Rapporter och meddelanden 141

# Geology of the Northern Norrbotten ore province, northern Sweden

Paper 13 (13)

**Editor: Stefan Bergman**




SGU
Sveriges geologiska undersökning
Geological Survey of Sweden

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# Geology of the Northern Norrbotten ore province, northern Sweden

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Sveriges geologiska undersökning
2018

ISSN 0349-2176
ISBN 978-91-7403-393-9

***Cover photos:***
*Upper left:* View of Torneälven, looking north from Sakkaravaara, northeast of Kiruna. ***Photographer:*** Stefan Bergman.
*Upper right:* View (looking north-northwest) of the open pit at the Aitik Cu-Au-Ag mine, close to Gällivare. The Nautanen area is seen in the background. ***Photographer:*** Edward Lynch.
*Lower left:* Iron oxide-apatite mineralisation occurring close to the Malmberget Fe-mine. ***Photographer:*** Edward Lynch.
*Lower right:* View towards the town of Kiruna and Mt. Luossavaara, standing on the footwall of the Kiruna apatite iron ore on Mt. Kiirunavaara, looking north. ***Photographer:*** Stefan Bergman.

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# Introduktion

Stefan Bergman & Ildikó Antal Lundin

Den här rapporten presenterar de samlade resultaten från ett delprojekt inom det omfattande tvärvetenskapliga Barentsprojektet i norra Sverige. Projektet initierades av Sveriges geologiska undersökning (SGU) som ett första led i den svenska mineralstrategin. SGU fick ytterligare medel av Näringsdepartementet för att under en fyraårsperiod (2012–2015) samla in nya geologiska, geofysiska och geokemiska data samt för att förbättra de geologiska kunskaperna om Sveriges nordligaste län. Det statligt ägda gruvbolaget LKAB bidrog också till finansieringen. Projektets strategiska mål var att, genom att tillhandahålla uppdaterad och utförlig geovetenskaplig information, stödja prospekterings- och gruvindustrin för att förbättra Sveriges konkurrenskraft inom mineralnäringen. Ny och allmänt tillgänglig geovetenskaplig information från den aktuella regionen kan hjälpa prospekterings- och gruvföretag att minska sina risker och prospekteringskostnader och främjar därigenom ekonomisk utveckling. Dessutom bidrar utökad geologisk kunskap till en effektiv, miljövänlig och långsiktigt hållbar resursanvändning. All data som har samlats in i projektet lagras i SGUs databaser och är tillgängliga via SGU.

Syftet med det här delprojektet var att få en djupare förståelse för den stratigrafiska uppbyggnaden och utvecklingen av de mineraliserade ytbergarterna i nordligaste Sverige. Resultaten, som är en kombination av ny geologisk kunskap och stora mängder nya data, kommer att gynna prospekterings- och gruvindustrin i regionen i många år framöver.

Norra Norrbottens malmprovins står för en stor del av Sveriges järn- och kopparmalmsproduktion. Här finns fyra aktiva metallgruvor (mars 2018) och mer än 500 dokumenterade mineraliseringar. Fyndigheterna är av många olika slag, där de viktigaste typerna är stratiforma kopparmineraliseringar, järnformationer, apatitjärnmalm av Kirunatyp och epigenetiska koppar-guldmineraliseringar. En vanlig egenskap hos de flesta malmer och mineraliseringar i Norr- och Västerbotten är att de har paleoproterozoiska vulkaniska och sedimentära bergarter som värdbergart. För undersökningarna valdes ett antal nyckelområden med bästa tillgängliga blottningsgrad. De utvalda områdena representerar tillsammans en nästan komplett stratigrafi i ytbergarter inom åldersintervallet 2,5–1,8 miljarder år.

Rapporten består av tretton kapitel och inleds med en översikt över de geologiska förhållandena, som beskriver huvuddragen i de senaste resultaten. Översikten följs av fyra kapitel (2–5) som huvudsakligen handlar om litostratigrafi och åldersbestämningar av ytbergarterna. Huvudämnet för de därpå följande fem kapitlen (6–10) är 3D-geometri och strukturell utveckling. Därefter kommer två kapitel (11–12) som fokuserar på U-Pb-datering av en metamorf respektive intrusiv händelse. Rapporten avslutas med en studie av geokemin hos morän i Norra Norrbottens malmprovins (kapitel 13).

# Introduction

Stefan Bergman & Ildikó Antal Lundin

This volume reports the results from a subproject within the Barents Project, a major programme in northern Sweden. The multidisciplinary Barents Project was initiated by SGU as the first step in implementing the Swedish National Mineral Strategy. SGU obtained additional funding from the Ministry of Enterprise and Innovation to gather new geological, geophysical and till geochemistry data, and generally enhance geological knowledge of northern Sweden over a four-year period (2012–2015). The state-owned iron mining company LKAB also helped to fund the project. The strategic goal of the project was to support the exploration and mining industry, so as to improve Sweden's competitiveness in the mineral industry by providing modern geoscientific information. Geological knowledge facilitates sustainable, efficient and environmentally friendly use of resources. New publicly available geoscientific information from this region will help exploration and mining companies to reduce their risks and exploration costs, thus promoting economic development. All data collected within the project are stored in databases and are available at SGU.

This subproject within the Barents Project aims to provide a deeper understanding of the stratigraphy and depositional evolution of mineralised supracrustal sequences in northernmost Sweden. The combined results in the form of new geological knowledge and plentiful new data will benefit the exploration and mining industry in the region for many years to come.

The Northern Norrbotten ore province is a major supplier of iron and copper ore in Sweden. There are four active metal mines (March 2018) and more than 500 documented mineralisations. A wide range of deposits occur, the most important types being stratiform copper deposits, iron formations, Kiruna-type apatite iron ores and epigenetic copper-gold deposits. A common feature of most deposits is that they are hosted by Palaeoproterozoic metavolcanic or metasedimentary rocks. A number of key areas were selected across parts of the supracrustal sequences with the best available exposure. The areas selected combine to represent an almost complete stratigraphic sequence.

This volume starts with a brief overview of the geological setting, outlining some of the main recent achievements. This is followed by four papers (2–5) dealing mainly with lithostratigraphy and age constraints on the supracrustal sequences. 3D geometry and structural evolution are the main topics of the next set of five papers (6–10). The following two contributions (11–12) focus on U-Pb dating of a metamorphic event and an intrusive event, respectively. The volume concludes with a study of the geochemical signature of till in the Northern Norrbotten ore province (13).

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# 13. Till geochemistry in northern Norrbotten – regional trends and local signature in the key areas

Anna Ladenberger, Madelen Andersson, Colby Smith & Mikael Carlsson


## ABSTRACT

2 316 new till geochemistry analyses are presented. Together with pre-existing data, they provide an overview of natural element concentrations in overburden within the Barents region. The primary influence on till geochemistry is the composition of underlying bedrock. Transport distances in Norrbotten are generally low (5–10 km maximum), allowing till composition to be used as a good analogue for the often poorly exposed bedrock. Correlation of anomalies with known ore deposits shows the value of this data as a preliminary exploration tool. Anomalies related to both glacial and post-glacial reworking can be recognised, as well as a distinct depletion of many elements in the southeast of the area due to inundation by seawater in the immediate post-glacial period. In the Key Areas additional samples were collected with higher sample density than on a regional scale. Elevated concentrations of many elements were obtained and correlated with the location of Fe, Cu and Au mineralisation, as well as zones of intense alteration.


## INTRODUCTION

In addition to geological mapping and geophysical surveys, extensive till geochemical mapping was carried out in the Barents Project. Glacial till has been used as a sampling medium in geochemical surveys for decades. As a widespread Quaternary deposit in high latitudes (till covers approximately 75% of the land surface in Sweden) it usually well reflects the underlying bedrock, which is not always well exposed and cannot be accessed and studied. This chapter is devoted to till geochemistry, including sampling strategy, analytical protocol, results and their interpretation in the regional (Norrbotten) and local (key areas) contexts.

Under the Barents Project, 2 300 till samples were collected from previously unmapped areas during field campaigns in 2012 and 2013 (Fig. 1). Earlier, the southern, eastern and central parts of Norrbotten, which have better road infrastructure, were sampled and analysed during SGU's regional mapping programme (1993–1995, 1998–2003, 2005–2007, 2009 and 2011–2012). A nominal sampling density of one sample per 6.5 km$^2$ was maintained.

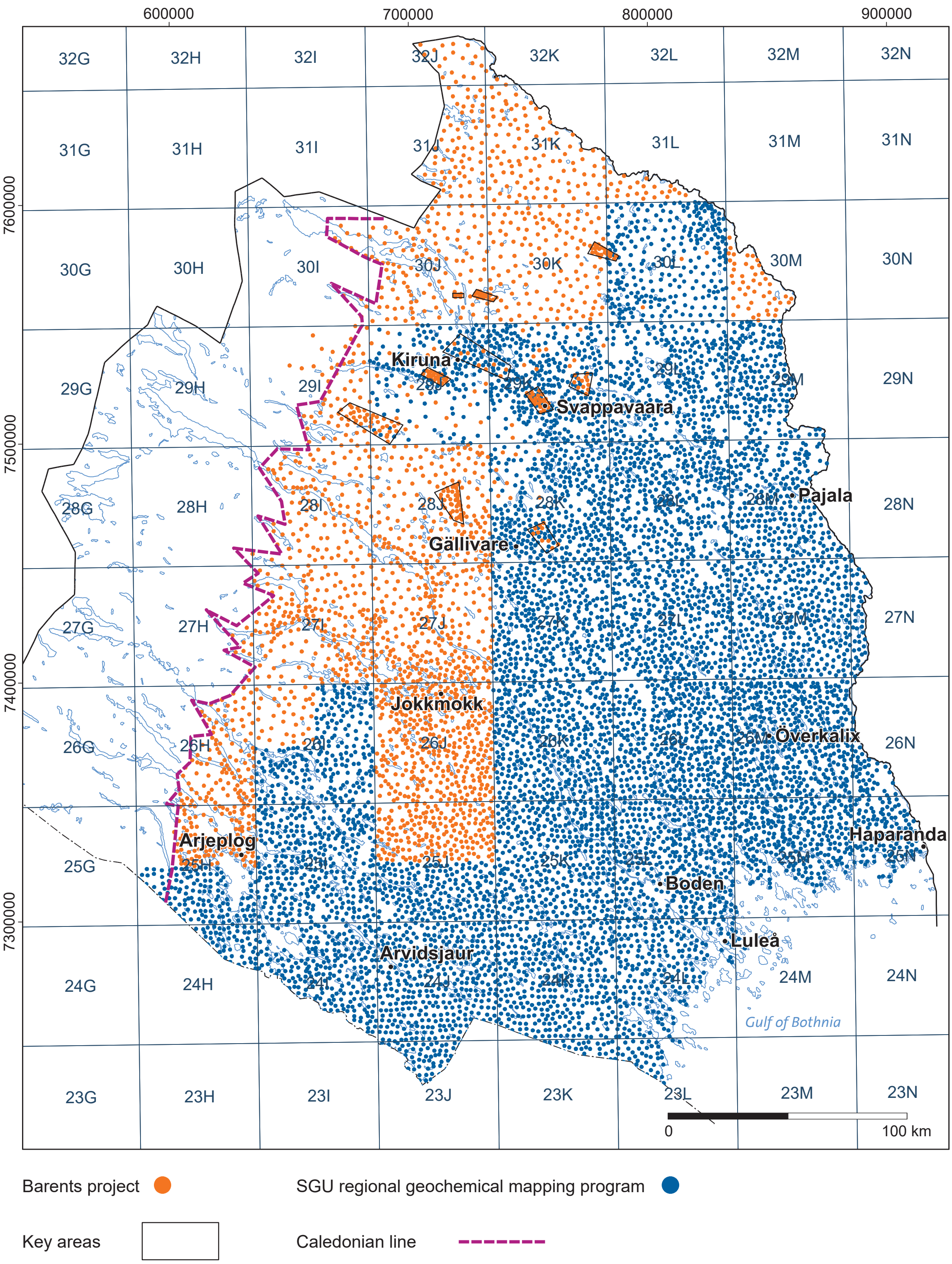


Figure 1. Sampling sites in Norrbotten from various field campaigns. Till samples collected under the Barents Project are marked in orange. Key areas (the subject of detailed geological and geochemical investigations) are outlined in black.

The results from the Nordkalott Project (sampled in 1981 and 1983; Bölviken et al. 1986) and the NSG/SGAB (Nämnden för Statens Gruvegendom/Sveriges Geologiska AB) database have also been used for regional interpretation.

The use of various methods for more than 30 years of different surveys, insufficient and varied quality control protocols and rapid improvements in analytical techniques have resulted in rather inhomogeneous datasets, thereby hampering a quantitative interpretation of the Norrbotten region. At local scale, however, the results perform satisfactorily and more quantitative methods can be used to evaluate the geochemical patterns and trends.

In general, geochemical results obtained during surveys described here show natural variation of element concentrations in till and provide reliable background levels of major and trace elements as well as pH. These can be used for evaluation of groundwater quality, availability of nutrients, for mineral exploration, for assessments of the weathering grade etc.

## GLACIAL GEOMORPHOLOGY AND QUATERNARY STRATIGRAPHY OF NORRBOTTEN

Information on the Quaternary geology of northern Sweden was compiled as part of the Nordkalott Project, a collaborative effort involving the geological surveys of Finland, Norway, and Sweden. The project produced a series of five 1:1 000 000 scale maps of the Quaternary deposits, glacial geomorphology, ice flow indicators, Quaternary stratigraphy, and ice flow directions (Nordkalott Project 1986a, b, c, d). While the Nordkalott maps provide an excellent overview of the region, more detailed (1:100 000 and 1:250 000 scale) maps of Quaternary deposits have been produced by the Geological Survey of Sweden (SGU digital database). Together, these map series provide the framework to interpret the glacial geomorphology and Quaternary stratigraphy of the study area (Fig. 2A and B).

Although tills from the previous glacial cycle – the Saalian – are sometimes encountered in excavations, most of the glacial landforms in northern Sweden date from the most recent glacial cycle, the Weichselian. During the Weichselian, ice advanced across northern Sweden several times. In the early Weichselian, ice advanced from the northwest, creating well-defined streamlined glacial landforms (Lagerbäck & Robertsson 1988). During the retreat of the early Weichselian ice sheet margin, there was an extended period of ice stagnation. This led to deposition of stagnant ice and associated water-lain sediments across large portions of northern Sweden (Lagerbäck 1988a). Collectively, these deposits are known as Veiki Moraine and are best expressed in a 30–50 km wide zone of hummocky topography that extends northeast to southwest along the entire length of Norrbotten (Lagerbäck & Robertsson 1988).

Following this ice-free period, stratigraphical evidence indicates at least two (Lagerbäck 1988a, Lagerbäck 1988b, Lagerbäck & Robertsson 1988) and perhaps three (Helmens et al. 2007) subsequent periods of ice advance in Norrbotten. But large areas of southern and central Norrbotten contain little geomorphic evidence of middle and late Weichselian ice advance(s) because of largely non-erosive frozen-bed conditions at the base of the ice. This lack of glacial reworking often causes middle and late Weichselian landforms to be undifferentiated from each other (Nordkalott Project 1986a, b, c, d). Ice flow during these periods was from the west and southwest.

Frozen-based glacial conditions may not have been limited to the Weichselian. It has been suggested that a landscape in northern Norrbotten is not of glacial origin. Thus, it must predate the Quaternary Period (Hättestrand & Stroeven 2002). The widespread presence of saprolites supports this hypothesis. Subsequent work has shown that this is not an isolated case. Landscapes interpreted to contain components more than 1 million years old persist throughout the far north of Sweden (Hall et al. 2013).

Glacial stratigraphy often changes dramatically over just a few hundred lateral metres. The patchwork of frozen-based and wet-based conditions beneath Weichselian ice sheets in northern Sweden exacerbates this phenomenon. Thus, descriptions of regional stratigraphy based on relatively few point

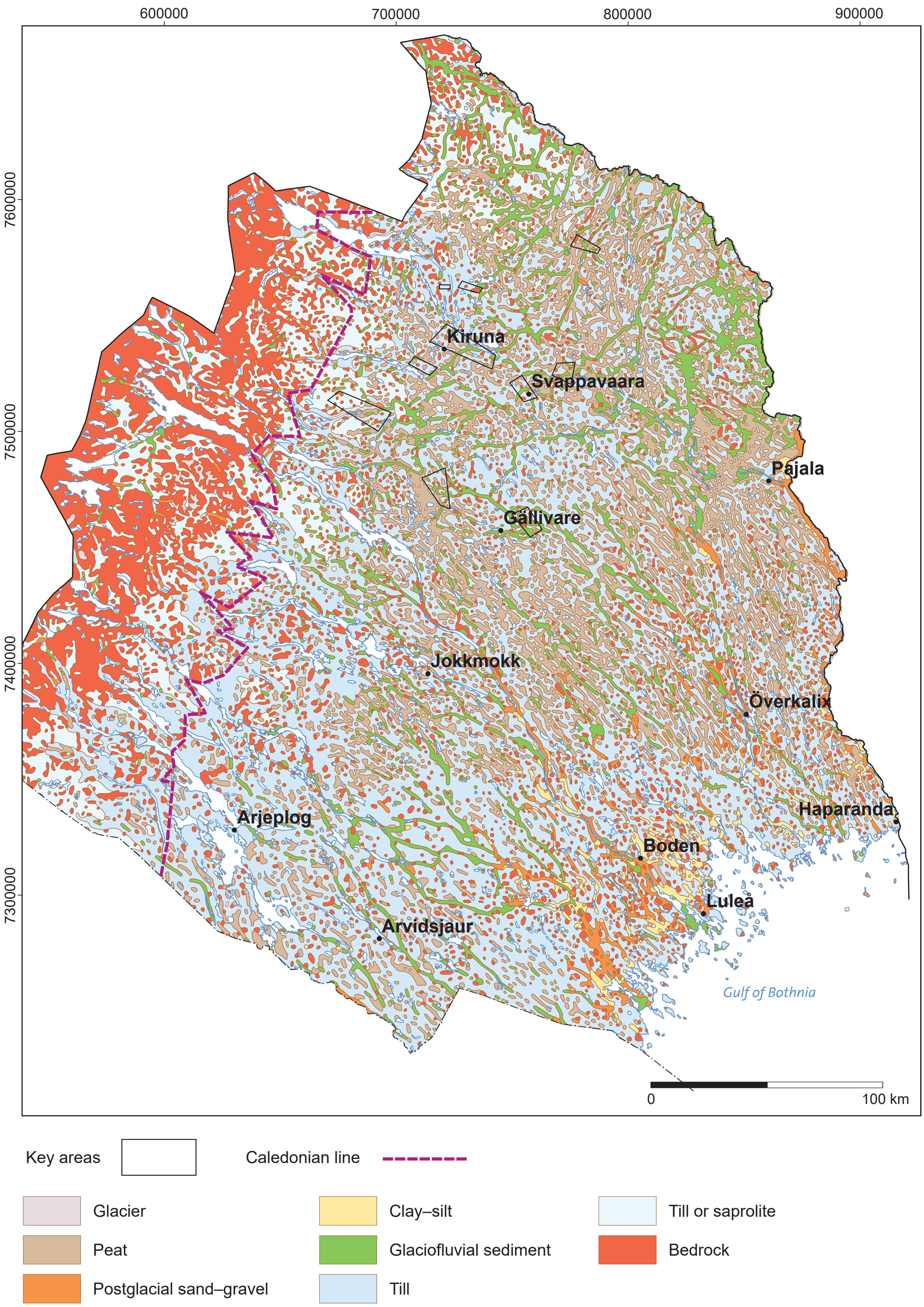


Figure 2. **A.** Quaternary map of Northern Sweden.

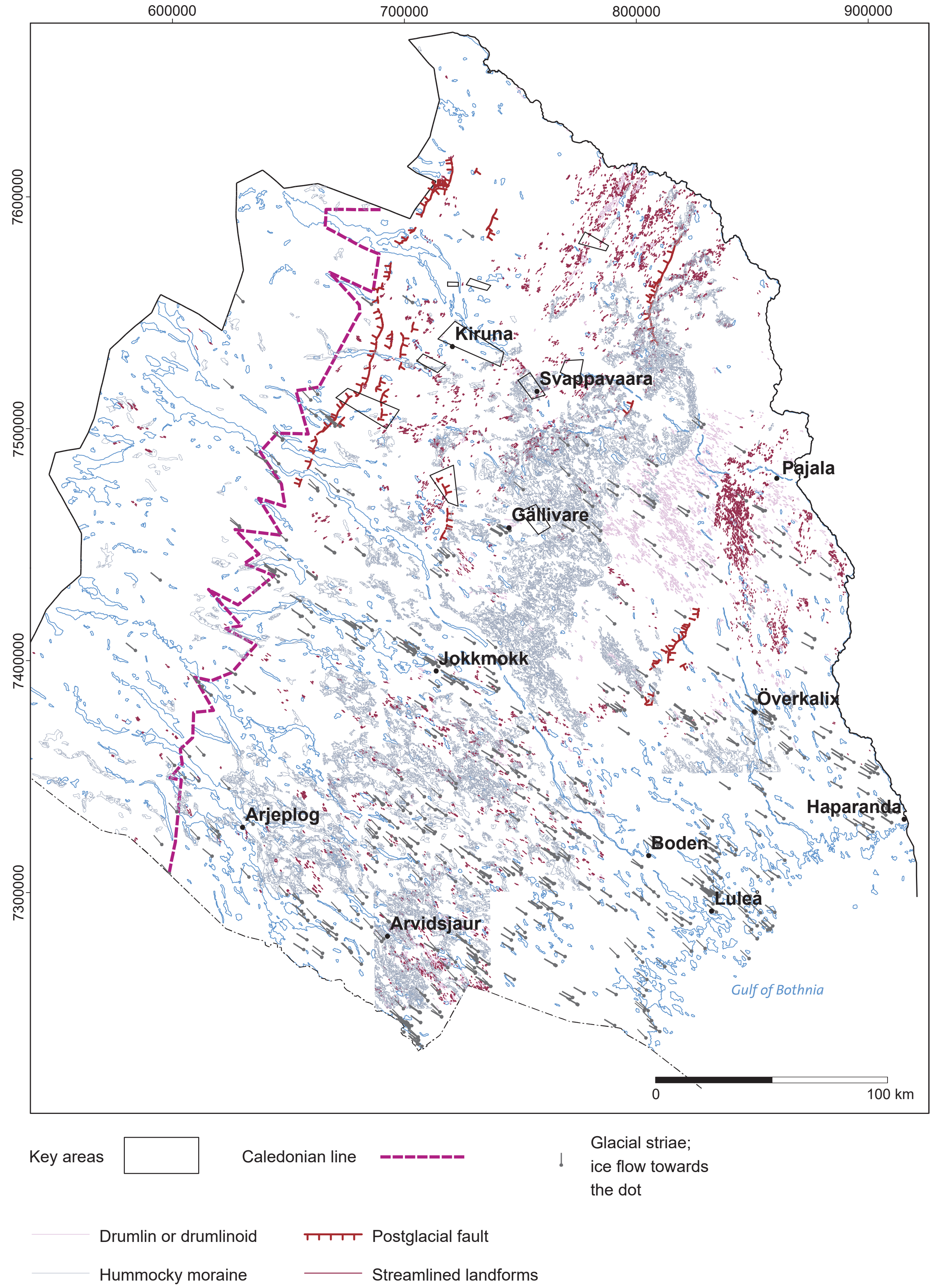


Figure 2. **B.** Major features of glacial and periglacial morphology of Northern Sweden (modified from SGU digital database).

observations should be viewed with caution. With that warning in place, an idealised stratigraphy in an excavated trench in northern Sweden may include the following units from the bottom up: saprolite, Saalian till, early Weichselian till, middle Weichselian till, and late Weichselian till. The till units are often, but not always, separated from each other by either organic or clastic water-lain sediments.

Following the retreat of the late Weichselian ice, water from the Gulf of Bothnia covered much of eastern Norrbotten due to depression of the crust caused by the mass of the ice sheet. Thick deposits of clay and silt were deposited over these submerged areas. Subsequently, the land surface rebounded, leading to a regional transgression. These large vertical displacements of the crust also contributed to reactivation of pre-existing faults immediately following deglaciation (Lagerbäck & Sundh 2008).

## SAMPLES AND METHODS

Since the 1980s, several sampling campaigns have been carried out both by SGU and exploration companies in Norrbotten County. This has resulted in relatively good coverage of geochemical data for the fine fraction (<0.06 mm) of till. The Nordkalott Project (1980–1986) delivered total concentrations for 11 elements analysed using optical emission spectrometry (OES) and 16 elements using neutron activation analysis (NAA). In addition, total concentrations of 25 elements in heavy mineral fractions (>2.96 g/cm$^3$, 0.06–0.5 mm) from till were obtained. In this chapter, we use chlorine results from that survey (Fig. 7). Field campaigns carried out by NSG/SGAB delivered results for 34 elements obtained by aqua regia extraction, but they only cover the western part of county.

### Sampling and preparation

As part of the Barents Project, 2 316 till samples were hand-dug from the C horizon at a depth of approximately 0.6–1.1 m. At this depth, till is generally not disturbed by intense weathering or anthropogenic activities (Fig. 3). The sampling grid varies, from a routine grid of 1 sample per 6.5 km$^2$ in areas with easy access, to 1 sample per 18 km$^2$ in remote areas sampled from a helicopter.

Figure 3. Typical sampling site of till C horizon in Norrbotten.

Sandy till predominates, especially in areas above the highest coastline, but till can vary from clayey to coarse-grained. Approximately 0.8 kg of sample was collected, vacuum dried (56 °C) and sieved with a nylon screen to a fine fraction of <63 µm.

### Chemical analyses

Two partial-leach methods have been used for the fine fraction of till (<63 µm): nitric acid leach (2 g of the till sample) and aqua regia leach (5g of the till sample). Both leachate types were analysed by ICP-MS at the SGU geochemical laboratory. Samples were analysed in random order to avoid systematic error. Duplicates and internal standards were used for quality control and to monitor instrument drift.

The nitric acid (7M $HNO_3$) method provides results for 52 elements: Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cu, Dy, Er, Eu, Fe, Ge, Gd, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Pr, Rb, Sc, Se, Sm, Sn, Sr, Tb, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn and Zr; the aqua regia method provides results for 13 elements: Ag, As, Au, Bi, Cd, Cu, Mo, Rh, Sb, Sn, Ta, Te and U. In practice, the aqua regia method is specifically designed for measuring Au, Rh, Sb, Ta and Te concentrations. More details of the methodology can be found in Morris & Ladenberger (2017). Depending on the type of leachate, element analysed and mineralogy of the sample, the efficiency of the leaching procedure varies from almost 100% (e.g. Cu, As, Cd) to <1% (e.g. Na, Zr).

Alkalinity (pH) was obtained from 4 grams of till sample (<63 µm), which was mixed with 20 ml deionised water (MilliQ®). After 48 hours, pH was determined by a Radiometer CDM83 electrode on a MeterLab® pHM240 system at SGU.

Combining various datasets often results in data quality and element levelling difficulties. Regional maps presented in this chapter should thus be treated as 'trend' maps, where the accurate element concentrations may vary due to the different analytical techniques used, or longer time-span between the series analysed.

## RESULTS AND DISCUSSION

### Regional distribution patterns in till

#### *Quaternary history of glaciations and deglaciations reflected in till geochemistry*

Although the major geochemical signature in till originates from the parent materials, there is a substantial influence on till chemical composition due to surficial processes such as till deposition, stratigraphy, age, till fraction, water activity and resulting sorting and transport with glacial meltwater, and other factors. The general spatial distribution of geochemical anomalies is controlled by ice movement directions and till transport distances. Ice directions have a rather complex pattern in northern Sweden, with prevailing ice flow from the west and southwest during the middle and late Weichselian and ice directions from the northwest during the early Weichselian. The major shift in ice directions is indicated by the ice divide observed in the central part of the project area. The NW–SE orientation of some geochemical anomalies (e.g. Ag, Cu, Na) in Norrbotten is consistent with predominant ice directions and the shape of glacial landforms such as eskers and drumlins.

Since ice in northern Sweden was frozen to the base for most of the time during glaciations, erosion-free conditions are assumed and the transport distances in most places are insignificant (Hättestrand & Stroeven 2002, Sohlenius et al. 2009, Lagerbäck 1988a). Along river valleys and postglacial lakes stretching from the Caledonian front in the west towards the Fennoscandian Shield in the east, till could have been transported further, however, and geochemical signatures in till can be influenced by material transported from the mountains.

During ice retreat and transgression of Baltic waters, submerged land and surface deposits were intensively reworked and till chemistry was modified. In southeast Norrbotten, where the deposition of clay and silt occurred, leaching of many elements resulted in depleted concentrations of Ag, Al, Ba, Be, Co, Cu, Fe, Mg, Mn, Na, Ni, P, Pb, REEs, Sr, Th, Ti, Y and Zn in exposed till, as well as some elements traditionally considered immobile, such as Ti and Y (Fig. 4). Additionally, development

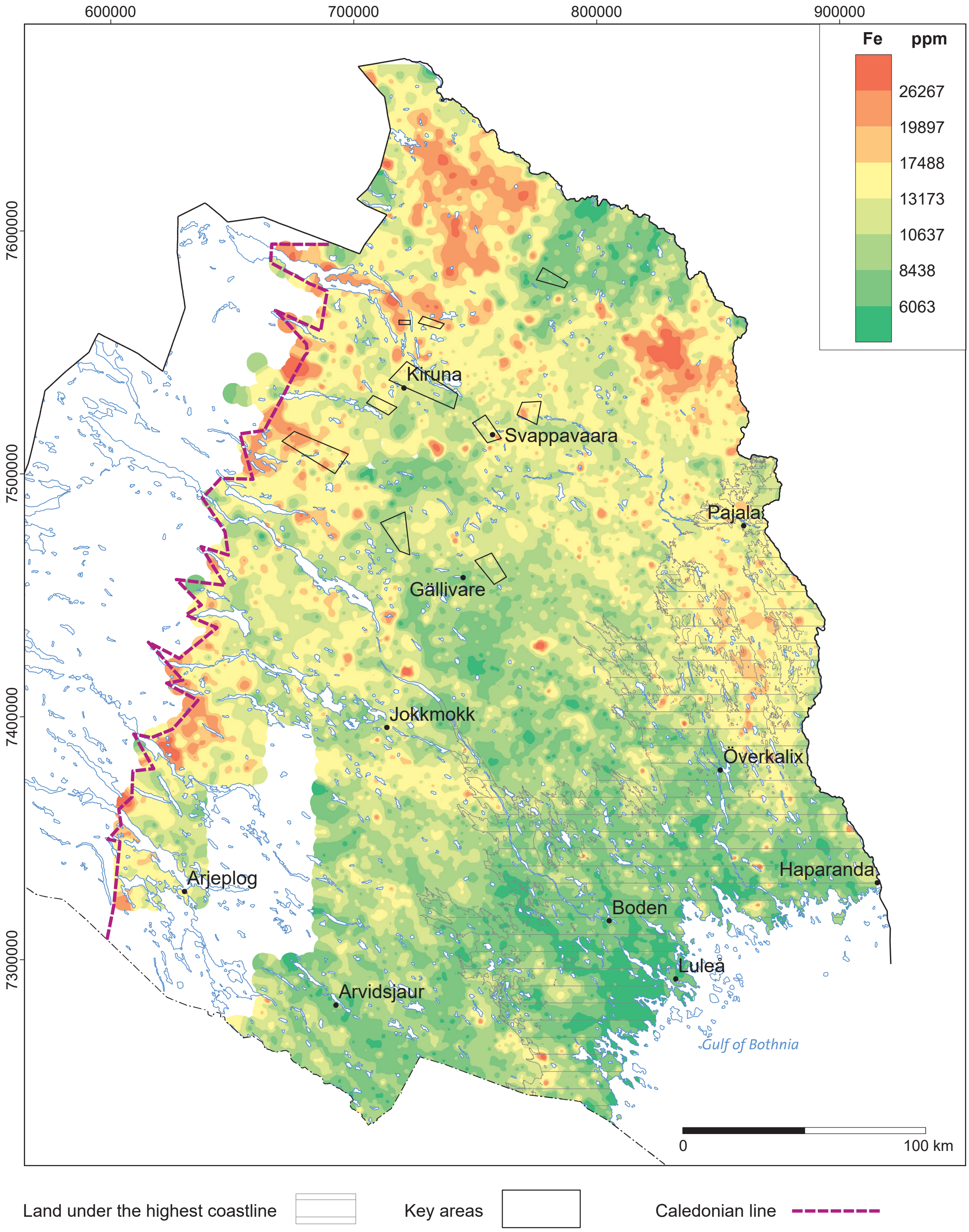


Figure 4. Fe in till ($HNO_3$ leach by ICP MS). The spatial distribution of Fe and several other elements reflects large morphological structures related to the Quaternary history of Norrbotten, e.g. leaching processes under the highest coastline.

of low pH (on average below 5) contributed to reduced concentrations of most metals (Ladenberger et al. 2014).

Similar depletion of many elements (Al, Ba, Be, Co, Cu, Fe, Li, Mg, Mn, Ni, Pb, REEs, Ti, Y and Zn) can be observed in NE Norrbotten (30 L map sheet Lannasvaara) within the "Kiruna fan" (Hätterstrand et al. 2004). The streamlined glacial landforms in this area date to the late Weichselian and indicate warm-based glacial conditions. The most viable explanation for the depletion of elements is intense glacial reworking of an older landscape, leading to removal and transport of elements (Fig. 4). On the SE side of the anomalous area lies the early Weichselian ablation till complex known as the Veiki moraine, and the associated end moraine known as the Lainio arc. The Lainio arc can be followed in the geochemical pattern of several elements, e.g. Ca and Na. The fact that Veiki moraine landforms have been preserved beneath at least two subsequent ice sheets confirms limited erosion and frozen-bed conditions in the area during the middle and late Weichselian. These conditions would limit reworking and transport of material from west to east.

Other areas with frozen-bed conditions and relict landforms (including drumlins and eskers transverse to the youngest ice flow direction) also experienced limited erosion beneath the late Weichselian ice sheet. For example, the geochemistry of till in the Pajala region was less affected than in areas of erosive wet-based conditions (Hätterstrand & Stroeven 2002).

To an extent, high or low metal content correlates with local pH (Fig. 5) and presence of organic matter (e.g. in peat regions). At low pH, elements like Cd, Co, Cu, Fe, Pb, Mg, Mn, Ni, P, Tl and Zn can be mobilised and redeposited to other depths or places, or released into ground and surface water.

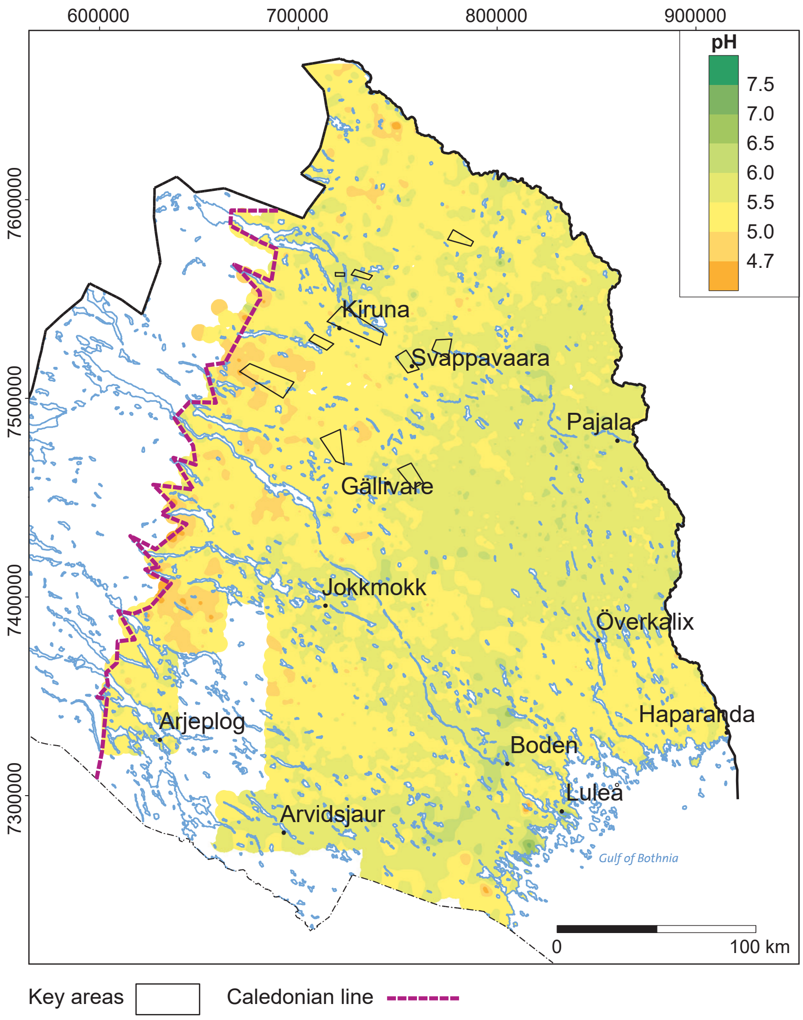


Figure 5. pH in till (source: Geochemical Atlas of Sweden).

### *Influence of underlying bedrock lithology, metamorphism and alteration of bedrock on till geochemical composition*

The type of the parent material has the greatest influence on the geochemical composition of till, which is commonly either older till or the underlying bedrock. In most cases, when the basal till is sampled, transport of till can be ignored. In Norrbotten, ice transport distances are generally short, but can be up to 5–10 km. This distance is estimated from block train counting, a method commonly used by exploration companies (Sohlenius et al. 2009). But the fine-grained fraction of till has been shown to have greater transport distances than pebbles (Klassen, 1999). The main advantage of till sampling in glaciated areas is the opportunity to obtain indirect information about the underlying bedrock, including regions without available outcrops, and covered by large peat bogs.

In the Barents Project study area the contrast between distribution of silica-rich (e.g. granitoids, pegmatites, rhyolites) and silica-poor magmatic rocks (e.g. gabbro, basalt, peridotite) can be easily observed (Fig. 6). Silica-rich intrusive rocks are usually a source of elevated concentrations of Al, Ba, Be, K, Na, Rb, REEs, U, Th and Zr in till, whereas silica-poor (mainly mafic) rocks give high concentrations of Mg, Ca, Co, Cr, Cu, Fe, Mg, Mn, Ni, Ti and V. Minor U and Th anomalies in till usually correspond to granites and pegmatites of the Haparanda and Lina types.

Till overlying metasedimentary rocks occurs in the west (by the Caledonian front, i.e. Stora Sjöfallet region) and in the east (south of Pajala) of the mapped area. This till has a similar chemical signature to till overlying granitic rocks. Occurrences of graphite-bearing metasedimentary rocks are reflected in till geochemistry by local anomalies of B, Co, Pb and V. The geochemical signature of volcanosedimentary complexes with intercalated sediments mainly comprises the volcanic members (e.g. Cr, Co, Ni, Mg, Fe, P, Ti, V) and the presence of limestone and dolomite (e.g. Ca, high pH).

In Norrbotten's till, concentrations of elements typically associated with felsic volcanic rocks (e.g. As, Bi, Cd, K, Mo, Pb, Rb, Sb, Se, Sn, Tl, W and Zr) are lower than the country's median values. However, a handful of elements (P, Ti and V) are enriched in till, their background values being the highest in Sweden (for comparison see Geochemical Atlas of Sweden by Andersson et al. 2014).

Archaean rocks, which are exposed in the northernmost part of the project area, tend to have a distinct geochemical signature in till as compared with the area with predominantly Palaeoproterozoic parent materials. Enrichment in Ba, Mn, Ni, Pb, Rb, Sr, Tl, LREEs and Zn, and depletion in Na, Zr, HREEs, U can be observed in the Archaean terrain, for example.

Till chemistry in the west and northwest of the area is influenced by material transported from the Caledonide mountain belt.

A notable characteristic feature of Norrbotten soil geochemistry is very high chlorine concentrations in till. This large Cl anomaly extends diagonally NW to SE across the area studied and correlates with a positive sodium anomaly. It overlaps with the extent of Palaeoproterozoic metavolcanic complexes (greenstone belts). Its origin has been attributed to the widespread scapolitisation of intrusive and supracrustal rocks belonging to the greenstone belts, such as the Kiruna Greenstone Belt. Scapolite is rare in the Archaean domain (Bergman et al. 2001). In general, alterations related to metamorphism and hydrothermal processes such as scapolitisation, albitisation, carbonatisation, and skarn formation can be reflected in enrichment in Ba, Ca, Cl, K, Na, Sr, La, Rb and P (Fig. 7). Such anomalies can occur locally (Ba, Sr, K, La, As) or regionally (P, Cl and Na), and often overlap with the location of known mineralisations (Ladenberger et al. 2012).

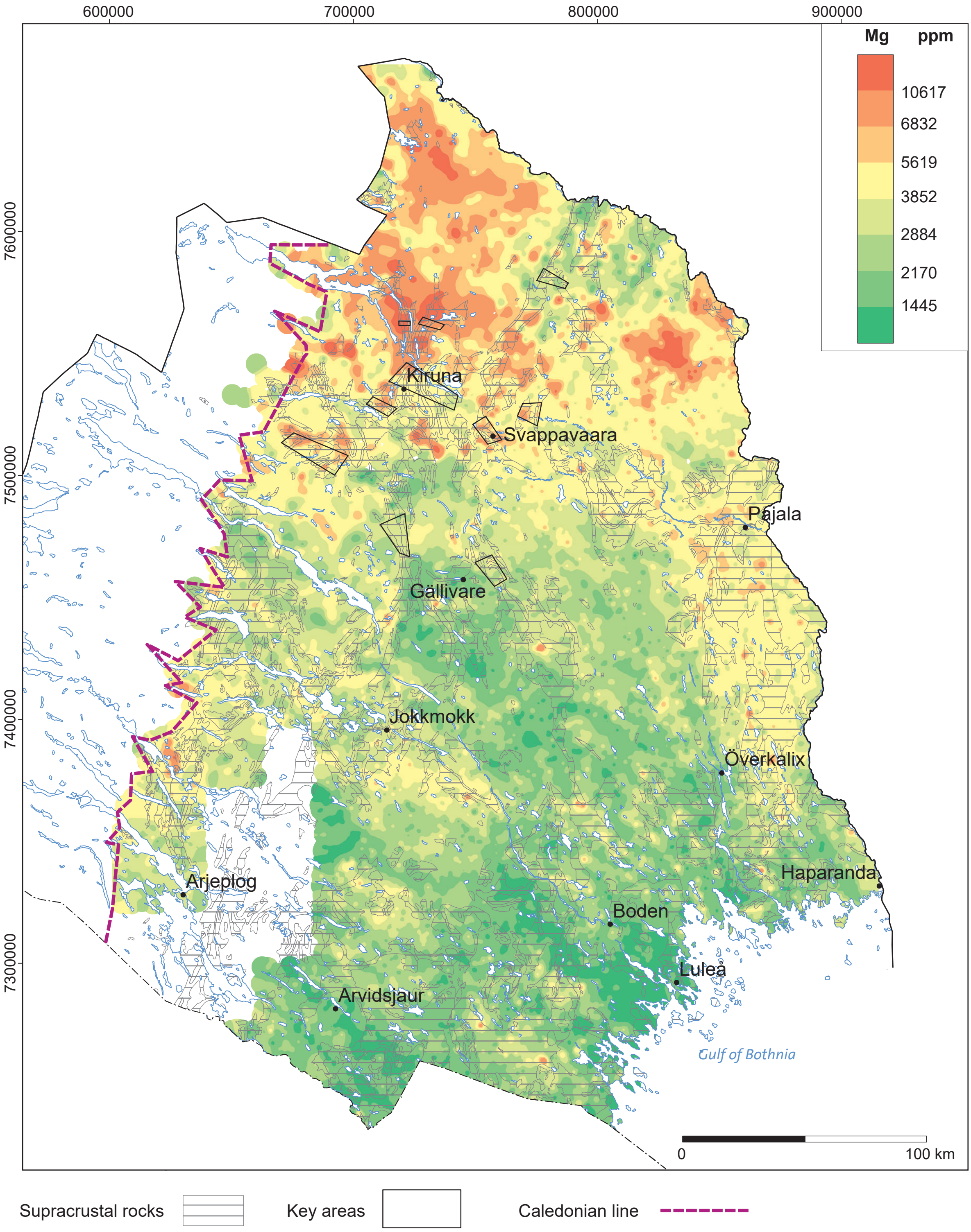


Figure 6. Major lithotectonic units reflected in Mg anomalies in till. Volcano-sedimentary units (greenstone belts) are clearly outlined by anomalously high concentrations of Fe, Ni, Co and Cu in till.

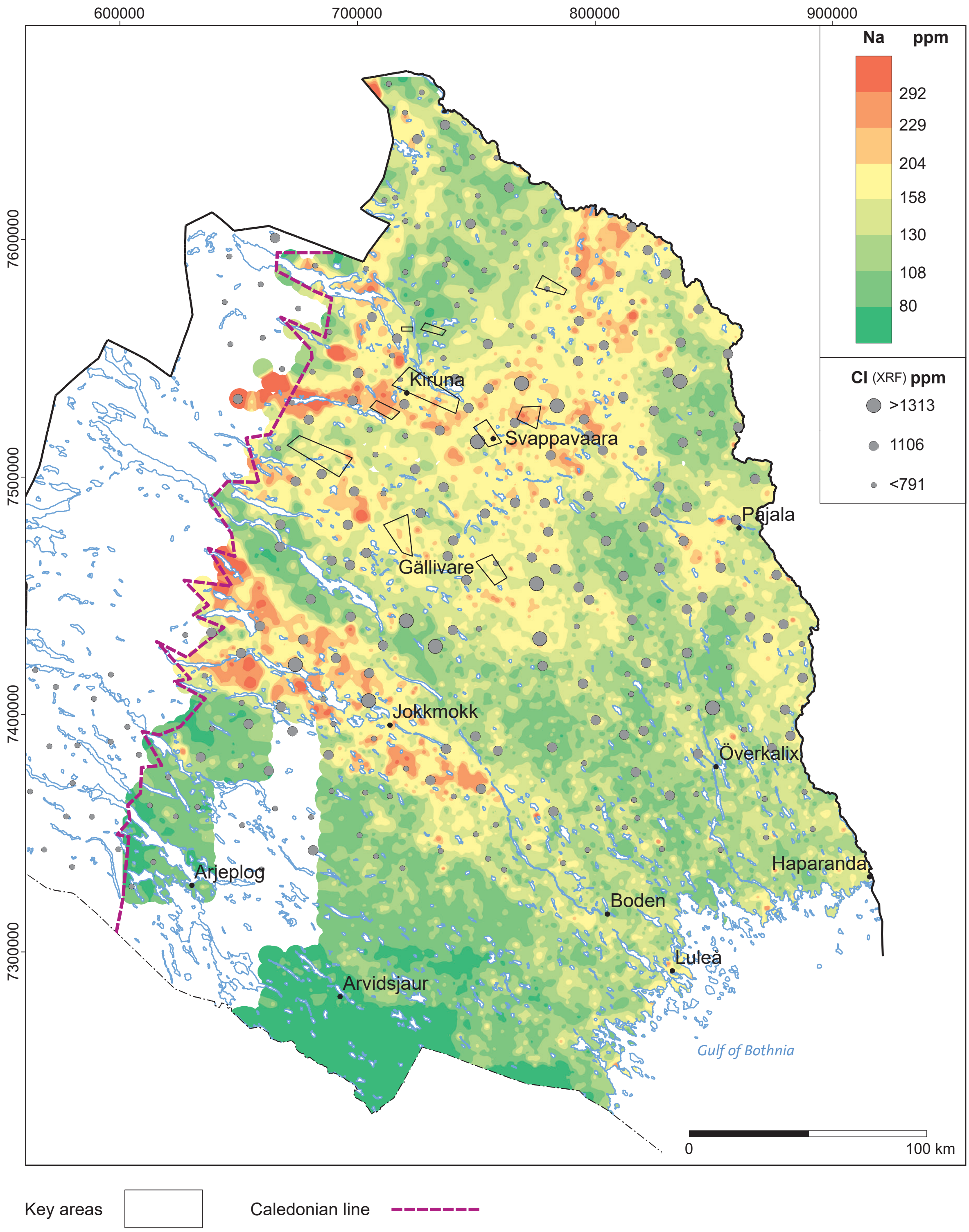


Figure 7. Na ($HNO_3$ leach by ICP MS) and Cl (XRF) anomalies reflect regional alteration zones with scapolitisation, which predominantly affects metavolcanic units.

### *Mineralisations and their impact on till geochemical anomalies*

The Barents Project study area is one of Sweden's major ore districts, with active iron mines at Kiruna and Malmberget, and a copper-silver-gold mine at Aitik. Apart from these active mines, there are many deposits that have previously been mined, and a large number of mineralisations are known in the region. Most of the mineral deposits are located within metavolcanic units of the greenstone belts and represent both iron-oxide type and sulphide deposits (Martinsson & Wanhainen 2013).

Major types of deposit are loosely classified as: iron oxide copper gold types (IOCG) e.g. iron formations, including typical Banded Iron Formation deposits (BIF, e.g. Törnefors); stratiform Cu-Fe deposits (e.g. Viscaria); Kiruna-type Fe oxide-apatite ores (e.g. Kiirunavaara, Malmberget); intrusion-related Cu-Au mineralisation (e.g. Aitik); and shear- or vein-style Cu-Au deposits (e.g. Nautanen). Some minor Mo occurrences are hosted by Archaean granites (Bergman et al. 2001).

Till geochemistry has been used in mineral exploration in glaciated areas for decades and has contributed to the discovery of many ore deposits of high economic value. Till sampling and analyses are cheaper and logistically less demanding than drilling. This methodology is therefore widely used in ore prospecting, mainly in the northern hemisphere, i.e. Scandinavia, Russia, Canada and Greenland.

Since the occurrence of major ore deposits is limited to areas with mafic to intermediate metavolcanic and volcanoclastic rocks, their locations overlap with large positive regional geochemical anomalies in till for elements such as Co, Cr, Fe, Mg, Ni, V and Ti (Fig. 8). Sulphide mineralisations often coincide with copper, cobalt, molybdenum and lead anomalies in till, the largest copper anomalies being between Kiruna and Vittangi, west of Pajala, and in the Tärendö–Svanstein area.

In central Norrbotten, natural concentrations of As, Ba, Pb, Co, Cu, Cr and V are locally higher than guideline values established for contaminated soil by the Swedish Environmental Protection Agency (Naturvårdsverket). The guideline values are exceeded naturally in, for example, Svappavaara (Ba, Co, Cu and Ni), Pahtohavare (Co, Cr, Cu and Ni), west and north of Kiruna (Co, Ni and Cu), northwest and north of Vittangi (Cu and Co), and in Poulalaki (As, Cu, Cr and V). All these anomalies are situated in the vicinity of known mineralisations. In Kitkiöjärvi and Pessinki concentrations of Ba, Co, Cu, Cr, Ni and V exceed guideline values but no mineralisations have so far been found at those locations.

The spatial distribution of metals associated with mafic magmatic rocks (Co, Cu, Fe, Ni, Ti and V), which constitute the main lithological units in greenstone formations, is as follows:

- The northern part of the study area has higher Co, Ni and Cu than the south, but Co-Cu-Ni enrichment also occurs along the Caledonian front.
- Co, Cu (+Ni) enrichment occurs in greenstone formations hosting numerous Fe-apatite mineralisations, occurring particularly in mafic, silica poor metavolcanic rocks, but also in skarn-type rocks, e.g. in the Kiruna area and in Archaean rocks.
- Co and Cu enrichment can be seen in Harrijärvi, Vittangivaara, Saarijärvi (near Pahtohavare Cu mineralisation), Svappavaara (Kiilavaara Cu-Zn-Pn deposit, Cu Gruvberget, Cu-Mo-Au Särkivaara), Nunasvaara (numerous Cu and Fe mineralisations) Tjårrojåkka–Makkak (near Cu mineralisation), Nautanen (northern part) and in the Akkiskera–Kuormakka key areas.
- Cu anomalies match known Cu mineralisations of various origin, e.g. Tjårrojåkka, Gruvberget, Kallosalmi, Saivo, Pahtohavare, Isovainio, Ferrum, Puolalaki, Tornefors near Tärendo, Marjajärvi near Pajala and Masugnsbyn.
- Ni has almost the same geochemical distribution as Co, with enrichment in greenstone belts with mafic rocks (e.g. gabbro, basalt, serpentinite and amphibolites), in the Archaean rocks in the north (correlates with Fe-oxide and Fe-sulphide mineralisations) and in the SW of the area studied along the Caledonian front. High Ni content in till often occurs in conjunction with Fe-oxide and Fe-sulphide mineralisations.

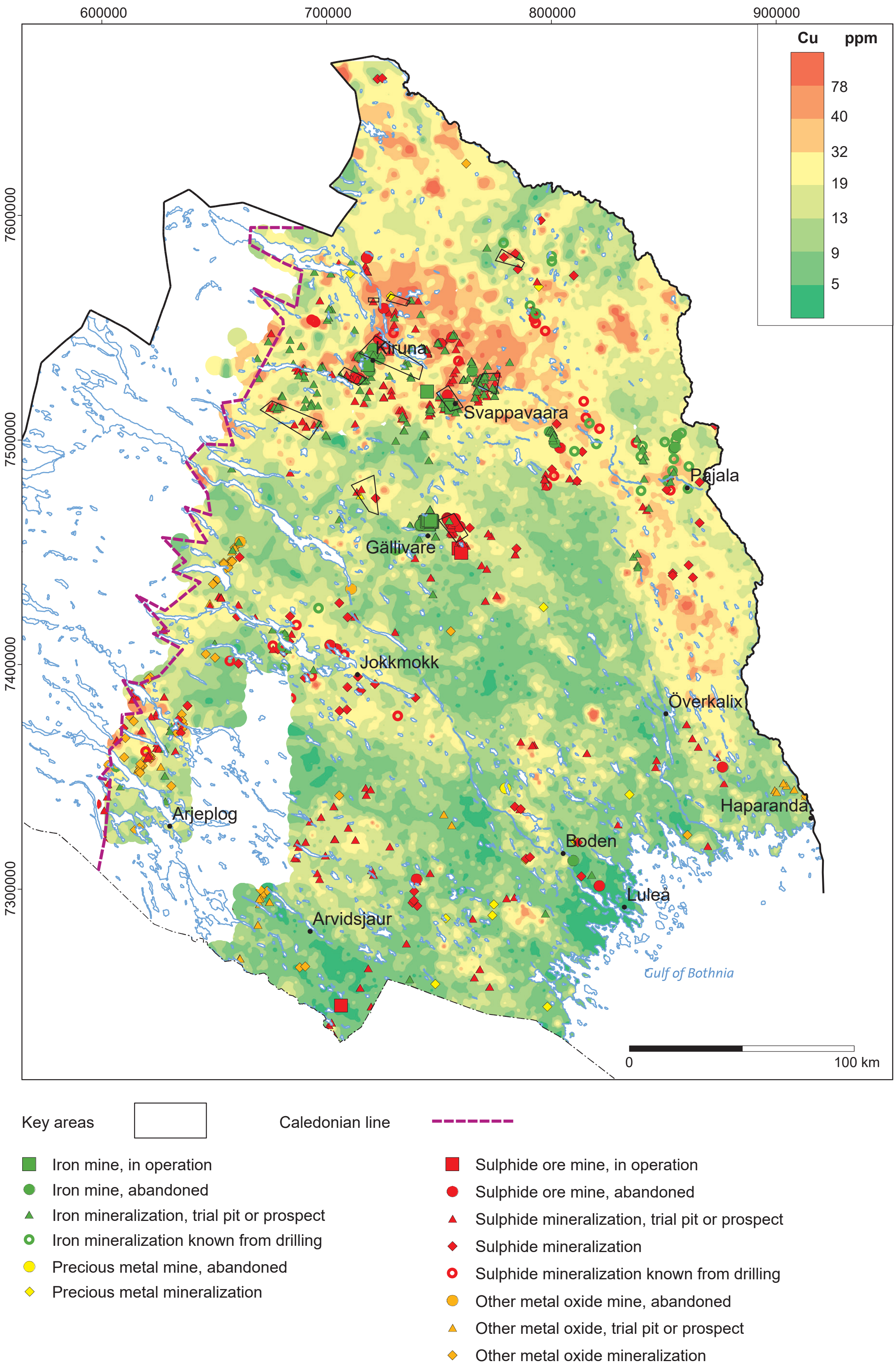


Figure 8. Example of regional trends in Cu ($HNO_3$ leach by ICP MS) in till pointing to major mineralisation zones in Norrbotten.

- The most prominent geochemical feature of apatite iron ore deposits is high P concentrations in overlying till.
- Ti and V are clearly enriched in Archaean rocks, in eastern and southeastern Norrbotten and in the southwest (NE part of the map sheet 26H – Jäkkvikk) by Lake Tjeggelvas.
- Ti concentrations in till are elevated in the following key areas: Harrijärvi, Tjårrojåkka–Makkak, Svappavaara and Nunasvaara, where there are known Ti mineralisations (with Fe-apatite-Ti-V mineralisations in intrusive alkaline rocks and mafic rocks)
- V content in till is high in Harrijärvi, Vittangivaara and Tjårrojåkka–Makkak key areas, and elevated concentrations occur in Svappavaara, Nunasvaara and the northern part of the Nautanen key area. A large and still unexplained Ti and V (and other metals; see text below) anomaly occurs in the NE (Lainio–Mounionalusta).

While elements characteristic of greenstone belts and related mineralisations in Norrbotten follow rather large-scale, regional trends, precious metals such as Au and Ag have a spatial outlier appearance and more local anomalies.

The geochemical distribution of gold may be summarised thus:

- Au concentrations in till are not particularly high in Norrbotten. However, several point anomalies with elevated contents can be related to known mineralisations, e.g. 5 km NE of Cu-Au Raggisvaara (north of Kiruna), 1.5 km east of Kovogruvan (Cu-Fe-Au), two anomalies east of Pahtohavare, and S of Kiruna in the vicinity of the Kallosalmi Au deposit, SW of Pajala in conjunction with known Au-sulphide mineralisations, within Harrijärvet and Vittangivaara key areas, approximately 20 km north of Övre Soppero (where a few small mineralisations containing Au are known), SW of Hakkas (accompanied by As and W anomalies) in the vicinity of the Puolalaki mineralisation with As, W, Cu and Au, approximately 12 km SE of Harrads (in the vicinity of Au anomalies in quartz veins and volcanic rocks, together with Cu, Sb, Bi, As and Ag).
- The highest Au concentrations in till occur on the map sheet 29 – Vittangi, with anomalies in the key areas studied, especially Svappavaara and Nunasavaara.
- Au anomalies commonly follow As, Cu, S, Sb and Bi anomalies west and southwest of Kiruna, southeast and northeast of Gällivare, and in the Svappavaara region.
- Examples of unexplained Au anomalies include two major Au anomalies by the border with Finland on map sheets 30L–30M (near the Saarikoskenvaara key area), and approximately 12 km SE of Junosuando, in Hakkas, 10 km SE of Nattavaara, NE of Gunnarsbyn.
- Many Au anomalies are interpreted as local, i.e. short transport by glacial drift along the main ice direction.

Ag enrichment in till correlates both with Au geochemical distribution and with the presence of sulphide mineralisations with Cu, Zn and Pb:

- Single Ag anomalies occurring within the Archaean unit in the northernmost part may be related to minor Au and Mo mineralisations.
- Examples where Ag anomalies correlate with sulphide mineralisations include Lieteksavo, Pårkajaure, Viscaria and Aitik.
- Elevated Ag concentrations in till occur in the following key areas: the Tjårrojåkka–Makkak key area (related to sulphide mineralisations with Cu, Mo, Au in andesite and quartz veins), the Kiruna and Saarijärvi key areas in conjunction with sulphide mineralisations with Cu and Au located SW and N of Kiruna.

- Silver enrichment in till occurs in the east of the project area, by the Finnish border between Kangos and Övertorneå.
- Generally higher Ag content in till occurs along the Caledonian front and along watercourses coming from the Caledonides (e.g. between Laisvall and Arjeplog, in the SW and S of the study area, the main source being felsic metavolcanic rocks and metasedimentary rocks with minor sulphide and noble metal mineralisations).
- High Ag content in till is observed south of Porjus, west of Arjeplog, west of Boden in the south of the study area, and towards the Caledonian front. Numerous precious metal and Cu-Zn-Pb (+W+As+U+Mo) sulphide mineralisations are spatially correlated with elevated or high Ag concentrations, e.g. approximately 7 km SE of Benbrytefors Cu-Au-Ag (between Vidsel and Moskosel, also accompanied by high Bi content in till).
- As and Bi anomalies often follow Ag anomalies in SW part of the study area.

As, Bi, Cd, Pb, Sb, Sn, Mo, U, W and Zn content in till is fairly low in Norrbotten, and localised anomalies with high concentrations of metals are usually associated with minor mineralisations.

High Bi concentrations occur along the Caledonian front, e.g. between Laisvall and Arjeplog, in the northern part of Stora Sjöfallet, in conjunction with the U mineralisations and Cu-Pb-Zn+Mo+Sn mineralisations in granite and metasedimentary and felsic metavolcanic rocks. Relatively high concentrations are present in the south of the study area, e.g. S of Alvsbyn, where there are known Au-Cu-As mineralisations in schist and granite, SE of Puolalaki sulphide (Cu-Zn, Ag-Pb-Zn with As-W-Au) deposit (approximately 40 km SE of Gällivare), approximately 12 km E of Niemisel (in the vicinity of the Hällkölen Sb-Bi-As-Au prospect). In Harrijärvet and Vitangivaara key area (N of Kiruna), elevated Bi concentrations in till occur in association with Cu mineralisations in quartz veins; vein and skarn Cu-Zn-Pb mineralisations occur in the Svappavaara key area (e.g. Kiilavaara), in the Nautanen key area, and Bi anomalies east of Aitik are associated with sulphide mineralisations (Cu-Au).

Molybdenum mineralisations have been reported from several localities in the area studied and molybdenum till anomalies, together with Ni, Co, Cu, Ag and Au, are often related to these mineralisations. A few Mo outliers occur near the Caledonian front (e.g. Stora Sjöfallet area, Kvikkjokk region), and NW of Boden, related to Cu (Ag+Au+Mo) deposits.

Pb outliers occur in Archaean rocks (but lack correlation to known Zn-Pb deposits) as well as in the Palaeoproterozoic rocks of the Masugnsbyn key area (approximately 5 km east of several Cu-sulphide mineralisations). Elevated Pb values occur along the Caledonian front (in the Caledonides Zn-Pb mineralisations are more common than in the Fennoscandian Shield), within the Stora Sjöfallet formation and in the SW corner of the study area, where numerous Pb-Zn+Ag mineralisations are known, mainly within the Caledonian autochthon (e.g. Laisvall, Maiva). The more prominent Pb (and Sb) anomaly in till stretches from the Caledonian front by the Laisvall Zn-Pb deposits towards the SE in the Arvidsjaur region.

The distribution pattern for Zn is similar to that of Pb, with higher concentrations in till overlying Archaean rocks in the north, enrichment in metavolcanic rocks and skarn-hosting sulphide mineralisations (Pb, Cu, Au, Ag, Mo) along the Caledonian front (east of Laisvall) and in the SW of the study area (e.g. southern part of Stora Sjöfallet). A regional-scale Zn anomaly (accompanied by Sb) stretches from Stora Sjöfallet southeast via Jokkmokk to Boden, with an outlier (343 ppm) near the Ravejaure Cu-Mo-Sn-Ti mineralisation, approximately 30 km east of Kvikkjokk. The maximum Zn concentration (1 384 ppm) has been found in the NW of the study area, approximately 30 km NW of Kiruna by lake Rensjön, near a Pb-Zn-Cu-Ag mineralisation hosted by metavolcanic and volcanoclastic rocks. Numerous Zn anomalies are found in northern part of the studied region. These correlate well with several known Zn mineralisations such as Viscaria, west of Kiruna. A single Zn outlier near Hournaisenvuoma is located near a Zn-Pb-Ag deposit enriched in Mn and Ba.

Low Sn concentrations in till dominate in the northern part of the study area. Elevated Sn concentrations occur in the SW (Jäkkvik–Jokkmokk–Arjeplog–Arvidsjaur), where they correlate with known Mo and U mineralisations in granite, felsic metavolcanic rocks and quartz veins.

Although U content in till is low, a number of exceptions exist. Elevated U concentrations can be observed between Kvikkjokk and Jokkmokk in the SW of the area, with an outlier located 5 km south of the known U mineralisation, approximately 30 km S of Kvikkjokk in the Lower Allochthon of the Swedish Caledonides. Minor uranium and thorium (together with REEs) anomalies occur south of Svappavaara (Leveäniemi). Two other uranium mineralisations are known in this area: Äijärova (together with copper and molybdenum) and Meutesvare (together with copper).

Certain local geochemical anomalies in till can be directly linked to known ore fields and mineralisations, for example:

1. In the **Kiruna area,** Cu, Co, Fe, P, REEs, Au, and V anomalies correlate with iron formations (Fe-apatite), stratiform sulphide deposits (Cu) and epigenetic sulphide deposits (Cu), e.g. Kiirunavaara, Lappmalmen, Nukutus, Henry, Rektorn, Haukivaara, Luossavaara, Pahtohavare. Na, Cl, K, Fe, Al, Ca anomalies can be related to alterations such as scapolitisation, albitisation, formation of actinolite, K-feldspar, chlorite, sericite, and carbonate. Locally, till overlying metal deposits influenced by metasomatic processes has elevated concentrations of alkaline elements (Ba and Rb) and point anomalies of metals such as As, Au, Bi, Sb, W, Tl and Sn, e.g. in till overlying the Lower Hauki series with apatite-iron deposits located north of Kiruna.
2. In the Gällivare area (Aitik and Nautanen Cu ores, Malmberget Fe-apatite ore), the best-defined anomalies in till occur north of the Nautanen ore field (Cu-Fe+Au + Ag mineralisations). Elevated concentrations of Ba, Na, Mn, Ca, Rb and K reflect the main type of alterations (scapolite, microcline, biotite, sericite, garnet, amphibole, epidote and tourmaline). Notably, neither the Aitik Cu ore nor the Malmberget apatite-Fe oxide ore is visible in the geochemical signature of local till. The most significant anomaly related to Aitik, for Bi, occurs approximately 5 km east. Elevated palladium and tellurium concentrations (obtained in an earlier survey, presented in the NSG database, occur in till in the Gällivare area and are related to the Dundret gabbro intrusion, southwest of Gällivare.
3. The **Svappavaara** and **Vittangi** areas are known for one of the largest former copper mines in Norrbotten (apatite-Fe ore and Cu deposits; e.g. Gruvberget). Till anomalies of Al, Au, Bi, Co, Cr, Cu, Fe, K, Na, Ni, P, V, and REEs can be observed here, and they are directly related to the type of local deposits whereas Al, Ca, K, and Na anomalies are explained by the types of alteration (e.g. scapolite, albite, biotite, sericite, K-feldspar).
4. In the **Pajala area,** various iron ore deposits (BIF deposits, Fe sulphides, skarn iron ore) occur, particularly north of Pajala (e.g. Tapuli skarn Fe deposits, Stora Sahavaara Fe deposit). The following geochemical anomalies have been observed in this region: Ag, Au, Co and Cu. The local alteration signature is characterised by low Na, Ba, Ca and Sr content in till.
5. The Masugnsbyn area (including the Masugnsbyn key area) is well known for its Fe ore skarn deposits such as Magnetgruvan (BIF and skarn Fe ore with magnetite), but no prominent geochemical anomalies in till have been observed in the immediate vicinity of these ore fields. The only distinct geochemical anomaly for several metals (Ag, Co, Cr, Ni, Fe, Pb, Zn) occurs in the central–western part of the Masugnsbyn key area, in conjuction to Zn, Pb and Cu mineralisation at Kurkkionvaara.

Several other unexplained anomalies can be found within the dataset, e.g. in the NE of the study area (map sheet 30M+SE of 30L+ NW 29M) many metals, such as Ni, Co, Cu, Au, Cr, Fe, P, Pb, Ti, V, and Zn, show high concentrations in till, but no mineralisations are documented in the area (Fig. 9).

The element association may imply the existence of another iron oxide-apatite deposit (with V and Ti), with associated sulphides, potentially located in an unexposed volcano-sedimentary unit.

It is notable that concentrations of elements typically associated with felsic volcanic rocks (e.g. As, Bi, Cd, K, Mo, Pb, Rb, Sb, Se, Sn, Tl, W and Zr) are low in Norrbotten's till. This contrasts with till located to the south, in the Skellefte Mining District of Västerbotten, where felsic volcanic rocks are the main host rock for sulphide deposits and a source of major metal anomalies in the till.

The southeast of the study area is almost devoid of metal anomalies. This is interpreted to result from lacustrine/marine inundation and glacial meltwater activity during deglaciation. Several mineral deposits in this area (e.g. Ni-Cu-Co-bearing layered intrusion at Notträsk) are not outlined by geochemical anomalies. This is more likely an effect of post-depositional leaching processes under relatively low pH conditions (Ladenberger et al. 2016).

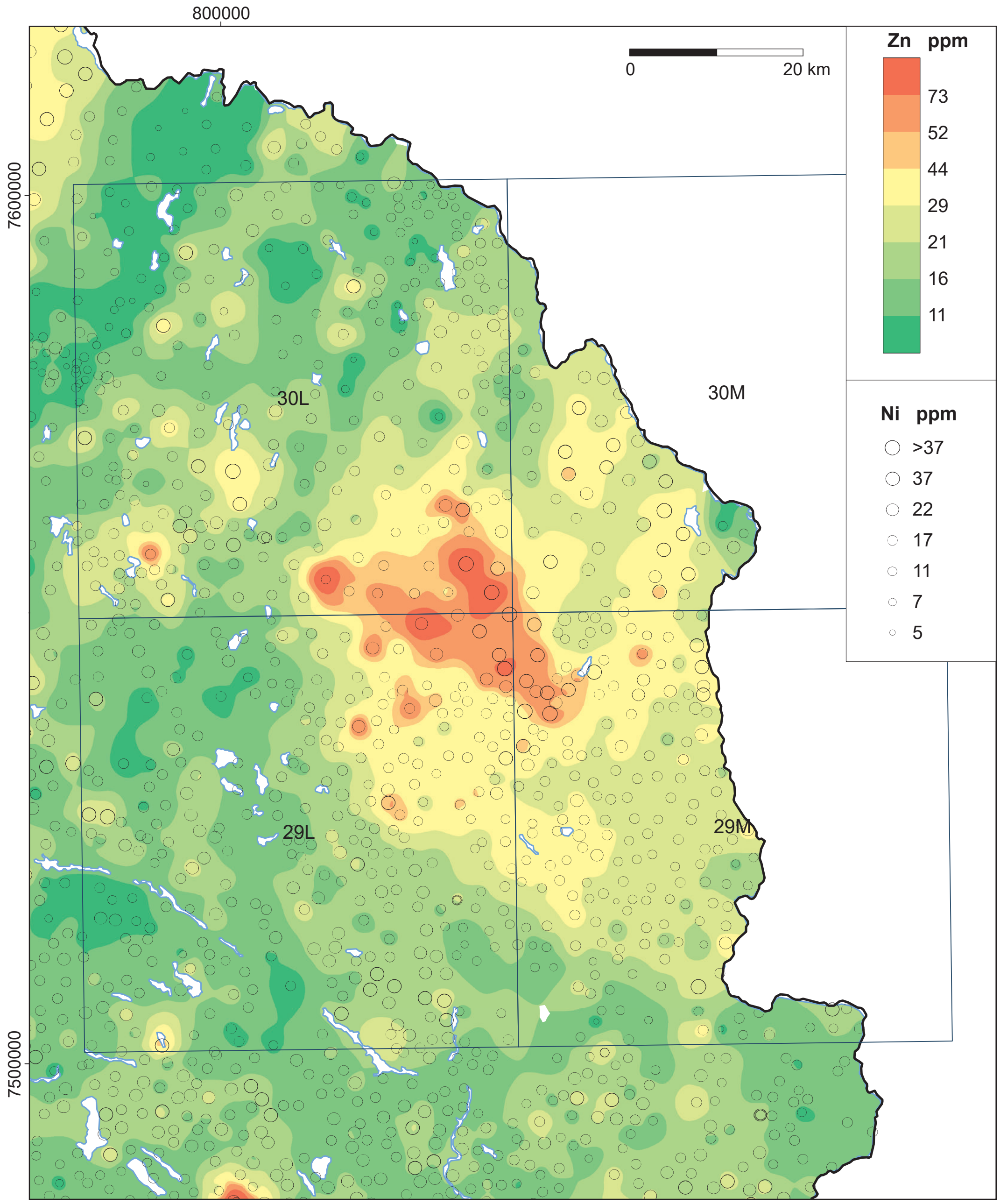


Figure 9. Zn (raster map as a background) and Ni (as dots) anomalies ($HNO_3$ leach by ICP MS) in the NE of the study area (map sheets 30L, 30M, 29L and 29M). Method: $HNO_3$ leach by ICP MS.

## Till geochemistry in the key areas

Key areas described in this volume have been chosen under the Barents Project for detailed geological investigations, mainly in relation to their mineral potential and previous history of mineral exploration (Grigull & Antal Lundin 2013, Luth & Antal Lundin 2013, Luth & Berggren 2013, Lynch & Berggren 2013, Lynch & Jönberger 2013a,b, Lynch et al. 2014). Geochemical sampling followed geological mapping and geophysical surveys in ten key areas in order to better understand local geological history in relation to ore-forming processes and Quaternary development.

Sampling of till (194 samples in total) was carried out in 2012 and 2013 in the following regions: Tjårrojåkka–Makkak, Saarijärvi, Kiruna–Jukkasjärvi, Harrijärvet, Vittangivaara, Akkiskera–Kuormakka, Nunasvaara, Nautanen, Allavaara and in Svappavaara (Fig. 1). Additional samples in the key areas originate from earlier geochemical surveys (2000–2007) reported in Ladenberger et al. (2012).

Among collected till, cover moraine predominates, but approximately 20% of samples were collected from hummocky moraine. Till parent material originates from various lithologies, which are reflected in the geochemical composition of till and median values for several elements are generally higher in key areas than for the Barents dataset as a whole (e.g. Au, Ca, Co, Cr, Cu, Mg, Na, Ni, P, Rh, Te, Ti and V) (Figs. 10 and 11).

### *Tjårrojåkka–Makkak*

The geology of this key area is described in Lynch & Berggren (2013) and in Lynch et al. (2014). The Tjårrojåkka–Makkak area is located approximately 50 km SW of Kiruna, and was chosen for detailed study mainly due to the apatite-iron (Täunatjåkka, Kuosatjvare), copper (-gold), and molybdenum (e.g. Tjårrojåkka, Hannåive) deposits, which are well documented by numerous drill cores. Local geology is predominantly represented by metamorphosed volcanic rocks (basalt, andesite, rhyolite), with minor occurrences of metasedimentary rocks (phyllite) and intrusive rocks such as gabbro, diorite, monzonite, syenite and granitoid. Most of the mineralisations are hosted in the metavolcanic units. Fe-oxide mineralisation usually occurs as banded or disseminations with magnetite, hematite and apatite as ore minerals, whereas Cu mineralisations occur as quartz veins and disseminations, with chalcopyrite and bornite as major Cu-bearing phases. Hydrothermal alterations have mainly affected metavolcanic units, with scapolitisation and epidotisation on a regional scale and local formation of sericite, tourmaline, epidote, albite, K-feldspar, hematite and carbonate.

38 till samples were collected in this area and have medium-high to high concentrations of Ag, B, Ba, Be, Li, Nb, REE, Sb, U and Zn. One of the highest silver, cobalt and Eu concentrations in till was found in the NW of the area. Elevated concentrations of Cu, Ag, Mo, Pb, Sb and Zn in the NW and SE are spatially related to known mineralisations. No Au anomalies in till have been noted in the vicinity of Cu-Au mineralisations, however. High concentrations of Ba, Be, Rb and Sr can be explained by the presence of hydrothermal alterations. The general trend for the bedrock to become increasingly felsic towards the east is reflected well in the till geochemistry, e.g. by decreasing concentrations of elements typical of mafic rocks, such as Co, Cr, Al, Fe, Mg, Mn, Ni, Sc, Ti, and V, from west to east. Elevated content of Be, Nb, Ta, Th, Y and REEs correlates well with outcrops of felsic metavolcanic rocks (andesite, rhyolite) and numerous quartz veins locally containing tourmaline.

### *Saarijärvi*

The geology of this key area is described in Lynch & Jönberger (2013a) and Lynch et al. (2014). The major rock units belong to the volcanic rocks of the Kiruna greenstone group, of predominantly basalt-andesite composition, and the overlying porphyry group. Minor metasedimentary horizons (e.g. conglomerate, schist, phyllite, marble) occur within the various volcanic sequences (e.g. Kurravaara conglomerate). Intrusive rocks are represented by variably metamorphosed syenitoid and gabbroid types, minor doleritic, granitic and syenitic dykes. Outcropping rocks show varying degrees of hydrothermal alteration, with scapolitisation-epidotisation in metavolcanic rocks and potassic metasomatosis in alkaline intrusive rocks and metasediments. There are several mineralisations in the area, hosted exclusively by metavolcanics, with significant Fe-oxide (magnetite ± apatite), Cu-Fe sulphides (chalcopyrite, pyrrhotite, bornite) and minor gold (native Au, auriferous Cu–Fe sulphides, auriferous tellurides) mineralisations, e.g. Pahtohavare, Rakkurijärvi, Saarijärvi, Pitkäjärvi and Puoltsa.

20 new till samples have been collected in this area and used, along with six samples from a previous campaign. Elevated concentrations of Be, Ca, Cr, Ge, Na, P, Sc, Y and REE have been noted. REE content in till is among the highest obtained for all key areas studied. Single Cu anomalies correlate well with known Cu mineralisations.

### *Kiruna–Jukkasjärvi*

The geology of this key area is described in Grigull & Antal Lundin (2013). The region belongs to the Kiruna mining district, with numerous mineralisations, including apatite-iron ores (e.g. Nukutus, Lappmalmen, Rektorn, Haukivaara, Luossavaara) and Cu sulphide ores (Viscaria type), and small precious metal deposits such as Au (e.g. Kallosalmi). The majority of mineral deposits occur in the west of the key area. The lithology predominantly comprises metavolcanic rocks with mafic to felsic compositions and associated metasediments, such as metasandstone, quartzite, conglomerate, phyllite, schist (locally with graphite) and dolomite. Plutonic rocks include gabbroid, tonalite, monzonite, granodiorite and granitoid. The prevailing alteration type is scapolitisation, epidotisation and albitisation. A detailed description of hydrothermal alterations in relation to mineralisation and till geochemistry can be found in Ladenberger et al. (2012).

Nine new till samples were collected in 2013. These complemented 42 existing samples from previous campaigns (Ladenberger et al. 2012). Elevated concentrations of several elements have been noted, particularly in the NW of the area, for example Co, Cu, Na, P and V. A signature typical of mafic lithologies (Co, Cr, Fe, Mg, Mn, Ni, Sc, Ti, V, Zn) prevails in the western part of the area, where the majority of mineralisations are located. Generally, high Na content in till can be interpreted as an indication of regional scapolitisation and albitisation, which affect metavolcanic rocks.

### *Harrijärvet*

The geology of this key area is described in detail in Luth & Antal Lundin (2013) and Luth et al. (2014). Most of the area is underlain by mafic to intermediate rocks forming metavolcanic units, mainly of the Kovo group and Kiruna greenstone group. In the west, Archaean gneisses (tonalite-granodiorite) are overlain by metaconglomerate (composed of granite and quartzite pebbles) and metasandstone. In the east, a belt of dolomite stretches N–S as a horizon within the metavolcanic sequence. Ultramafic metavolcanite (komatiite) crops out in the NE corner of the key area. The main prospect is a Cu mineralisation (Harri), with chalcopyrite, pyrite and cubanite hosted by the metavolcanic complex in the central part of the key area.

Five till samples have been collected in the Harrijärvet key area. Elevated concentrations of Al, Au, Ba, Ca, Co, Cr, Fe, Ge, K, Mg, Mn, Ni, P, Rb, Sc and Ti, V have been observed, with concentrations generally decreasing eastwards. A single anomalous sample with high Te (144 ppb) and Bi concentrations was collected in the northeast of the area, which predominantly comprises mafic metavolcanic rock units (basalt-andesite and komatiite). Relatively high pH (>6) was encountered in this area.

### *Vittangivaara*

The geology of this key area is presented in detail in Luth & Antal Lundin (2013). Most outcropping lithologies are volcanosedimentary sequences of basaltic and andesitic composition, intercalated with metaarenite and dolomite. A sulphide deposit, with pyrite, pyrhhotite and chalcopyrite associated with skarn, occurs in the NE of the area. Locally, iron oxide mineralisations (ilmenite, hematite, goethite) occur within an altered tuff. In the NE, a small vein mineralisation with Au in association with Fe oxide occurs in abrecciated granite.

20 till samples have been collected in the Vittangivaara key area, and they show elevated or high concentrations of several elements, including Ag, Au, Ba, Bi, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Ni, Pb, Rb, REE, Te, Ti, Tl, V and Zn. The prevailing geochemical signature is typical of mafic lithologies (Co, Cr, Ni, Fe, Mg). There is no great difference between the geochemical composition of till overlying metavolcanic, mainly mafic rocks and till overlying metasedimentary rocks. Elevated content of Rb, K and Ba may indicate the presence of secondary alterations. Local occurrences of dolomite and marble (near Kåvvojaure) contribute to local basic pH values (>7).

### *Akkiskera–Kuormakka*

The geology of this key area has previously been summarised in Luth & Berggren (2013). The Akkiskera–Kuormakka region is the northernmost area studied under the Barents Project. Apart from mineralised blocks and boulders found in the northwest of the area, there are only three known outcrop-scale deposits, which are in fact located just outside the key area itself (Cu and Au Luspavaara deposit in a quartz vein cutting basalt, the Juoluvaaranjärvi Fe deposit in skarn, and Kuormakka, a sulphide prospect within silicified greenstones, with Cu, Au, Ag, S and Zn). A significant feature in the west of this area is the NE–SW trending Karesuando–Arjeplog deformation zone (KADZ). The geology is dominated by the Kiruna greenstone group (KGG) with mafic volcanic rocks (basalt) and a thin series of clastic metasediments consisting of mica- and feldspar-rich quartzite and conglomerate of the Tjärro Quartzite group resting on the Archaean basement in the west. In addition, zones and veins of ankerite-albite rich rocks are often bounded by faults. Carbonate-rich horizons with skarn, graphite-bearing schists and tuffitic layers occur in the easternmost part of the key area. The Archaean basement and the supracrustal rocks are intruded by granite and gabbro belonging predominantly to the Haparanda suite. Mafic and ultramafic rocks have been the subject of mineral exploration for Ni and Cr.

20 new till samples were collected in 2012 and 2013. Apart from generally elevated Au, Cr, Sr, P, Na and Ca concentrations, and single anomalies (e.g. Cu with 195 ppm in the NW), no major element anomalies have been observed in this region.

### *Nunasvaara*

Details of the geology of Nunasvaara are provided in Lynch & Jönberger (2013b) and Lynch et al. (2014). The geology predominantly comprises volcanosedimentary units of the Vittangi greenstone group, with mainly mafic volcanic and plutonic rocks, intercalated with metasedimentary units represented by quartzite, graphite-bearing schist, marble and related skarn. The main alteration types are scapotilisation, carbonitisation and albitisation of mafic rocks, with local presence of tourmaline and epidote. Several mineralisation types occur in the area, including schist-hosted graphite deposits (Nunasvaara), banded iron oxide mineralisations in skarn and copper mineralisation (e.g. Tievakoski). South of the key area itself, mineralisations with uranium, molybdenum, cobalt and gold are known.

12 new till samples have been collected in this key area, complementing eight till samples from a previous campaign. Elevated and locally high element concentrations are seen for Au, Co, Cr, Cu, Ni, P, Rh, V, Ti and Te. These present a typical geochemical signature related to the presence of mafic rocks and graphite-rich metasediments (especially in the west of the key area). In general, higher ab-

solute element concentrations occur in the west and SW than in the east. High Na content in till is related to regional scapolitisation of metavolcanic rocks and correlates with high Cl content (XRF method) in till obtained during previous campaigns (2002–2003). High Ca content correlates with high pH values and is related to local occurrences of carbonates and skarn (calc-silicate rocks).

### *Nautanen*

The geology of the Nautanen key area is described in detail in Lynch & Jönberger (2014a) and in Lynch et al. (2015). The geology predominantly consists of Palaeoproterozoic metavolcanic (basalt, andesite, tuff) and metasedimentary (metaarenite, marble, skarn, phyllite, schist) rocks metamorphosed during the Svecokarelian orogeny (c. 1.9–1.8 Ga). Subordinate Palaeoproterozoic intrusive rocks of gabbroic, dioritic and granitic composition occur at the periphery. The area was influenced by intense hydrothermal alteration, including scapolitisation, sericitisation, potassic alteration, and the formation of tourmaline, apatite, magnetite, amphibole, garnet and epidote. The rocks at Nautanen are situated within the brittle–ductile Nautanen deformation zone. Numerous sulphide deposits with Cu, Au, Fe, Ag (Nautanen, Liikavare, Fridhem, Ferrum, Snålkok) and Pb (Muorjevaara) occur along the deformation zone, particularly in the north. Copper-gold prospects from the Nautanen area are thought to have a genetic affinity to the broad iron oxide-copper-gold (IOCG) family of hydrothermal mineral deposits. Chalcopyrite and bornite are the commonest ore minerals, associated with minor magnetite, sphalerite, galena, molybdenite and scheelite. Numerous mineralised boulders are seen in the area, which may have influenced the general composition of till.

Ten new till samples were collected in the Nautanen key area (together with 14 samples from an earlier survey; Ladenberger et al. 2012). These show elevated concentrations of Ag, As, B, Ba, Li, P, REEs, Sb, Ta, Th, U and W. Single Au (up to 9 ppb Au) and Bi (+Co, Cr, Cu, Fe, Li, Rb, Sc, Te, Ti, Tl and Zn) anomalies have been observed in the NE part, 1.5 km west of an Au-Pb mineralisation drilled at Muorjevaara, and north of several Cu-Au mineralisations, all hosted by a quartz vein. The till geochemical signature of the key area accords well with the mineralisation types and related alterations along the Nautanen deformation zone.

### *Allavaara*

The geology of the Allavaara area is described in Lynch & Jönberger (2014b), and is predominantly made up of Palaeoproterozoic metavolcanic (basaltic andesite, andesite, dacite, rhyolite, and rare komatiite) and metasedimentary (skarn and carbonate) rocks, with minor monzonitic and granitic intrusives. The key area is cut by a broad, mainly ductile deformation zone trending N-NW–S-SE. The major types of hydrothermal alterations are sericitisation, saussuritisation and chloritisation.

Known mineralisations in the area include Cu, Au, Ag and Pt vein-type with azurite, bornite, chalcopyrite and malachite at Fjällåsen, hosted by metavolcanic rocks, and minor veins with Cu (e.g. Risbäck).

36 till samples were collected during surveys in 2012 and 2013. Apart from elevated concentrations of Ca, Cu, Na, P, REEs, Se, Sr, Ti and V, no significant element anomalies are noted in this area. A single till sample located only 1.5 km west of the Risbäck Cu mineralised vein (in the central part of the key area) has slightly anomalous W (1.6 ppm), Cu, Ce, Sb concentrations.

### *Svappavaara*

The detailed geology of the Svappavaara key area is described in Grigull & Jönberger (2013). Palaeoproterozoic rocks in the area belong to four major units: the upper part of the Vittangi greenstone group (basaltic tuffite, schist, graphite schist and skarn), the Kilavaara quartzite group (biotite schist, quartzite and arkose), the porphyry group (basalt, andesite, rhyolite, trachyte), and younger intrusive rocks (e.g. gabbro, quartz diorite, monzonite, granite). The Svappavaara key area extends between the major SW–NE trending Karesuando–Arjeplog deformation zone (NW) and the intrusive rocks of the NW–SE oriented Luongastunturi massif. The most common mineral deposits in the area are iron ore and Cu-hosting (with Au and Mo) sulphide deposits. The most important iron ore deposits are the Tansari, Gruvberget, and Leveäniemi, the last-mentioned being recognised as the third-largest apatite iron ore deposit in Norrbotten. The commonest alteration types are scapolitisation, albitisation and skarn formation.

24 till samples were collected in 2013, together with 14 till samples from previous surveys. High or moderately elevated concentrations of several elements (Au, Ca, Co, Cu, Mg, Ni, P, Sc, Ti, V and Rh) are noted. The highest Au (44 ppb), Mn, Pb (30 ppm) and Rh (173 ppb) single-point concentrations from all key areas studied are located in this area. High Cd and Mo concentrations occur locally in till. High concentrations of Al, Ba, Ca, and Na correlate with high Cl concentrations (XRF dataset from previous campaigns) and can be interpreted as an indication of the various types of alterations, e.g. scapolitisation and albitisation. High Ca content in till overlaps with elevated pH values and indicates the presence of carbonates and skarn-type rocks. The general geochemical signature accords well with the predominantly mafic to intermediate metavolcanic rocks underlying the till.

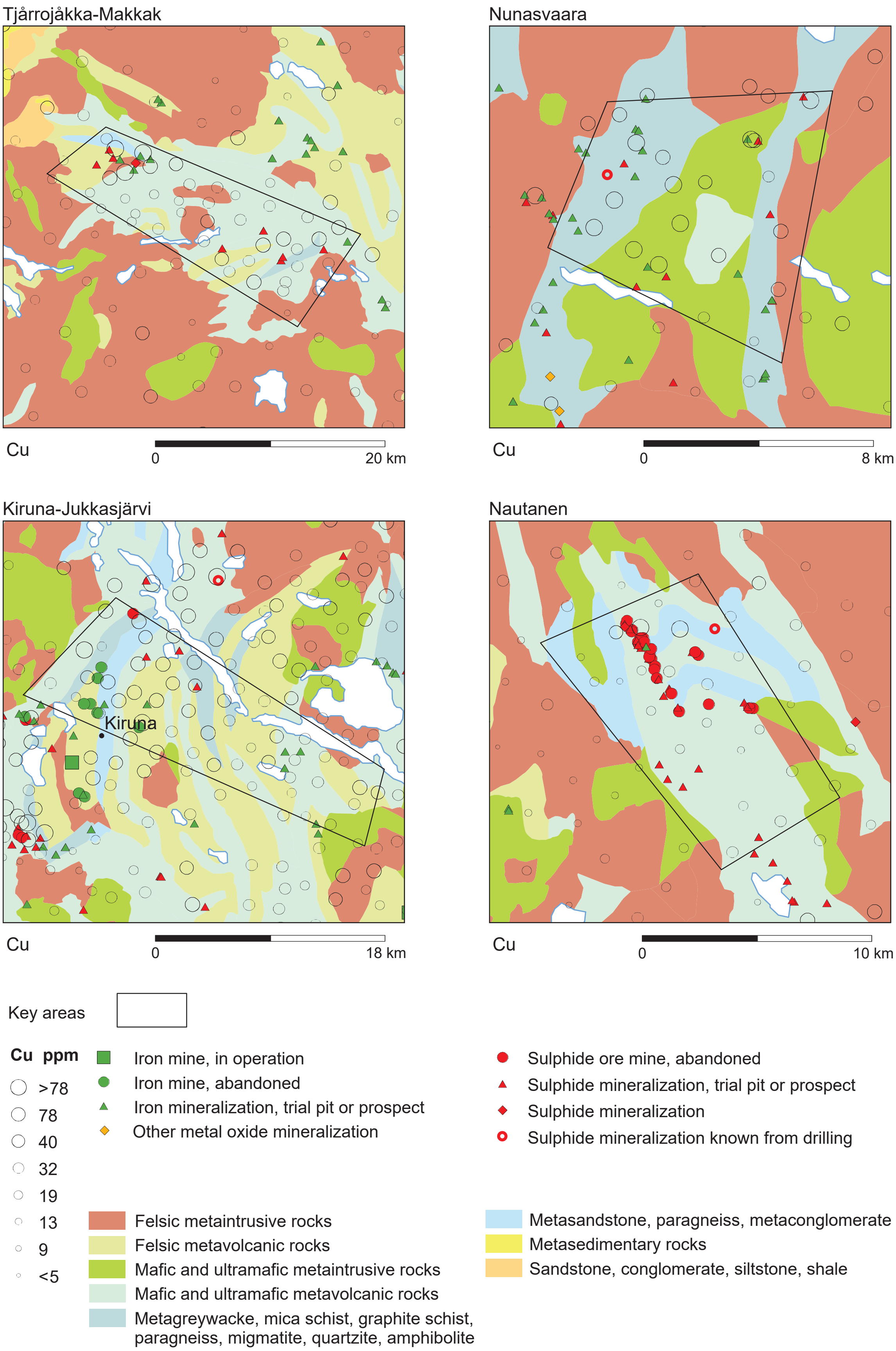


Figure 10. Cu (ppm, $HNO_3$ leach by ICP MS) in till in selected key areas. Bedrock map 1:1 000 000 as background layer and mineral resources according to the SGU digital database.

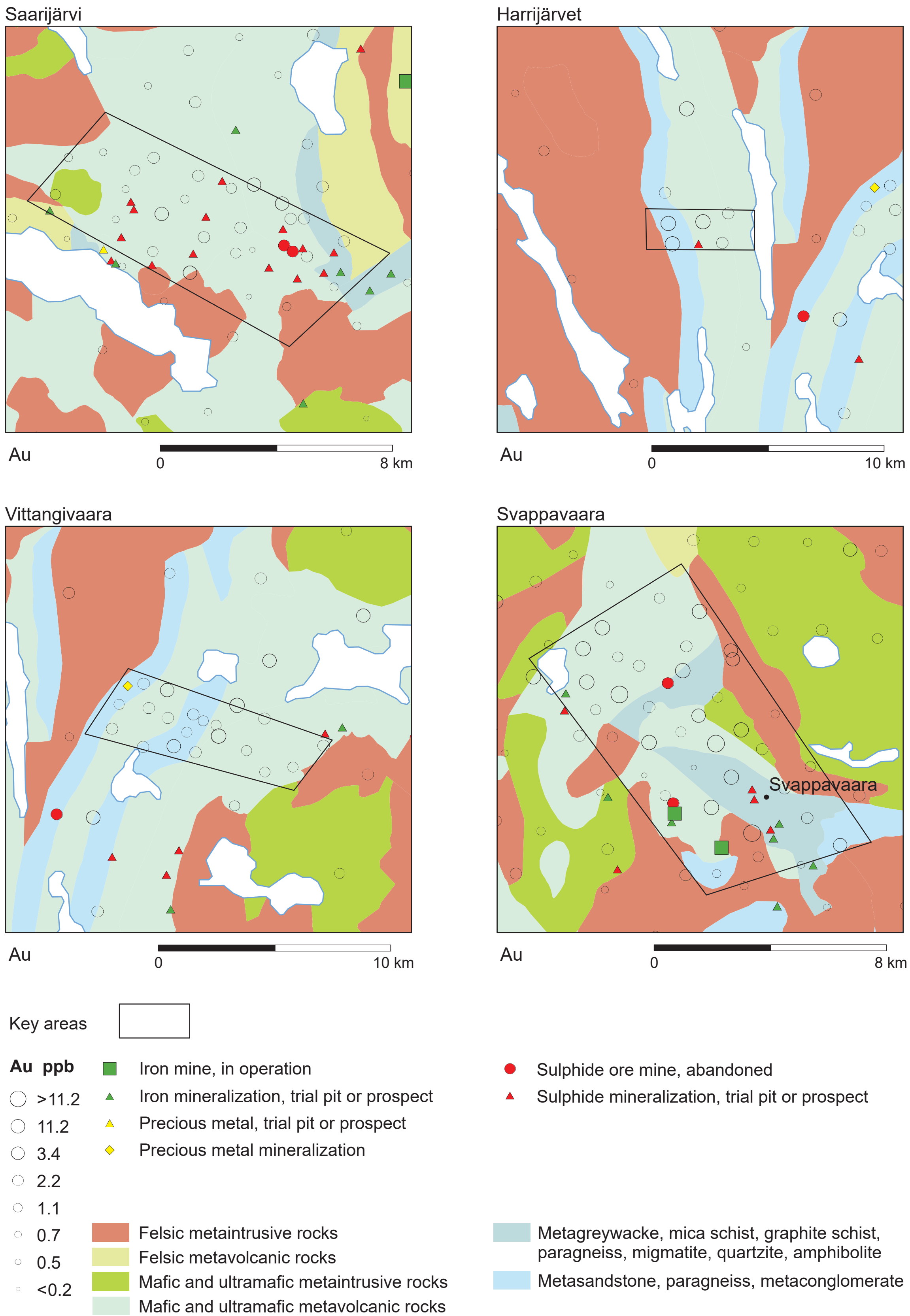


Figure 11. Au (ppb, aqua regia leach by ICP MS) in till in selected key areas. Bedrock map 1: 1 000 000 as background layer and mineral resources according to the SGU digital database.

## CONCLUSIONS

The compilation of new till geochemical data obtained under the Barents Project and older datasets resulted in a large database that can be used for multipurpose interpretations of element spatial distribution in northernmost Sweden. The area studied is a well-preserved glacial landscape featuring a relatively complete glacial stratigraphy due to limited erosion during frozen-base ice conditions. The glacial geomorphology contains components from multiple stadials.

The regional till geochemistry signature is mainly governed by underlying bedrock lithology, which is defined by rock origin, its mineralogy and chemical composition. The main compositional contrast related to geology originates from the distribution of silica-rich (e.g. granitoid, pegmatite, rhyolite) and silica-poor magmatic rocks (e.g. gabbro, basalt, peridotite). Silica-rich intrusive rocks are usually a source of elevated concentrations of Al, Ba, Be, K, Na, Rb, REEs, U, Th and Zr in till. High concentrations of Mg, Ca, Co, Cr, Cu, Fe, Mg, Mn, Ni, Ti and V in till are characteristic of silica-poor parent materials (typically mafic rocks). Till resting on bedrock primarily consisting of metasedimentary rocks usually has a similar chemical signature to till overlying granitic rocks. Norrbotten bedrock has a long polymetamorphic history and was intensively deformed during orogenies and influenced by metasomatic and hydrothermal processes contributing to the formation of large ore deposits, some of high economic value. The most common alterations are scapolitisation, albitisation, carbonatisation, and skarn formation. These alterations are reflected in till geochemistry as enrichments in Ba, Ca, Cl, K, Na, Sr, La, Rb and P. Anomalies related to secondary alterations occur locally (Ba, Sr, K, La, As) or regionally (P, Cl and Na), and often overlap with known mineralisation locations.

Norrbotten County is one of the richest ore districts in Europe, and till geochemistry reflects the location of known ore deposits and minor mineralisations, and outlines areas with high mineral exploration potential. The geology of the northern part of the Barents Project is characterised by Co, Cu, Fe, Ni, Ti and V anomalies in till, typical of apatite-Fe ore deposits located in volcanosedimentary complexes of greenstone belts and associated sulphide mineralisations, mainly with Cu and Au. Au anomalies are more localised but often overlap with known Au occurrences. Silver shows enrichment in till overlying sulphide deposits (Cu, Zn, Pb, W, As, Bi, U, Mo) and in areas mainly featuring volcanic and metasedimentary rocks. As, Bi, Cd, Pb, Sb, Sn, Mo, U, W and Zn content in till is rather low in Norrbotten, and single anomalies with high concentrations of metals can usually be related to minor mineralisations.

The element distribution pattern in till geochemistry is modified by long-lasting surficial processes as well as glacial history. The shape of the anomalies has been influenced by ice movement direction and transport, formation of glacial features (e.g. drumlins, ribbed moraines) and meltwater reworking during ice retreat. These can best be observed for major elements that are evenly distributed over the area studied, such as Ca and Na. The southeastern part of the Barents Project represents an area that was below sea level during the last deglaciation, and intense water activity resulted in leaching of many elements e.g. Ag, Al, Ba, Be, Co, Cu, Fe, Mg, Mn, Na, Ni, P, Pb, REEs, Sr, Th, Ti, Y and Zn. Local till conditions, defined mainly by pH, contributed to the depletion or enrichment of elements whose mobility depends on acidity and redox conditions.

Additional till samples were taken in the key areas to investigate the specific geochemical signatures related to mineralisation and their link to the local geology. It has been noted that median concentrations of several elements (e.g. Ca, Co, Cr, Cu, Mg, Na, Ni, P, Rh, Te, Ti and V) are higher than for the whole dataset analysed under the Barents Project. Bedrock lithology, alteration type and mineralisation in the key areas (mainly Fe, Cu, Au) correlate well with elevated metal concentrations in till, e.g. Ag, Ba, Be, REE, Sb, U and Zn in Tjårrojåkka–Makkak; Be, Ca, Cr, Ge, Na, P, Sc, Y and REE in Saarijärvi; Co, Cu, P, Fe, Mg, Mn, Na, Ni, Sc, Ti, V and Zn in Kiruna; Au, Ba, Ca, Co, Cr, Fe, Ge, K, Mg, Mn, Ni, P, Ti and V in Haarijärvet; Ag, Au, Ba, Bi, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, REE, Ti, V and Zn in Vittangivaara; Au, Cr, Sr, P, Na and Ca in Akkiskera–Kuormakka; Au, Co, Cr, Cu, Ni, P, Rh, V, Ti in Nunasvaara; Ag, As, Au, Ba, Bi, P, REEs, Sb, Ta, Th, U and W in Nautanen; Ca, Cu, Na, P, REEs, Se, Sr, Ti and V in Allavaara; and Au, Ca, Co, Cu, Mg, Ni, P, Sc, Ti, V and Rh in Svappavaara.

The geochemical till survey, together with bedrock mapping and geophysical measurements, proved to be a very useful tool for reconnaissance studies in glaciated areas, providing valuable information about the predominant bedrock lithology, presence of mineralisation (confirmation of existing anomalies and discoveries of new ones), as well as surface processes that may play an important role in modifying the regional and local geochemical signature.


## ACKNOWLEDGEMENTS

The authors would like to thank a number of field geologists who helped to collect samples in the Barents Project. Sten-Åke Ohlsson, Alicja Kawalec-Majka, George Morris and Jo Uhlbäck are thanked for their assistance in performing analyses. Kaj Lax and George Morris are kindly acknowledged for reviewing the manuscript and for their valuable comments on the text.


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Uppsala 2018
ISSN 0349-2176
ISBN 978-91-7403-393-9
Tryck: Elanders Sverige AB