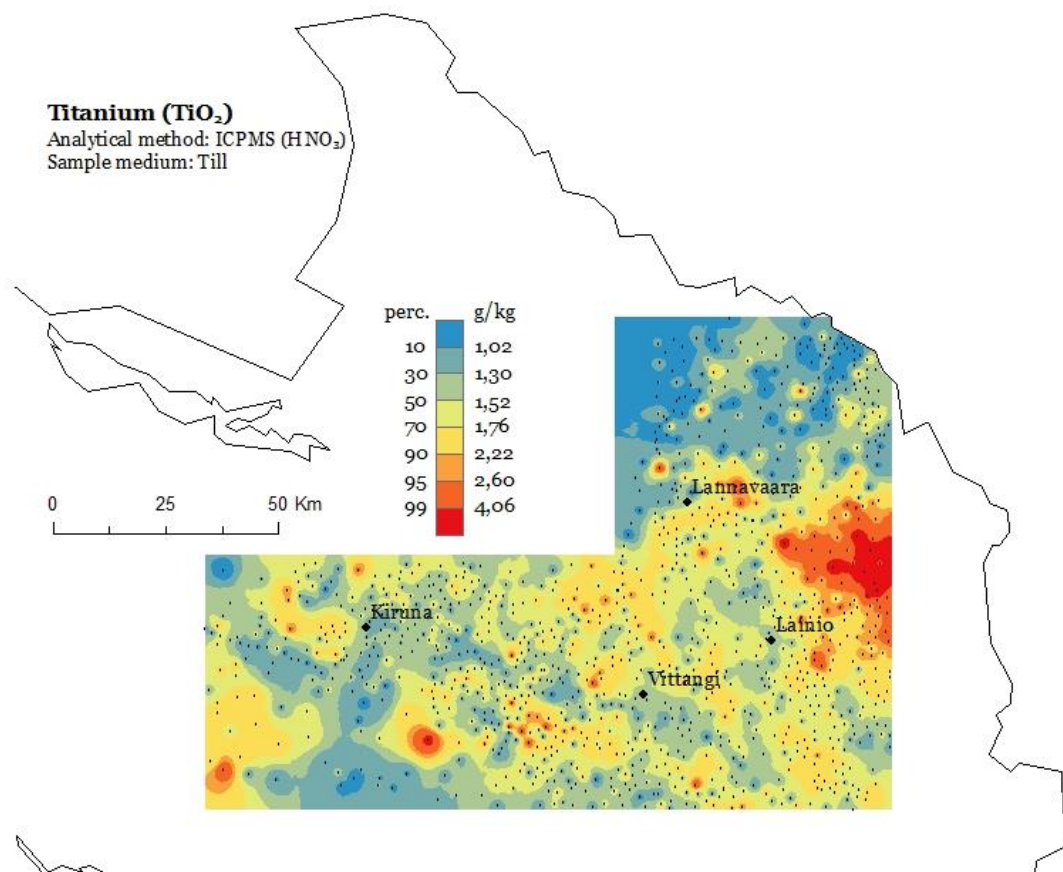
Appendix, figure 3. Map showing the spatial distribution of acid leached concentrations for iron.



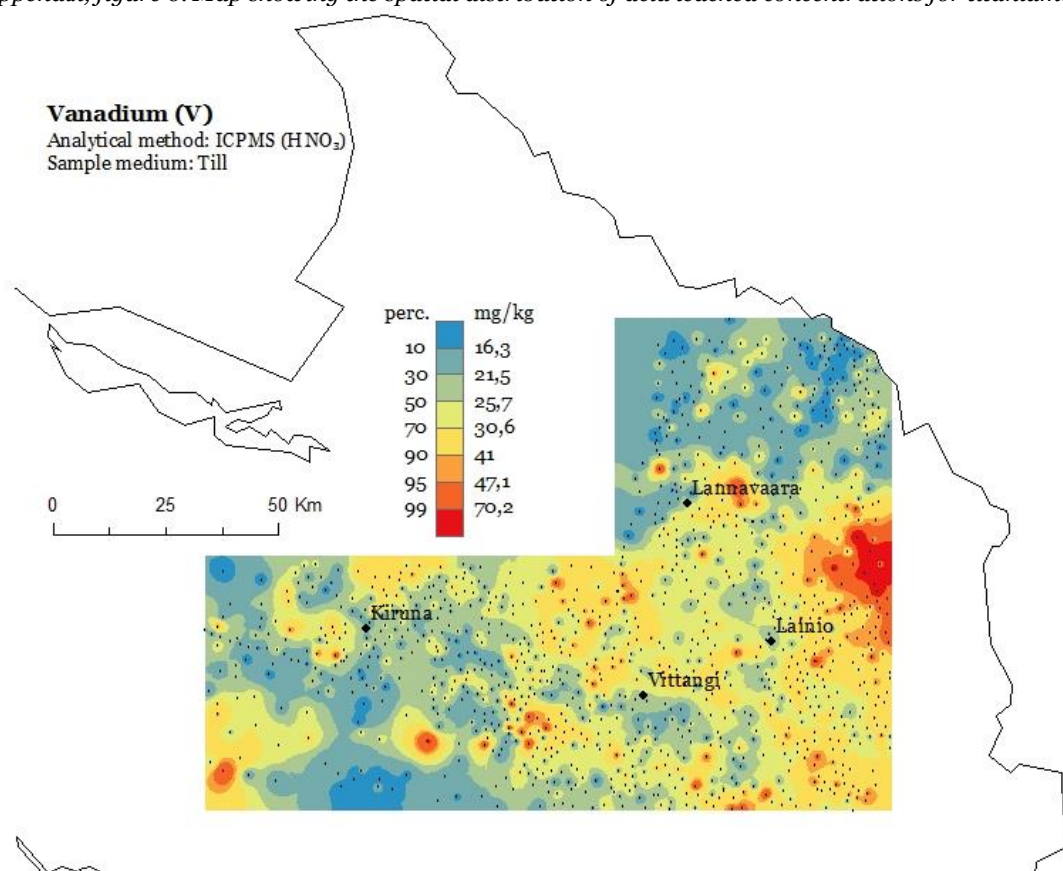
Appendix, figure 4. Map showing the spatial distribution of acid leached concentrations for magnesium.



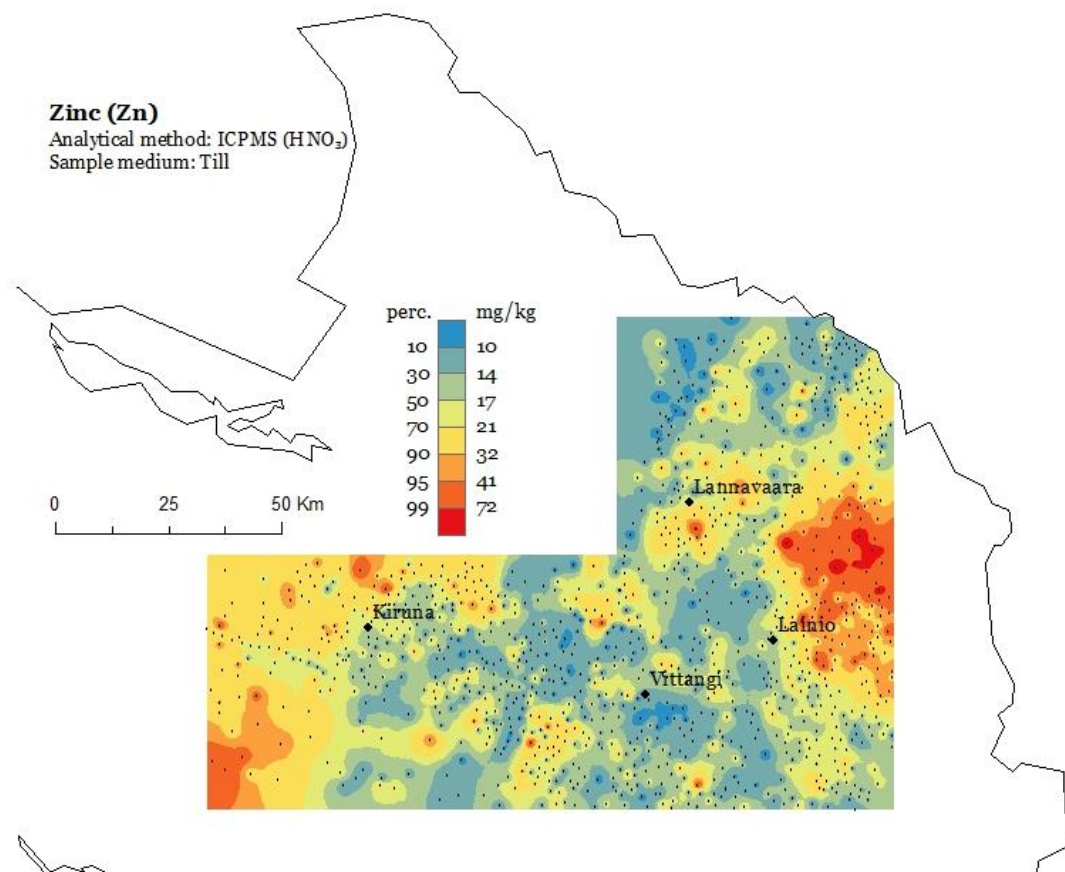
Appendix, figure 5. Map showing the spatial distribution of acid leached concentrations for manganese.



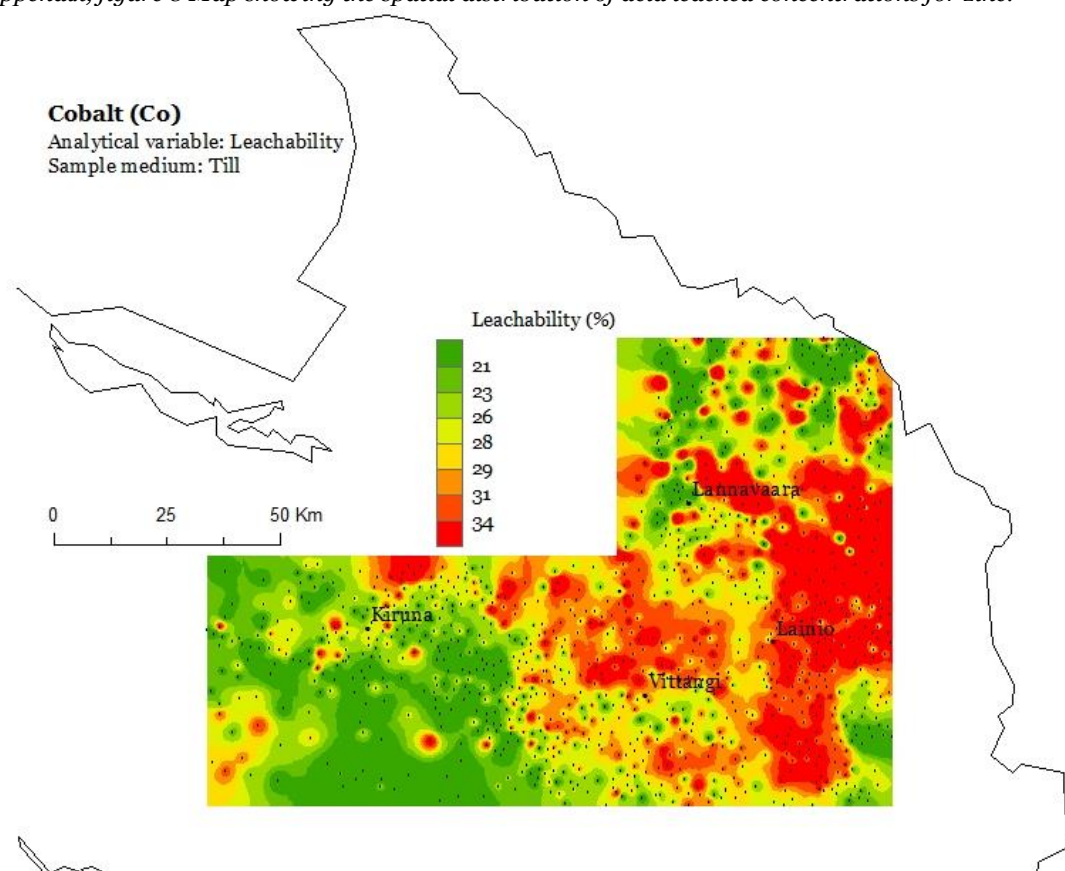
Appendix, figure 6. Map showing the spatial distribution of acid leached concentrations for titanium.



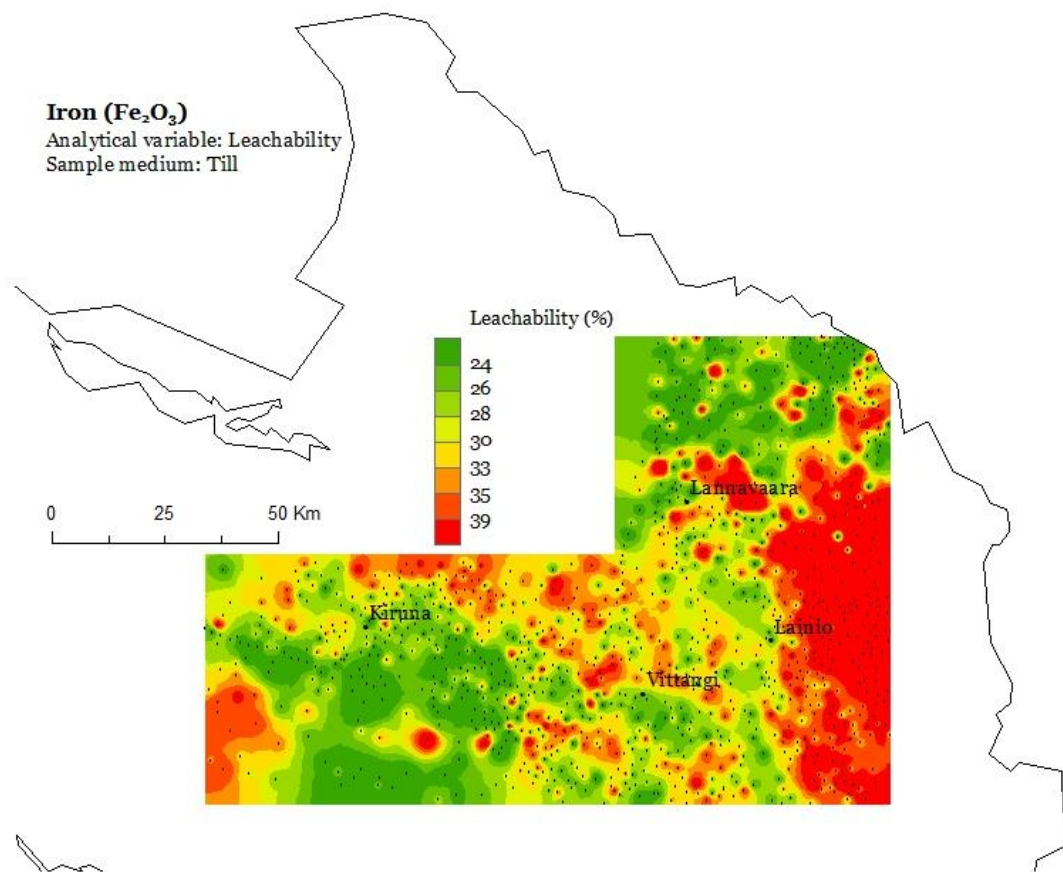
Appendix, figure 7. Map showing the spatial distribution of acid leached concentrations for vanadium.



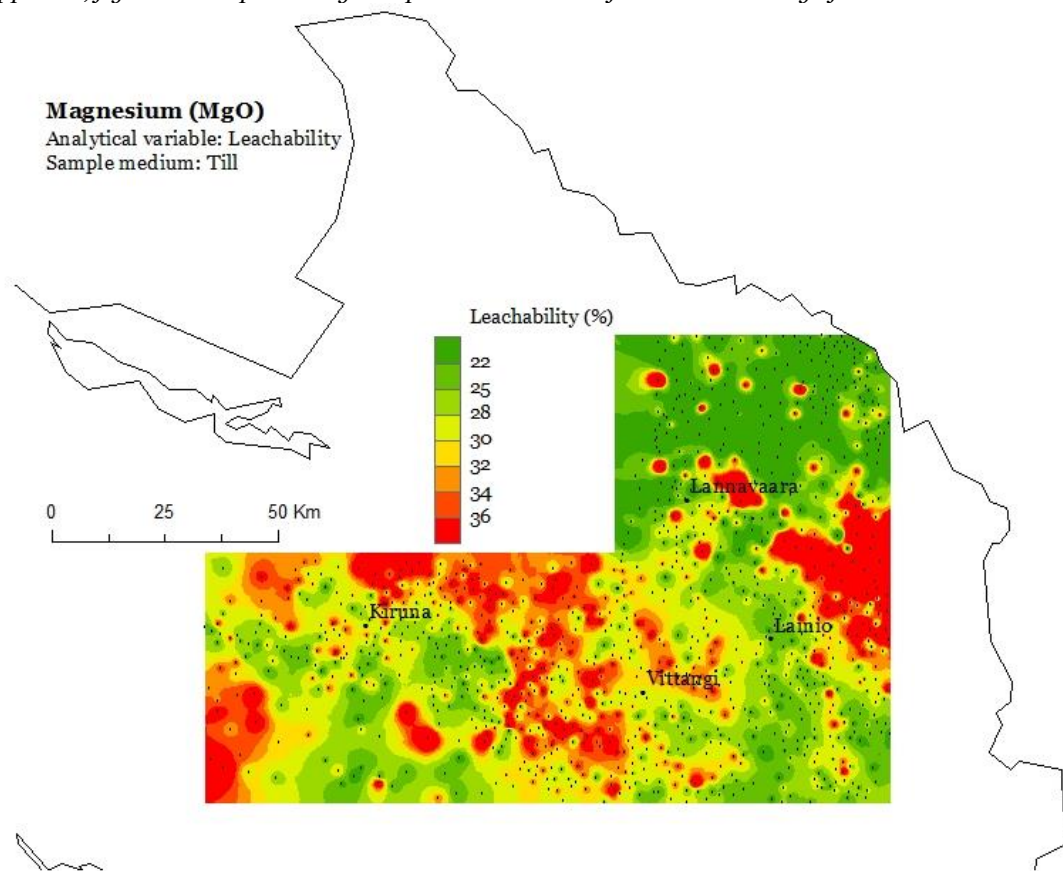
Appendix, figure 8 Map showing the spatial distribution of acid leached concentrations for zinc.



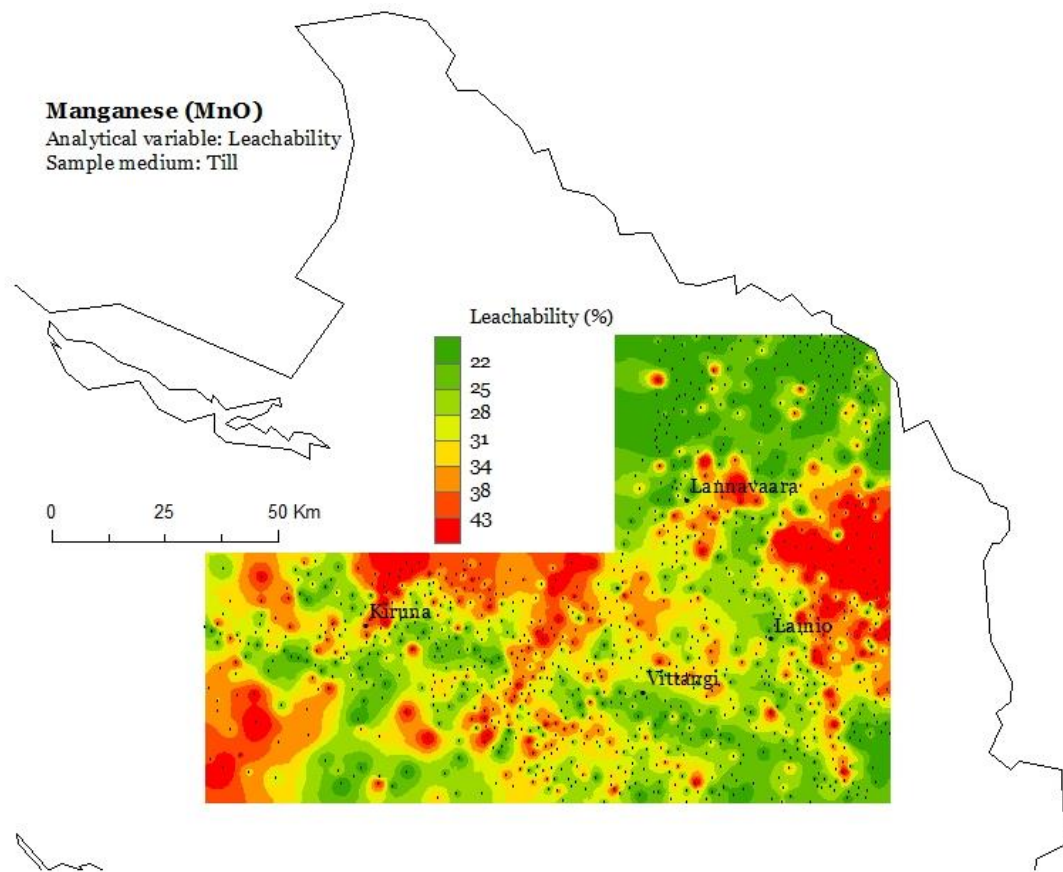
Appendix, figure 9. Map showing the spatial distribution for the leachability of cobalt.



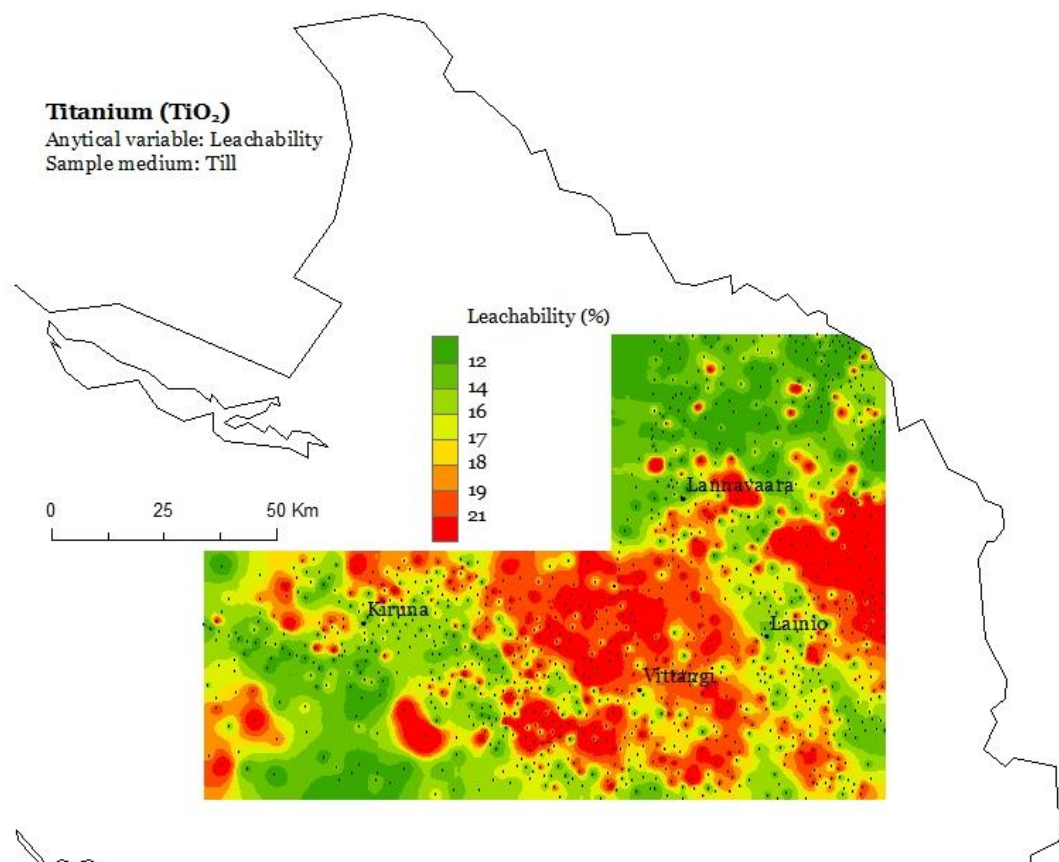
Appendix, figure 10. Map showing the spatial distribution for the leachability of iron.



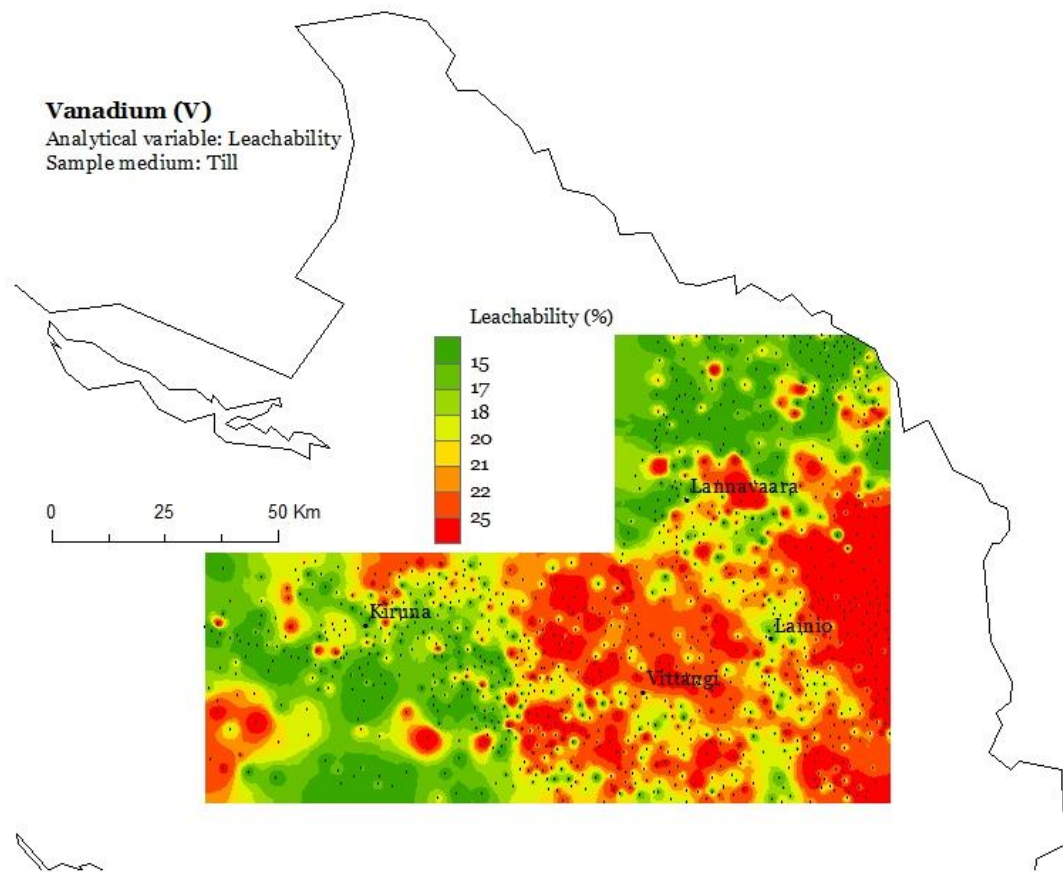
Appendix, figure 11. Map showing the spatial distribution for the leachability of magnesium.



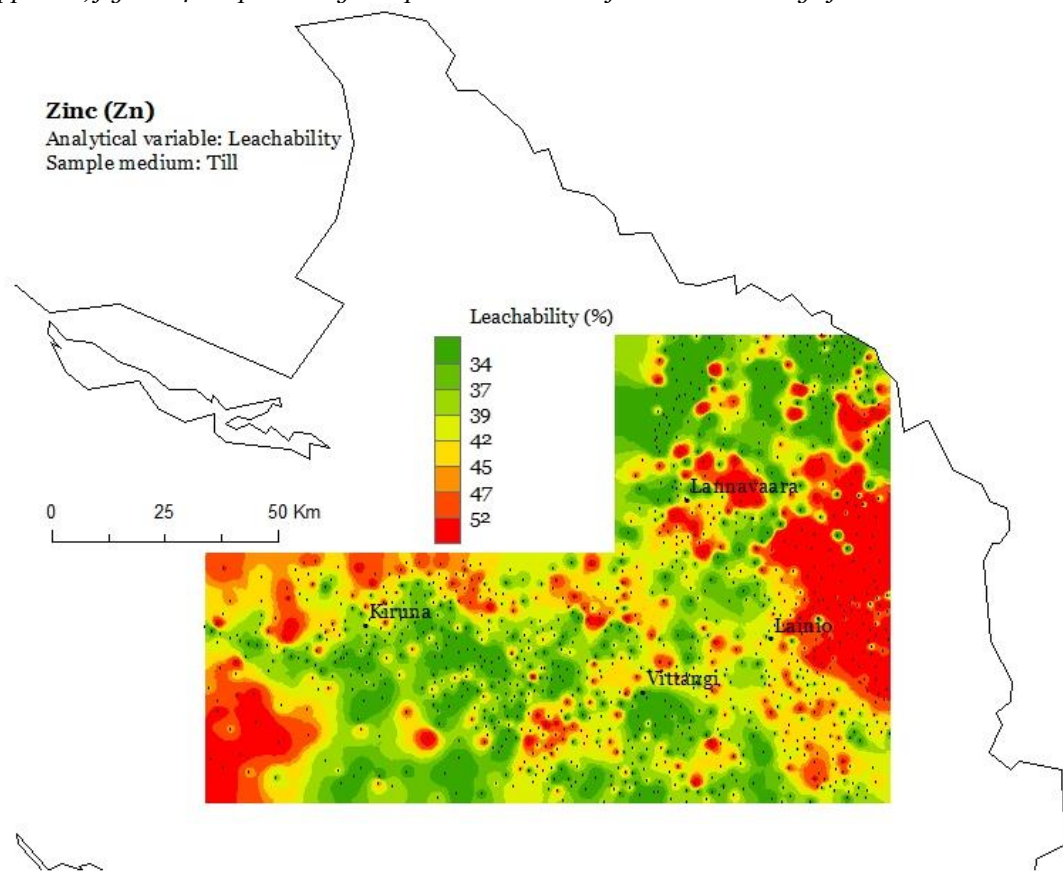
Appendix, figure 12. Map showing the spatial distribution for the leachability of manganese.



Appendix, figure 13. Map showing the spatial distribution for the leachability of titanium.



Appendix, figure 14. Map showing the spatial distribution for the leachability of vanadium.



Appendix, figure 15. Map showing the spatial distribution for the leachability of zinc.



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