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Metal anomalies in till in the Sarvlaxviken area, Lovisa, southern Finland

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ABSTRACT

Geochemical investigations of till is a widely used method in metal exploration as the till commonly inherits the geochemical signature (including the metal contents) of the parent bedrock. In this investigation, over 2000 till samples were collected in the Sarvlaxviken area, southern Finland, where several polymetallic (Cu, Zn, Pb, As, Sn, W and In) veins recently have been discovered in Proterozoic crust along the border between Late Svecofennian granites and the Wiborg Batholith. The bedrock is commonly covered by compact and poorly sorted basal till, formed during the Late Weichselian glaciation event. Several glacial-transported boulders, with high contents of Cu, Zn, As, Sn, Mo and Bi and derived from the local bedrock, have also been discovered on top of the till and provide evidence for concealed mineralisation in the local bedrock under the till cover. The frequent distribution of till in the Sarvlaxviken area provides excellent conditions for the search of such hidden mineralisation by means of systematic till sampling, even if large farm field areas, composed of clay-rich sediments, and seawater-covered areas (Sarvlaxviken bay), had to be avoided in the sampling program. The till samples were collected during university courses and training programs led by the authors and were analysed in a cost-efficient and certified laboratory. Obtained geochemical data were statistically processed by using K-means clustering algorithms which can be used to treat large sets of geochemical data. The results provided anomalies that mainly occur in till with a thickness of <1 m and are considered to be derived from a local bedrock source. The discovered anomalies provide strong evidence for numerous undiscovered veins beneath the till cover.

1. Introduction

Till geochemical methods are considered an essential tool for mineral exploration in Finland (Sarala, 2015) and elsewhere in glaciated terrains. With these methods numerous metal-rich targets have been identified, of which some have led to commercial exploitation, e.g. the Björkdal gold deposit in northern Sweden (Sundblad, 2003). For geochemical prospecting in glaciated terrains, it is crucial to have an in-depth knowledge of the glacial history and morphology as well as till stratigraphy. In Finland, such background knowledge is provided by e.g. Sarala and Ojala (2008), Hartikainen and Damsten (1991) and Lunkka et al. (2004).

The study area, Sarvlaxviken, is located in southern Finland, where geochemical prospecting is straight-forward and easy method, since no complex glacial transportation conditions or multiple till units (with variable formation processes) exist in the area (Geological Survey of Finland, 2015; Punakivi, 1970). Mineralogical and geochemical features of metal mineralisation in the area were described by Cook et al. (2011) and Valkama et al. (2016). Moreover, geochemical features of the local granite intrusions responsible for mineralisation were outlined by Nygård (2016) and Villar (2017). This contribution presents the results from a geochemical investigation of till in the Sarvlaxviken area, in which a wide spectrum of metal anomalies was revealed. Besides demonstrating that a number of undiscovered metal anomalies likely exist under the till cover in this area, the study also shows that till geochemistry can be a highly useful tool when exploring for metals elsewhere in the Wiborg Batholith, where proper ore-fertile granites are identified.

2. Background geology

2.1. Bedrock

The Fennoscandian Shield constitutes a multi-orogenic crustal

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complex that formed from the Late Archaean to the Neoproterozoic (Gaál and Gorbatschev, 1987). The central and southeastern parts of the Fennoscandian Shield are dominated by juvenile Svecofennian crust that formed at c. 1.9 Ga after which it was subject to repeated phases of deformation and metamorphism (Andersson et al., 2006). The last phase reached locally anatectic conditions, resulting in migmatization, partial melting and formation of Late Svecofennian granites at 1.84 Ma. The metamorphosed Svecofennian crust was in turn intruded from 1.64 Ga to 1.50 Ga by anorogenic rapakivi granites, which constitute a characteristic group of granites that formed in an extensional tectonic setting in the central-southeastern parts of the Fennoscandian Shield (Rämö and Haapala, 2005).

Southern Finland (Fig. 1) provides an excellent example geological section detailing the evolution of Svecofennian meta-sedimentary formations, mafic-felsic volcanic rocks and Early Svecofennian granitoids to the creation of anatectic Late Svecofennian granites and the development of incipient continental rifts, including A-type rapakivi granites, lacustrine sandstone basins and tholeiitic dolerite dykes.

The Wiborg Batholith (Fig. 1) is the largest of the rapakivi granites in the Fennoscandian Shield and is dominated by coarse-grained porphyric wiborgites and less abundant equigranular and more fine-grained late granite phases. The rapakivi granites show within-plate granite (WPG) geochemical signatures with a strong enrichment of REEs and a moderately negative Eu anomaly (Rämö and Haapala, 2005). The late stage, topaz-bearing granites show even deeper negative Eu anomalies and are often associated with metallic mineralisations (Haapala and Lukkari, 2005).

The Sarvlaxviken area displays a complex relation between the Svecofennian crust and four phases of rapakivi granites belonging to the southwestern part of the Wiborg Batholith (Fig. 2). The Svecofennian crust is dominated by the Late Svecofennian granites, but older rock units like Early Svecofennian granites and amphibolites, belonging to the Häme belt, occur at a distance less than 4 km from the study area. A characteristic feature of the Late Svecofennian granites in this area is that all primary (igneous) microcline grains were replaced by orthoclase during emplacement of the Wiborg Batholith (Villar et al., 2016), in accordance with the observations of Vorma (1972) who recognized a 10–20 km wide zone of orthoclase alteration in the Svecofennian units along the entire border of the Wiborg Batholith.

The rapakivi granites in the Sarvlaxviken area (Fig. 2) display intrusive relationship with the Late Svecofennian granites. As in other parts of the Wiborg Batholith, the wiborgites, with their spectacular plagioclase-mantled round orthoclase porphyroblasts, constitute the most common rock type around Sarvlaxviken. In addition, three types of late rapakivi granite plutons, each with a regional distribution of <1 km^2, have been recognized (Fig. 2). The Stormossen granite occurs as an elongate unit in contact with the Late Svecofennian granites and locally carries amphibolite xenoliths from the Svecofennian Häme belt. The Hormnäs granite has a rounded shape and is associated with at least one NS-trending granite dyke to the NE of the Hormnäs pluton. The Marviken granite constitutes an irregular-shaped body west of the Sarvlaxviken bay and is also associated with a NS-trending granite dyke at the same site as the Hormnäs granite dyke. The wiborgites show similar geochemical features as elsewhere in the Wiborg Batholith, while the Stormossen, Hormnäs and Marviken granites are typical late phases with pronounced negative Eu anomalies (Nygård, 2016). According to the classification diagram of El Bouseily and El Sokkary (1975), the wiborgites are normal granites while the Stormossen and Hormnäs granites, and in particular the Marviken granite, are strongly differentiated (Nygård, 2016).

2.2. Mineralisations

Polymetallic mineralisation, associated with late stage granites in the Wiborg Batholith, was first recognized by Haapala (1997) and Haapala and Lukkari (2005) in the Kymi and Liljendal stocks (Fig. 1). Significant concentrations of indium-bearing polymetallic sulphide mineralisation have been recognized in the Sarvlaxviken area (Fig. 2) (Cook et al., 2011; Valkama et al., 2016).

2.2.1. Wiborgite-hosted, indium-bearing veins east of Sarvlaxviken

A set of NNW-trending, In-bearing polymetallic quartz veins occur in wiborgites on the eastern side of the Sarvlaxviken bay (Cook et al., 2011; Valkama et al., 2016) (Fig. 2). These veins have been subdivided into three generations, the Högberget arsenopyrite-sphalerite-chalcopyrite-bearing veins (generation 1) and the Virbäcken and Korsvik chalcopyrite-arsenopyrite-sphalerite-roquesite-bearing veins (generations 2a and 2b) (Valkama et al., 2016). Several veins belonging to generations 1 and 2b have been recognized at the Högberget hill (K1-3, KB1 and HB1-2) and along the shore line to the Sarvlaxviken bay, while a vein belonging to the 2a generation (VB1) is located on a small hill west the Virbäcken river.

The first generation (1) is associated with a characteristic alteration rim of the vein while the last generation (2b) formed under brittle conditions and is In-bearing (Valkama et al., 2016). In spite of three distinct vein generations, with three populations of metal contents and mineral parageneses, the ore-forming fluids have been shown to be quite similar for all three vein generations, which indicate chaotic conditions for the metal precipitation (Broman et al., 2018).

Only one, very small, magnetite-galena-sphalerite-bearing vein (Mjölknäs, MN1) has been discovered on the western side of the Sarvlaxviken bay. As on the other side of the bay, this vein is wiborgite-

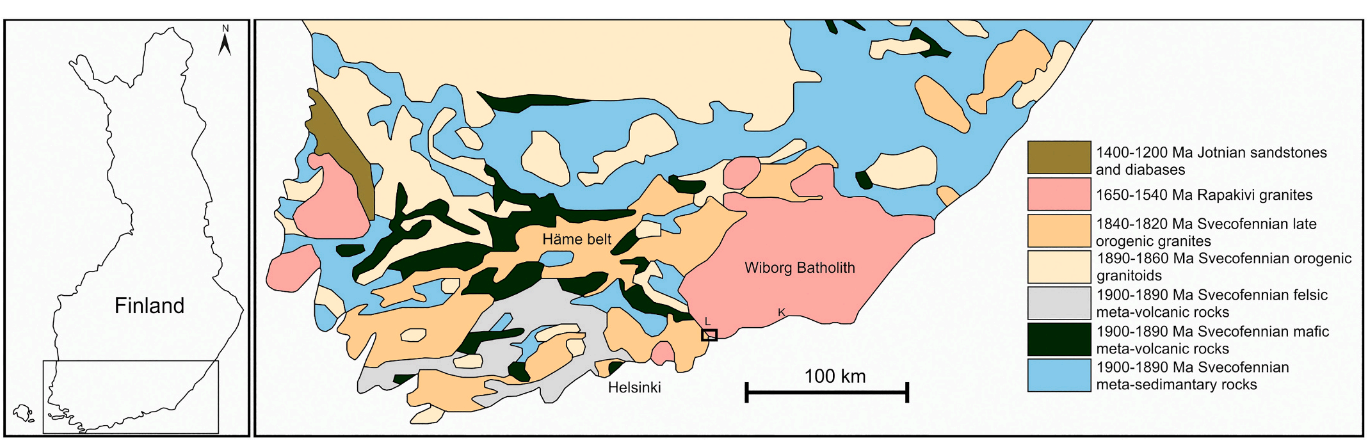

Fig. 1. Precambrian geology of southern Finland, simplified from Kähkönen (2005). The Sarvlaxviken area is indicated with a rectangle, Kymi = K and Liljendahl = L.

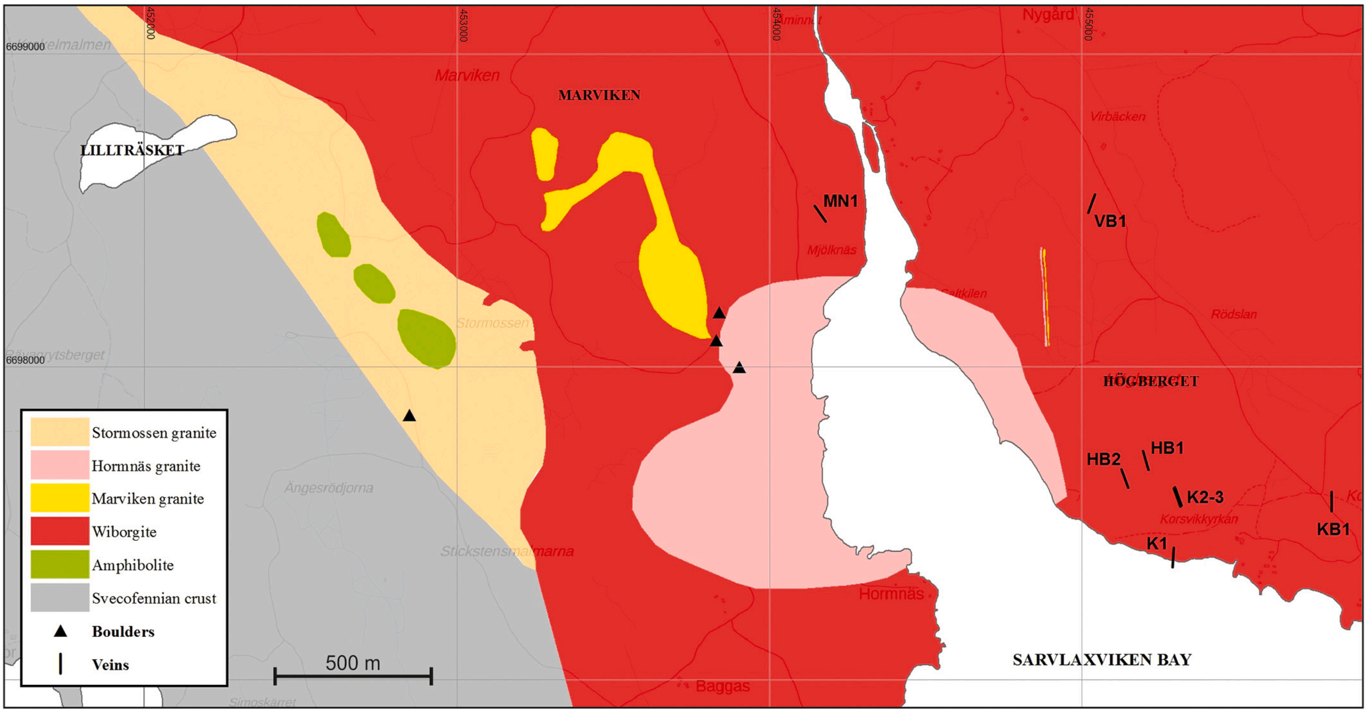

Fig. 2. Bedrock geology of the Sarvlaxviken area.

hosted and is only associated with moderate hydrothermal alteration.

2.2.2. Polymetallic alteration zones in boulders of the Marviken granite

More than 10 glacial-transported boulders, each consisting of the Marviken granite with one or several cm-dm-wide metal-rich alteration zones, have been found in a NNW-trending linear trend, 500 m south of the Marviken farm field. The metal-bearing alteration zones form two populations, the most common carries visible arsenopyrite and chalcopyrite, and occasionally cassiterite (Valkama et al., 2016). In one case, molybdenum-bismuth-bearing mineralisation was observed in a two dm wide beryl-dominated hydrothermal zone, hosted by a m^3-sized glacial-transported boulder of the Marviken granite (Valkama et al., 2016). This boulder train strongly indicates that a dense pattern of hydrothermal alteration zones, enriched in Cu, As and Sn as well as Mo, Bi and Be, must exist in the Marviken granite somewhere between the bolder train and the Marviken farm field.

2.2.3. The Lillträsket Zn-rich boulder

A 5 dm thick, zinc-rich alteration zone has been recognized in a granite boulder 1 km SE of lake Lillträsket close to the border between the Wiborg Batholith and the surrounding Late Svecofennian granite.

2.3. Quaternary deposits

During the Quaternary cold stages, northern Europe was covered by thick ice sheets at repeated intervals. The glaciers advanced and retreated over Finland in several stages (Johansson et al., 2011), eroded the bedrock and deposited the eroded material as glaciogenic sediments (Koljonen and Tanskanen, 1992). The latest glaciation took place in the Late Weichselian, about 25 ka ago (Lunkka et al., 2004) and created the topmost till layers of the study area.

Several ice lobes formed during the glaciation (Fig. 3a) and the three Salpausselkä ice marginal formations (I–III) deposited during the last deglaciation. According to Saarnisto and Saarinen (2001), the Salpausselkä formations deposited in front of the Baltic Ice Lake, a former stage of Baltic Sea; the first Salpausselkä formation deposited ca. 12.1–12.3 ka ago, the second formation ca. 11.6–11.8 ka ago and the third formation ca. 11.4–11.5 ka ago. The southernmost coastal areas of Finland were free from ice c. 13,100 years ago (Saarnisto and Saarinen, 2001; Johansson et al., 2011). Most of the present coastal area was still water-covered when the Litorina Sea, the latest Baltic Sea stage, formed around 8.5 ka ago (Ning et al., 2017), and was gradually exposed during the mid-Holocene (Donner, 1995).

The Quaternary deposits in the study area were mapped by the Geological Survey of Finland at the scale of 1:20,000–1:100,000 (Punakivi, 1970; Geological Survey of Finland, 2015; Fig. 3b). It was noted that the area mainly is covered by compact and poorly-sorted basal till (Punakivi et al., 1977), which represents debris transported under or within the basal part of the ice (Edén and Björklund, 1995). Most of the basal till in the study area is composed of sandy material, although the area also locally includes deposits of gravely till.

The main ice movement direction in the study area, deduced from clast fabric measurements and bedrock cross-striae, is NW-NNW (320–330°), although some glacial cross-striation observations also indicate a younger and weaker ice-movement in the direction NNW-N (350–360°) (Punakivi et al., 1977, Johansson et al., 2011, Fig. 3b).

Most of the bedrock in the study area is covered by till. However, in some topographically low areas (e.g. the Marviken farm lands) late glacial clays (topmost sediment is Litorina Sea clay) overlie the till deposits and can locally form up to 8 m thick clay layers (Punakivi et al., 1977, Fig. 3b). Furthermore, areas with gyttja clay, with at least 2–6% humus, occur in the northern parts of the Sarvlaxviken bay. The Stormossen mire, in the centre of the study area, has developed on top of clay and detritus gyttja and contains mainly sphagnum peat. Glaciofluvial sandy and gravelly deposits occur outside the study area (Fig. 3b) and were not included in this study.

3. Material and methods

Till samples for this study were collected from 2008 to 2013 by students participating in summer training programs and an international annual course in ore prospecting, organized by the University in Turku (Sundblad, 2013). All steps in this field work, from the selection of the target areas to the evaluation of the results were conducted and

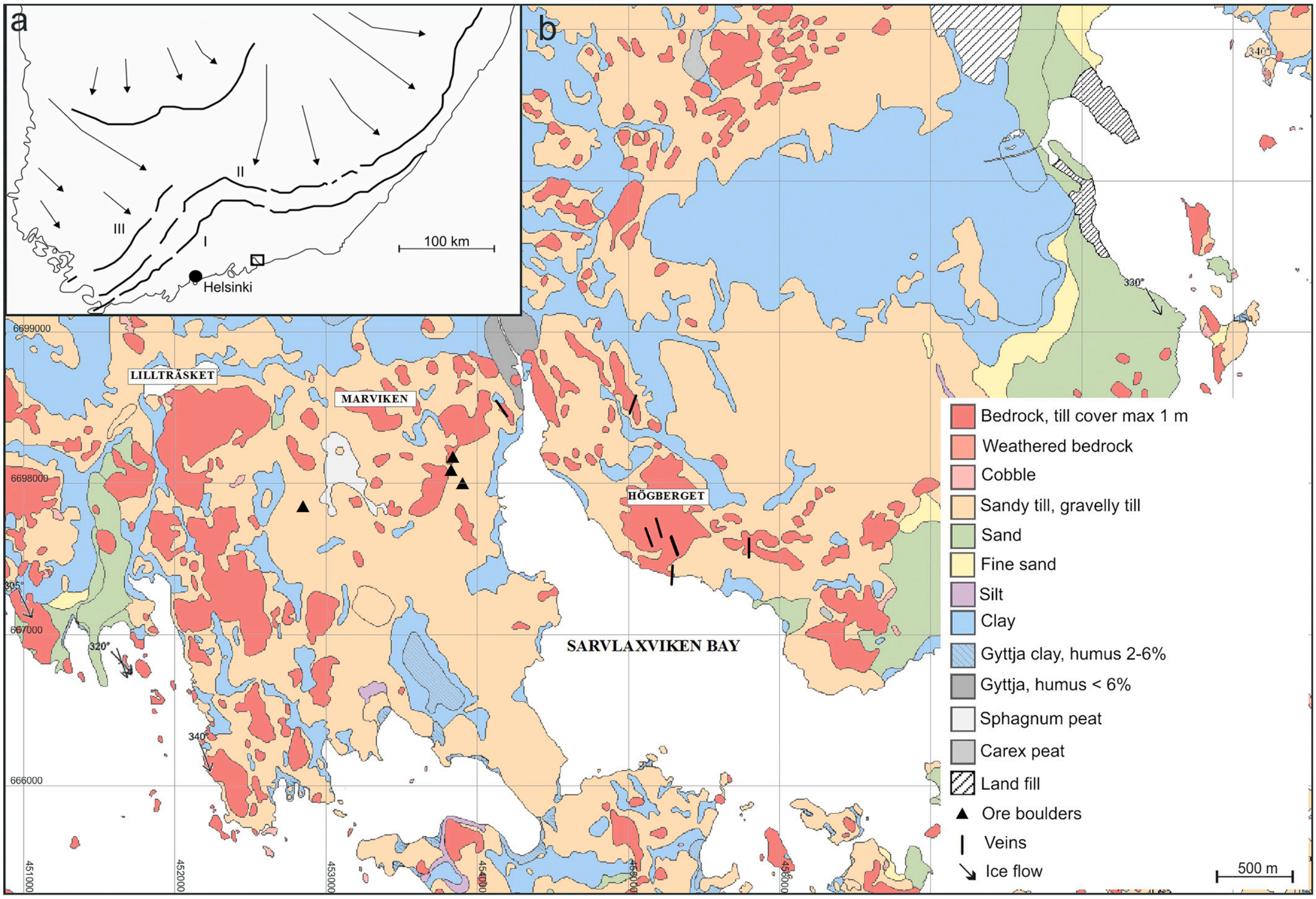

Fig. 3. a. Location of ice lobes, the three Salpausselkä formations and glacial transport directions in southern Finland during the Weichselian glaciation (modified from Ahokangas, 2019). b. Distribution of bedrock outcrops and topmost Quaternary sediments in the Sarvlaxviken bay area (modified from Geological Survey of Finland, 2015).

controlled by two of the authors. The till geochemistry activities were part of a major project on the metallogeny of indium in southeastern Finland, including the PhD work by Valkama (2019) and numerous MSc projects, all supervised by the authors, as well as detailed mapping of the bedrock and the magnetic field.

The target selection for the first till sample campaign (2008) was based on the discovery of a polymetallic vein at Korsvik and several of As-Cu-Sn-bearing glacial-transported boulders at Marviken, made by the private explorer Rune Nygård. In the 2008 sample campaign, approximately 100 till samples were collected in two 100 m grid systems. The successful results from that year led in 2009 to more detailed (20 m grid) sampling in the best anomalies from the 2008 campaign, parallel with an extension of the 100 m grid sample program into new areas. The most important achievement during the 2009 field campaign was the discovery of the Lillträsket Zn boulder, which led to the development of a new target area for 100 m and 20 m till sampling campaigns in 2010. The discovery of the Marviken Mo-Bi-Be boulder in 2011 widened the metallogenetic scope of the region further and provided enough target areas for till collections campaigns for several years. In this way, altogether 207 students from more than twenty countries, representing all continents, managed to collect over 2000 till samples during the years 2008–2013 from the nearly 20 km^2 wide area in the Sarvlaxviken surroundings. A summary of the sample locations for the study area is shown in Fig. 4.

All samples were collected from the non-weathered till horizon and the location for each sample was secured with GPS equipment with an accuracy of 7 m. Samples from clay-rich areas were not collected because such sediment types are unable to track the geochemical signature of the local bedrock (Sarala, 2015). The samples collected in the 100 m intervals included three sub-samples; a main sample and two satellite samples. The satellite samples were taken 25 m south-west and north-east of the main sample point, i.e. perpendicular to the ice movement direction, in order to optimally catch any anomalous contents in the bed rock to the northwest of the sample point(s). The samples collected in 20 m intervals were taken in one sample point, i.e. without any satellite samples. All samples collected in 20 m intervals were taken at sites where the 100 m interval samples already had indicated a metal anomaly in a previous sampling campaign. In this way, metal anomalies obtained in the 20 m sample grids served as one control mechanism for the anomalies detected in the preceding year's 100 m sampling.

Another control mechanism was to randomize the sample numbers and a third was to re-analyse the samples in the rare case when suspect results had been achieved. In this context, the generous cooperation with the Activation Laboratories Ltd. (Ancaster, Canada) company was fruitful. Yet another factor to maintain a constant sampling procedure from year to year was to use the same teaching assistants, both in the field work and in the drying/sieving process during all six years.

The sample pits were dug as deep as possible (normally 2–5 dm) with a large metal spade after which each sample was collected with a smaller plastic spade from the fresh pit wall and put into a low-density polyethylene (LDPE) bag. The samples were dried for 24 h at 70–80 °C during the field course and sieved with a plastic framed screen cloth nylon with a sieve opening of 0.25 mm. In this way, c. 20–30 g fine

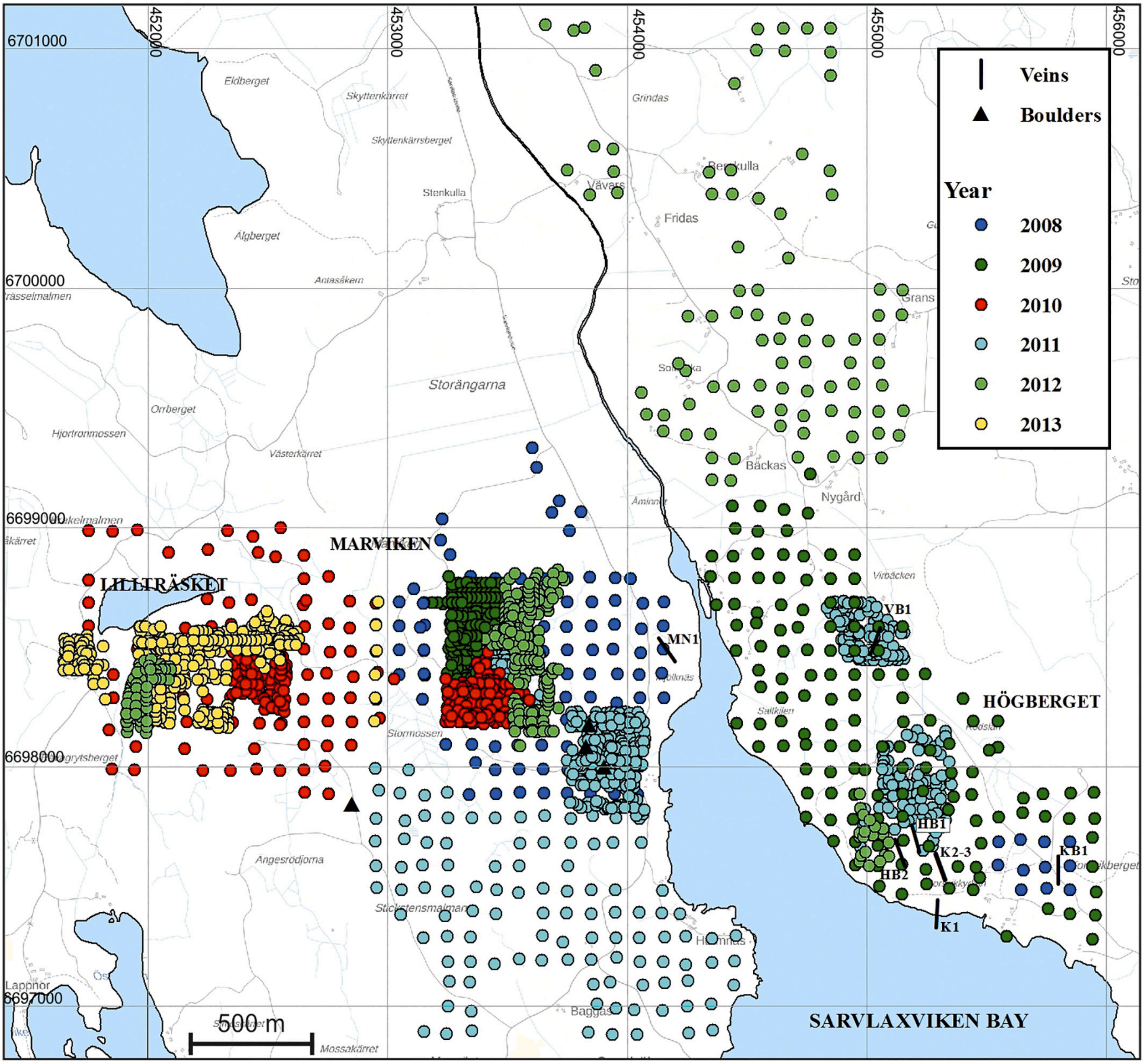

Fig. 4. Location and sampling year of all till samples collected in this study.

fraction of hundreds of till samples were ready for shipment for analytical work already by the end of each field course. The analytical work was carried out with the Ultratrace 4 – 4 Acid "near total" digestion ICP-MS analytical package at Activation laboratories, Ancaster, Canada. The samples were digested by four acids and heated until the samples were dry. Afterwards, the samples were brought back into solution. Digested samples were diluted and analysed by inductively coupled plasma emission mass spectrometry (ICP-MS) with a Perkin Elmer-SCIEX ELAN 6000, 6100 or 9000 equipment. Replicate analyses of internal standards (run every 80 samples) and duplicate analyses (after every 15 samples) indicate error values less than 1%. Standards, measurement conditions and detection limits are more detailed described in the Ultratrace 4-Total Digestion report (ActLabs Ltd).

Geochemical values, under the detection limits, were reassigned to 50% of the detection limits for each element to allow for meaningful treatment in the cluster analysis and when creating the maps. K-means clustering analysis (SPSS) was used for the entire data set ($n = 2167$) for Ag, As, Ba, Be, Bi, Cd Cu, Co, Fe, Ga, In, Li, Mn, Mo, Ni, Pb, Sn, Te, U, W and Zn in order to classify the samples into groups. The clusters were examined statistically and graphically in order to determine the geochemical differences between groups and the spatial distribution of clusters. Proportional symbol maps and cluster maps were plotted in ArcMap 10.8 to show the distribution of base and precious metals. The maps were drawn on the Transverse Mercator projection in the EUREF FIN TM35FIN coordinate system.

4. Results

A summary of the average contents of selected elements in the till samples is presented in Table 1. The metal contents in the till samples are also presented in proportional symbol maps (Figs. 5–16) where the size of each dot indicates the concentration.

K-means clustering algorithms are useful to process large sets of geochemical data (Zhou et al., 2018). In this study, the samples

Table 1
Summary of the average contents of 20 elements in till in the Sarvlaxviken area.

Analyte symbol	Ag	As	Ba	Be	Bi	Cd	Cu	Fe	Ga	In	Li	Mn	Mo	Ni	Pb	Sn	Te	U	W	Zn
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	wt%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
All (2167)																				
Min	<0.05	<0.1	<1	<0.1	<0.02	<0.1	0.2	0.23	<0.1	<0.1	2.2	<1	<0.1	1.1	4.7	<1	<0.1	<0.1	<0.1	3.3
Max	4.14	153.0	1630	86.9	68.30	1.6	182.0	17.30	65.1	0.7	137.0	4500	29.0	80.3	284.0	53	4.3	111.0	10.3	597.0
Arithmetic mean	0.22	4.4	523	3.9	0.51	0.2	9.5	3.03	20.4	0.1	20.5	416	1.5	6.6	33.0	3	0.2	6.7	0.6	78.1
Median	0.16	3.1	536	3.2	0.32	0.1	7.4	2.28	18.7	0.1	16.1	321	0.8	5.1	28.2	2	0.1	4.5	0.1	58.8
Std. deviation	0.24	5.7	104	3.2	1.53	0.1	9.8	2.22	6.3	0.1	14.9	304	2.2	5.3	15.6	3	0.3	7.7	1.0	67.2
Western side of Sarvlaxviken																				
Högberget (166)																				
Min	<0.05	<0.1	<1	<0.1	0.05	<0.1	0.2	0.45	<0.1	<0.1	4.8	<1	<0.1	1.1	5.1	<1	<0.1	<0.1	<0.1	11.9
Max	1.15	43.9	1060	86.9	68.30	0.8	174.0	15.30	50.0	0.7	66.5	1770	10.9	55.4	284.0	43	2.0	57.4	6.3	367.0
Arithmetic mean	0.11	5.4	534	4.4	0.75	0.2	10.9	2.34	19.6	0.1	16.2	299	1.2	6.7	33.8	3	0.2	5.8	0.5	51.4
Median	0.06	4.0	536	3.1	0.39	0.1	7.8	1.89	17.8	0.1	14.0	276	0.6	5.1	28.2	2	0.1	4.6	0.1	41.0
Std. deviation	0.14	6.2	107	6.4	3.51	0.1	12.6	1.61	6.0	0.1	9.3	155	1.7	5.9	19.2	4	0.3	4.4	0.9	37.5
Eastern side of Sarvlaxviken																				
Marviken (875)																				
Min	<0.05	<0.1	112	0.5	<0.02	<0.1	0.2	0.23	2.8	<0.1	2.2	55	<0.1	1.1	4.7	<1	<0.1	0.7	<0.1	3.3
Max	4.14	153.0	817	15.6	5.45	0.8	72.2	16.00	47.7	0.7	137.0	4500	29.0	80.3	212.0	53	2.8	40.2	10.3	597.0
Arithmetic mean	0.19	3.4	530	3.5	0.39	0.2	8.5	2.92	19.8	0.1	19.1	449	1.4	6.4	30.7	2	0.2	5.2	0.5	76.1
Median	0.14	2.5	536	3.1	0.28	0.1	6.4	2.24	18.4	0.1	14.5	333	0.6	4.9	26.9	2	0.1	4.2	0.1	55.4
Std. deviation	0.21	5.9	72	1.4	0.39	0.1	7.6	2.22	5.6	0.1	15.9	362	2.6	5.4	13.9	3	0.3	3.4	1.0	74.0
Lillträsket (529)																				
Min	<0.05	<0.1	45	1.0	<0.02	<0.1	0.6	0.41	10.9	<0.1	3.3	81	<0.1	1.4	17.7	<1	<0.1	1.0	<0.1	13.2
Max	2.86	44.9	1630	19.4	3.33	0.9	117.0	17.30	65.1	0.7	98.2	2170	11.6	76.3	190.0	20	4.3	101.0	7.2	513.0
Arithmetic mean	0.35	5.6	474	4.5	0.65	0.2	10.9	4.11	23.3	0.1	26.2	489	1.8	6.6	39.1	3	0.1	11.0	0.7	105.9
Median	0.26	3.6	496	3.9	0.49	0.2	8.6	3.37	21.3	0.1	23.3	377	1.0	5.0	34.7	2	0.1	6.9	0.2	85.3
Std. deviation	0.30	5.8	138	2.1	0.50	0.1	9.8	2.64	7.7	0.1	15.9	302	1.9	5.6	16.2	3	0.3	12.4	1.1	71.2

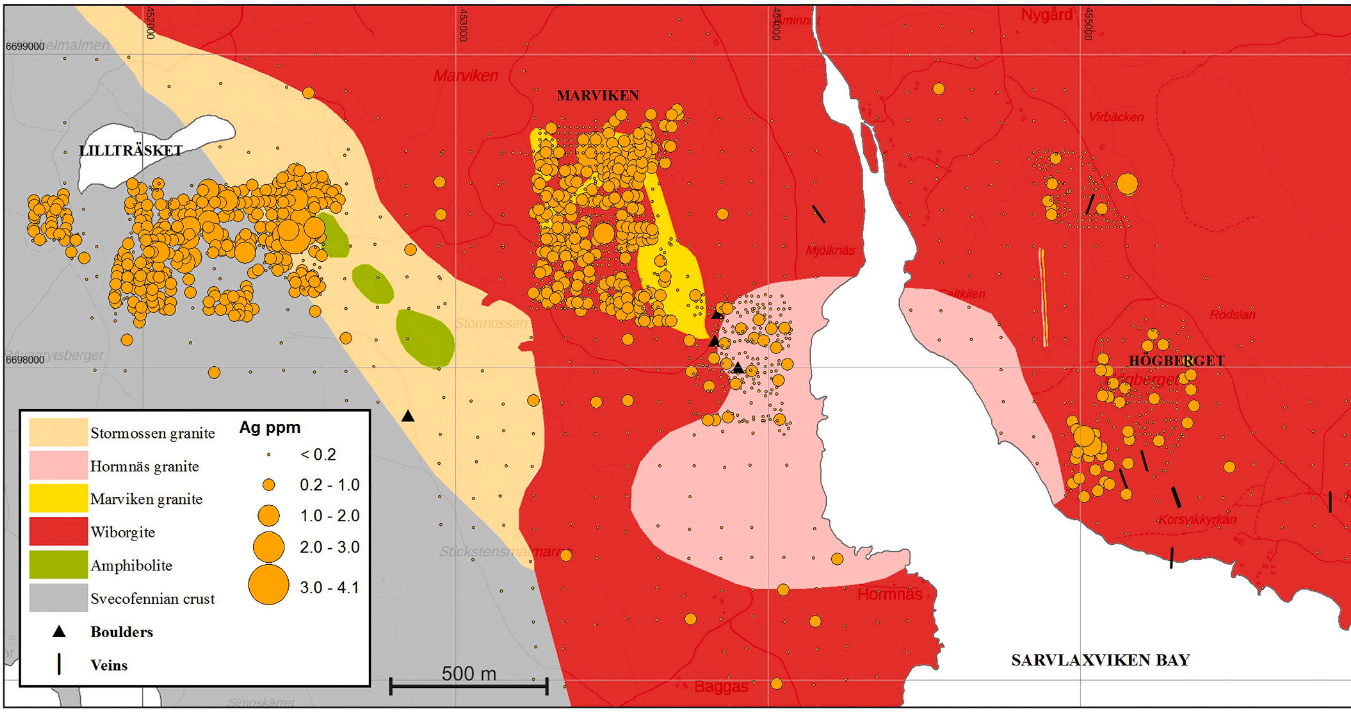

Fig. 5. Proportional symbol map displaying the Ag contents in till in the Högberget, Marviken and Lillträsket areas.

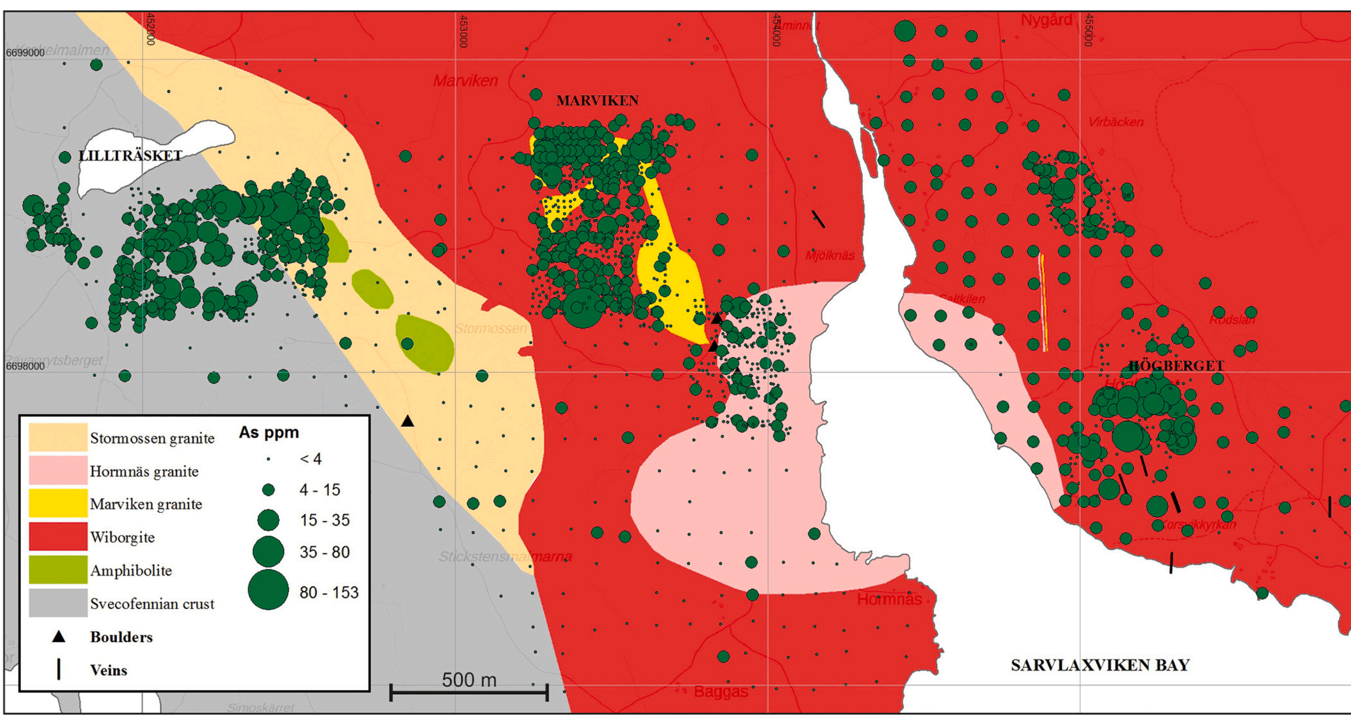

Fig. 6. Proportional symbol map displaying the As contents in till in the Högberget, Marviken and Lillträsket areas.

constitute two clusters as shown in Table 2. Most of the samples (n = 1999) form cluster 1, which can be considered as a background, while the 168 samples in cluster 2 are characterized by anomalous concentrations of Mn, In, Fe, U, Sn, W, Zn, Mo, Cu, Pb, Ag, As, Bi, Co, Cd, Be, Ga, Li, Ni and Te. The distribution of the data in cluster 2 is presented as a dot map (Fig. 17).

4.1. *The eastern side of Sarvlaxviken*

The most significant polymetallic veins in the Sarvlaxviken area are located in wiborgites on the eastern side of the bay (Cook et al., 2011; Valkama et al., 2016; Broman et al., 2018). Most of the veins occur on the Högberget hill and represent generations 1 and 2b. One vein, belonging to generation 2a, is known from a smaller hill west of the Virbäcken river, where it is cut by a vein belonging to the 2b generation.

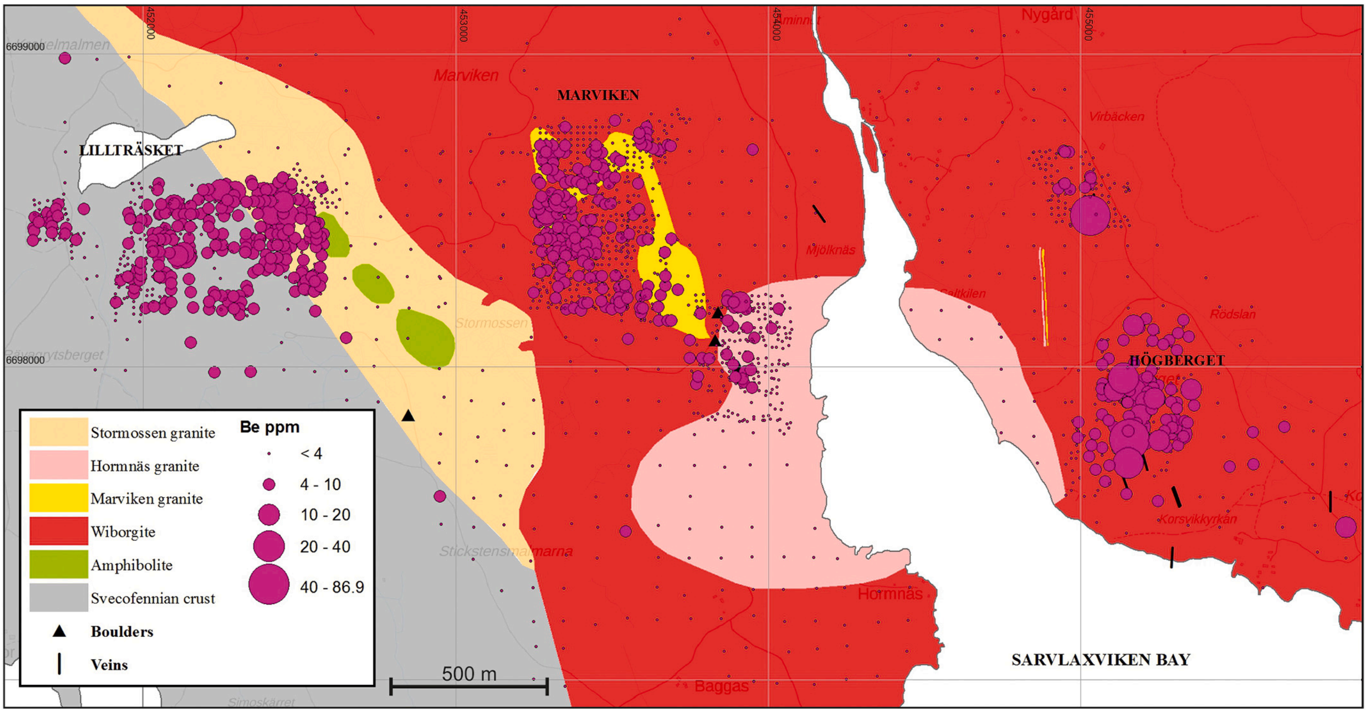

Fig. 7. Proportional symbol map displaying the Be contents in till in the Högberget, Marviken and Lillträsket areas.

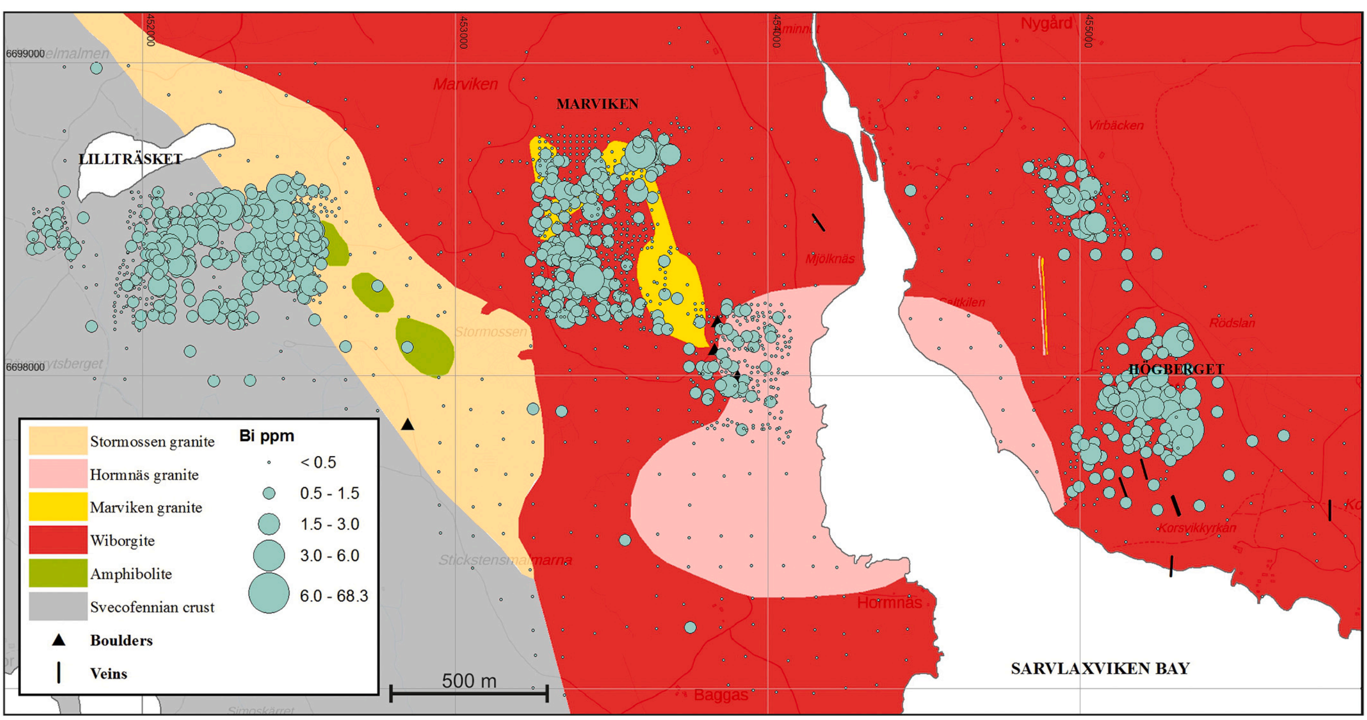

Fig. 8. Proportional symbol map displaying the Bi contents in till in the Högberget, Marviken and Lillträsket areas.

Significant parts of the till samples collected on these two hills are anomalous with Ag (up to 1.2 ppm), As (up to 44 ppm), Be (up to 87 ppm), Bi (up to 68 ppm), Zn (up to 367 ppm), Cu (up to 174 ppm), Fe (up to 15.3 wt%), Pb (up to 284 ppm), Sn (up to 43 ppm), W (up to 6.3 ppm) and In (up to 0.7 ppm), notably in all cases north of these known veins. Some of these anomalous samples are also visible in the K-means cluster plot (Fig. 17).

4.2. *The western side of Sarvlaxviken*

Large areas, with anomalously high metal contents in till, are recorded on the western side of the Sarvlaxviken bay. The anomalies in the Marviken area are underlain by wiborgitic granites as well as the Marviken granite while the anomalies in the Lillträsket area are underlain by wiborgitic granites as well as Late Svecofennian granites. Thus, this area can be divided into two anomalous areas; Marviken and

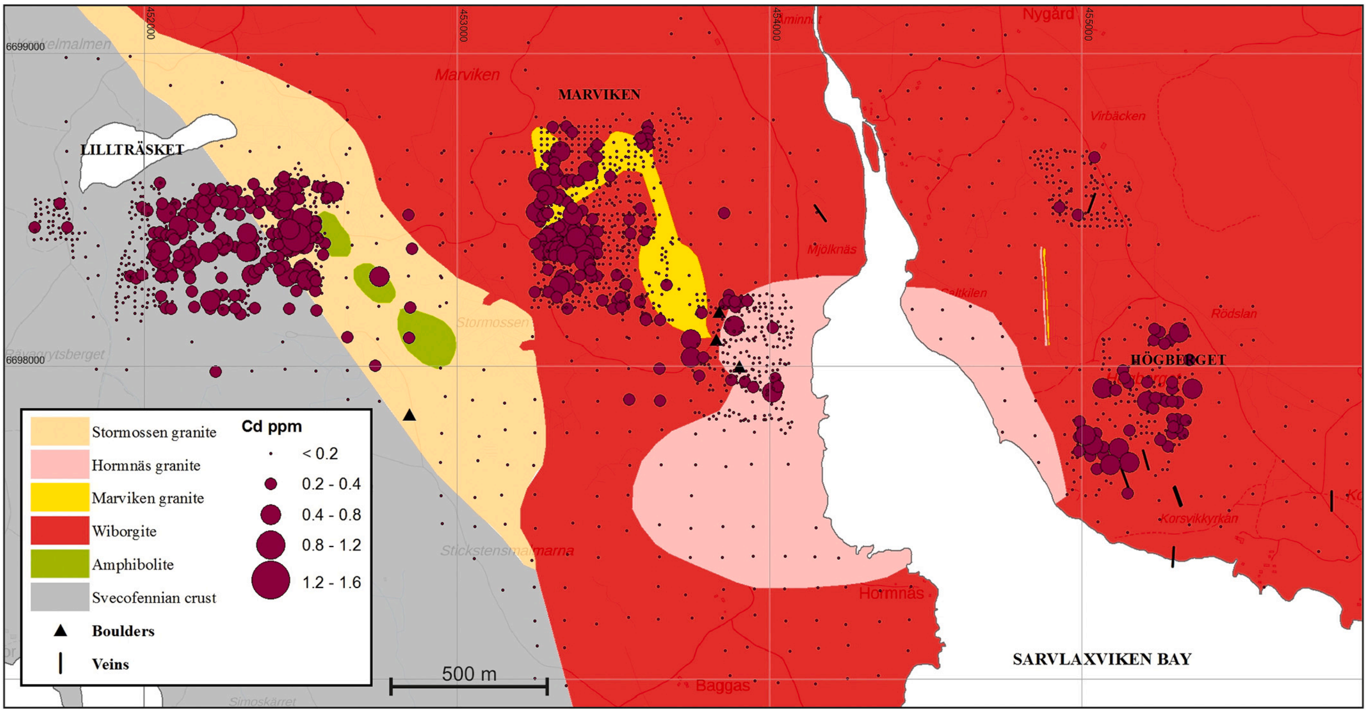

Fig. 9. Proportional symbol map displaying the Cd contents in till in the Högberget, Marviken and Lillträsket areas.

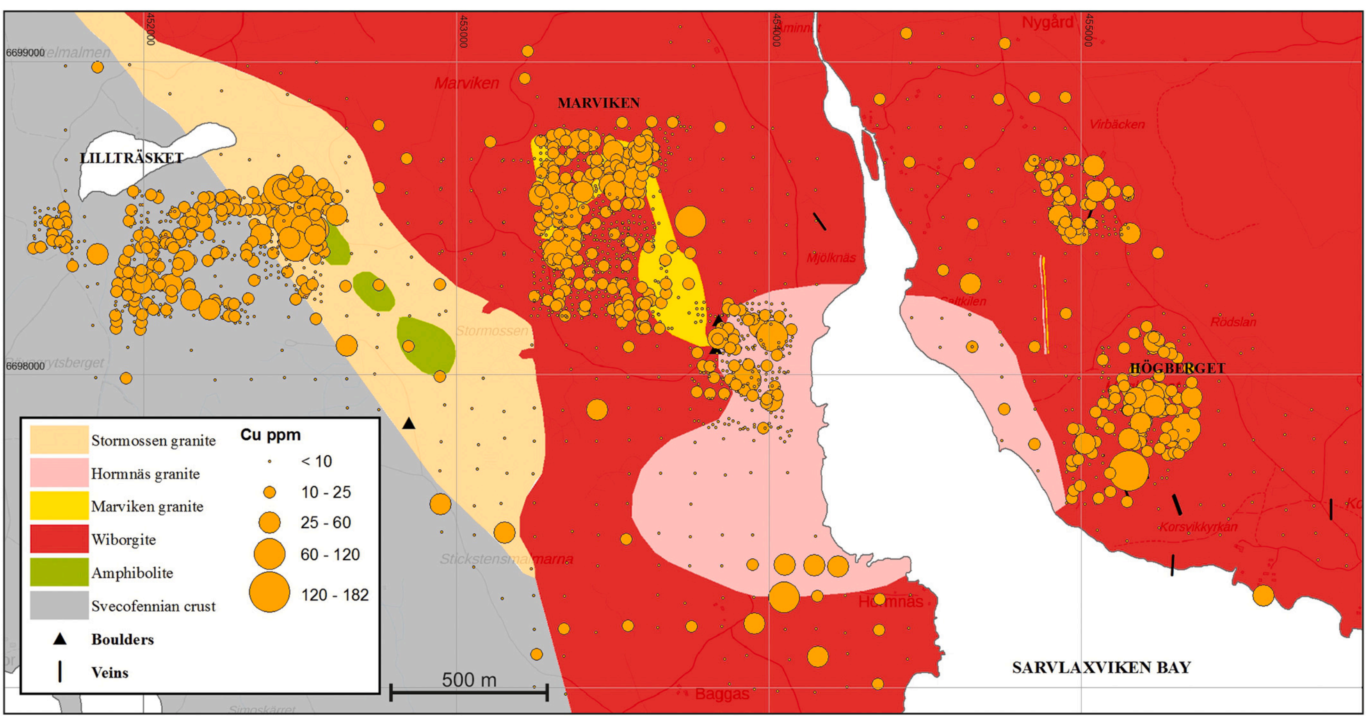

Fig. 10. Proportional symbol map displaying the Cu contents in till in the Högberget, Marviken and Lillträsket areas.

Lillträsket (Fig. 2).

In the Marviken area, anomalously high contents were recorded for In (up to 0.7 ppm), Zn (up to 597 ppm), Fe (up to 16 wt%), Ag (up to 4.1 ppm), Mo (up to 29 ppm), Mn (up to 4500 ppm), Li (up to 137 ppm), Sn (up to 53 ppm), As (up to 153 ppm), Cu (up to 72 ppm), Pb (up to 212 ppm) and Bi (up to 5.45 ppm). No anomalies were detected around the Pb-Zn vein. The K-means clustering analyses display a N(N)W to SE trending anomaly.

The Lillträsket area is located south of a lake with the same name. The majority of the anomalous samples were collected in till overlying the Stormossen granite, but numerous anomalous samples were also collected in till overlying the Svecofennian granite. Anomalously high contents were recorded for Ag (up to 2.9 ppm), As (up to 44.9 ppm), Be (up to 19.4 ppm), Bi (up to 3.3 ppm), Cu (up to 117 ppm), Cd (up to 0.9 ppm), Fe (up to 17.3 ppm), In (up to 0.7 ppm), Mn (up to 2170 ppm), Mo (up to 11.6 ppm), Pb (up to 190 ppm) and Zn (up to 513 ppm). The K-

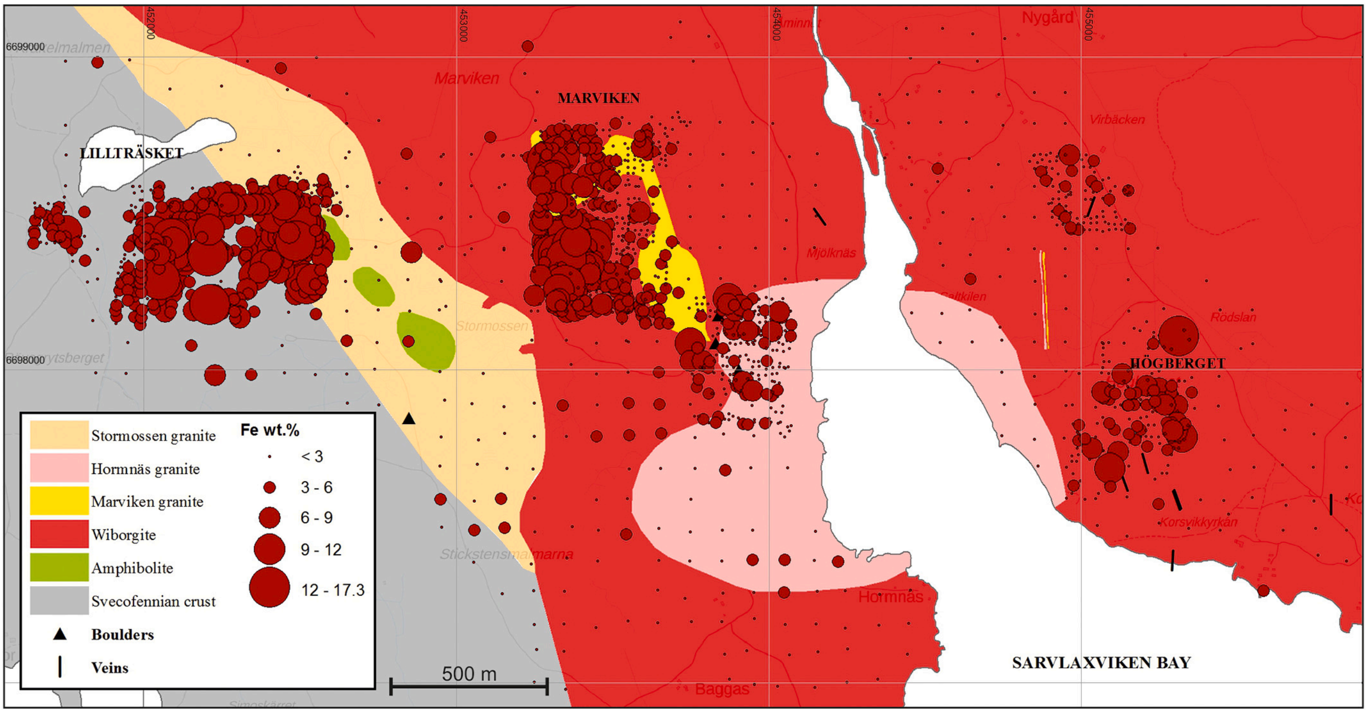

Fig. 11. Proportional symbol map displaying the Fe contents in till in the Högberget, Marviken and Lillträsket areas.

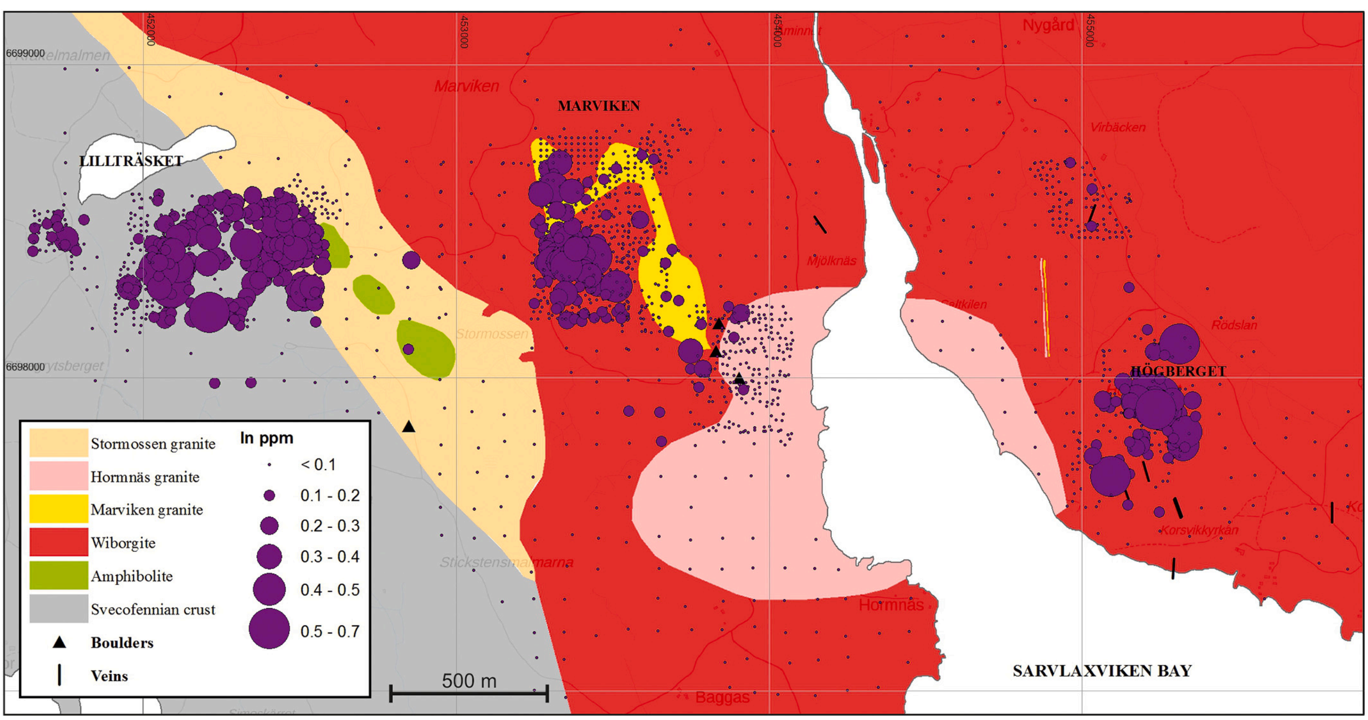

Fig. 12. Proportional symbol map displaying the In contents in till in the Högberget, Marviken and Lillträsket areas.

means clustering analyses display a rather continuous E-W trending anomaly.

5. Discussion

5.1. Transport distance of till

Glacial sediments in the C-horizon, or deeper, are affected by glacial dispersal that can be tracked by till sampling (McClenaghan et al., 2000). Material eroded from the bedrock is deposited down-ice in a dispersal train which can be used to explore the source of the material. Commonly, these dispersal trains are ribbon or fan shaped and much larger than the bedrock sources. McClenaghan et al. (2000) and McClenaghan and DiLabio (1993) concluded that the proper sampling spacing to detect mineralisations should be adjusted to the size of the mineralisation. A small occurrence in the Mira-Framboise area, Nova

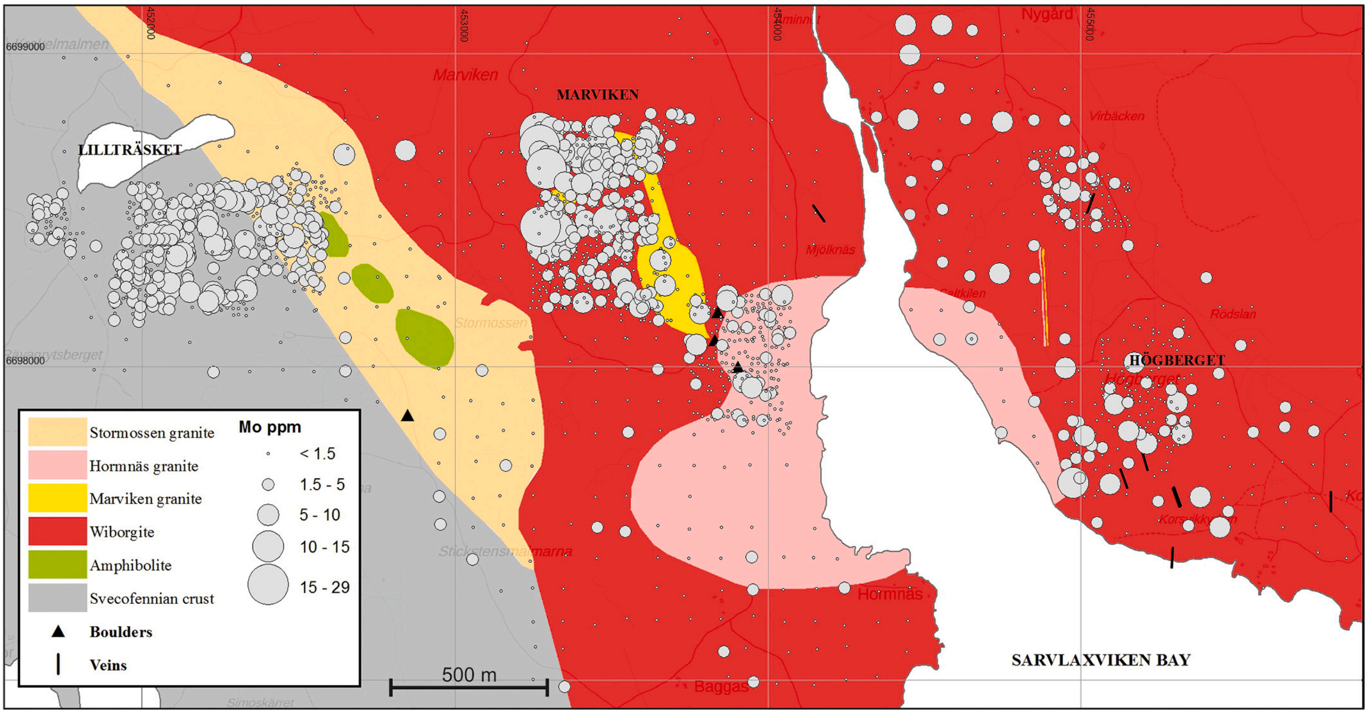

Fig. 13. Proportional symbol map displaying the Mo contents in till in the Högberget, Marviken and Lillträsket areas.

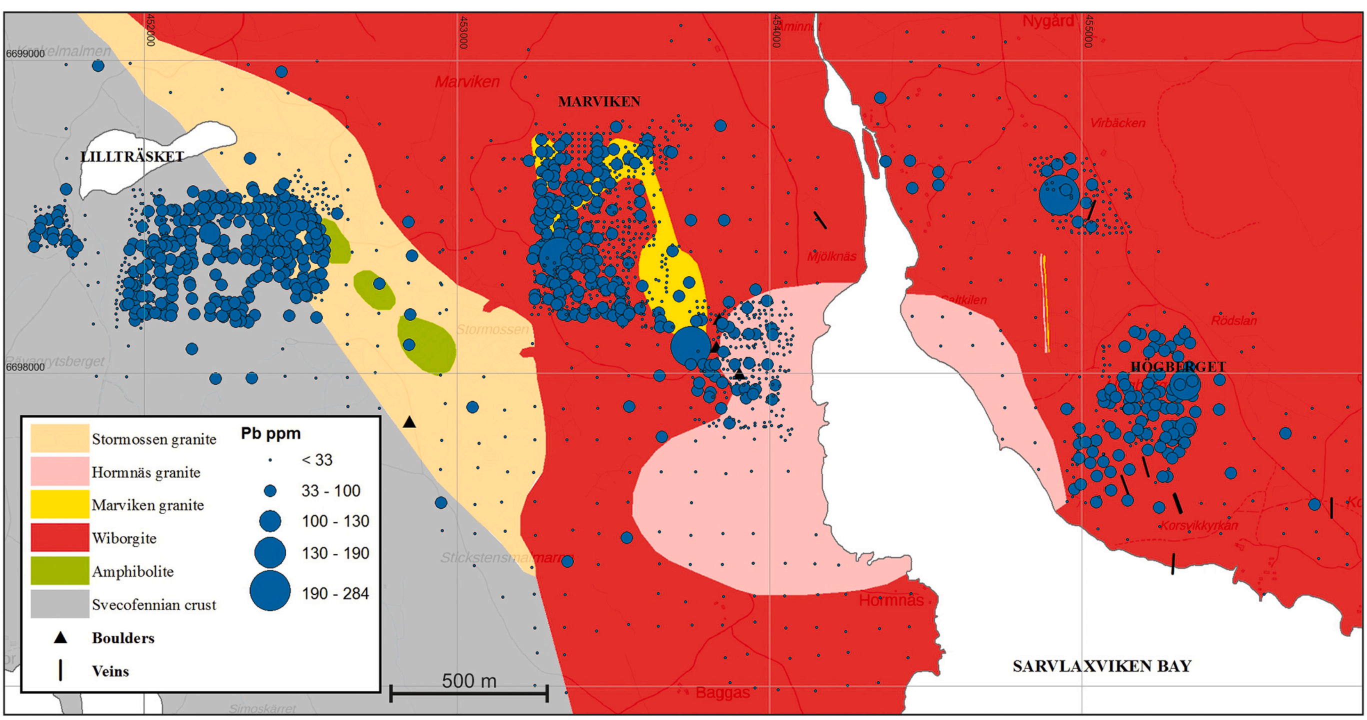

Fig. 14. Proportional symbol map displaying the Pb contents in till in the Högberget, Marviken and Lillträsket areas.

Scotia, Canada, was e.g. detected with a <3 km sampling spacing (McClenaghan and DiLabio, 1993). In this way, a sampling grid with 1 km spacing could be used to detect the mineralised environments while a more narrow sampling grid (100 m) could be used to find more narrow trains. In the Sarvlaxviken area, where cm-dm-wide mineralised veins have been discovered in the bedrock and in glacial-transported boulders (Cook et al., 2011; Valkama et al., 2016), 100 m and 20 m dense sampling grids were used to explore for veins of similar (or larger) sizes.

Several studies indicate short transport distances from the bedrock sources to the metal anomalies. A Sn-rich dispersal train was recognized in km-spaced till samples from the C-horizon, immediately adjacent to the bedrock source, the Kuusisuo greisen vein in the Ahvenisto rapakivi massif, 100 km north of Sarvlaxviken (Peuraniemi et al., 1984). Garrett (1971) noted that a Cu-anomaly in the 1–2 m thick Loven deposit (Val d'Or, Quebec) was an immediate derivation product from the ore body. Furthermore, it has been demonstrated that the proportion of local

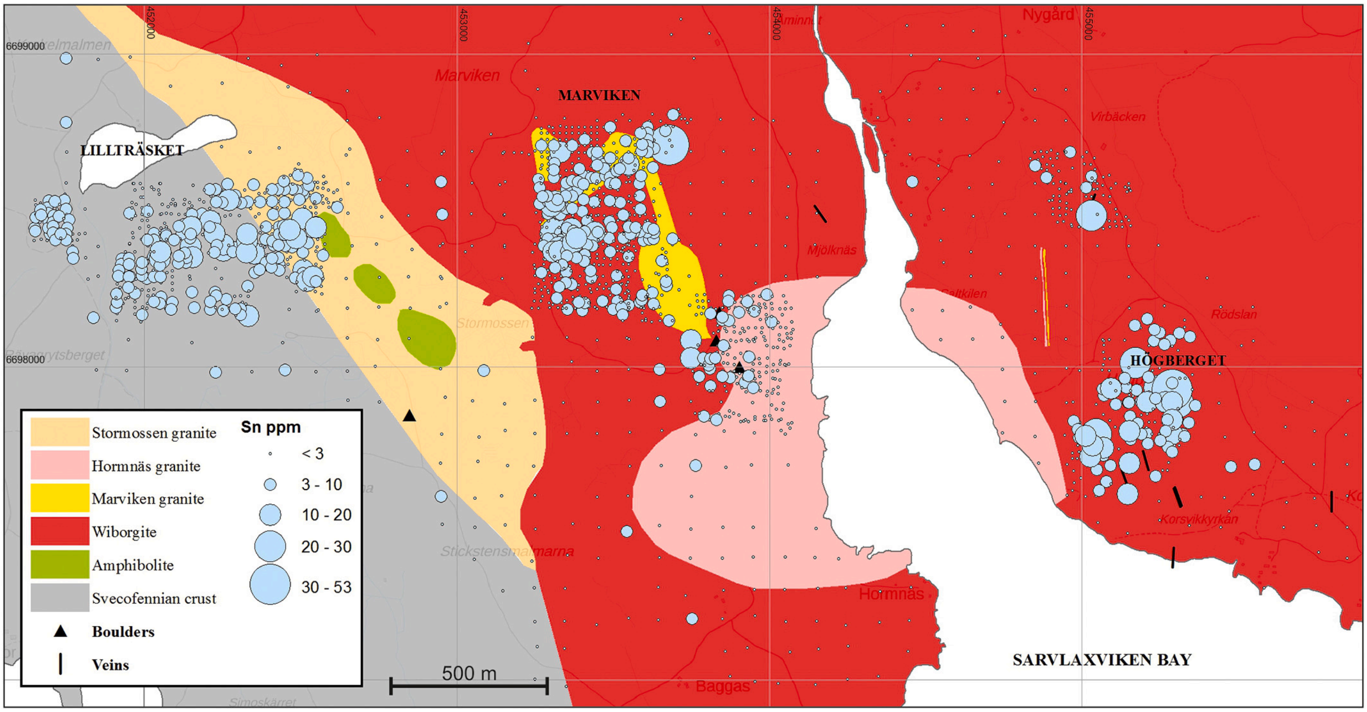

Fig. 15. Proportional symbol map displaying the Sn contents in till in the Högberget, Marviken and Lillträsket areas.

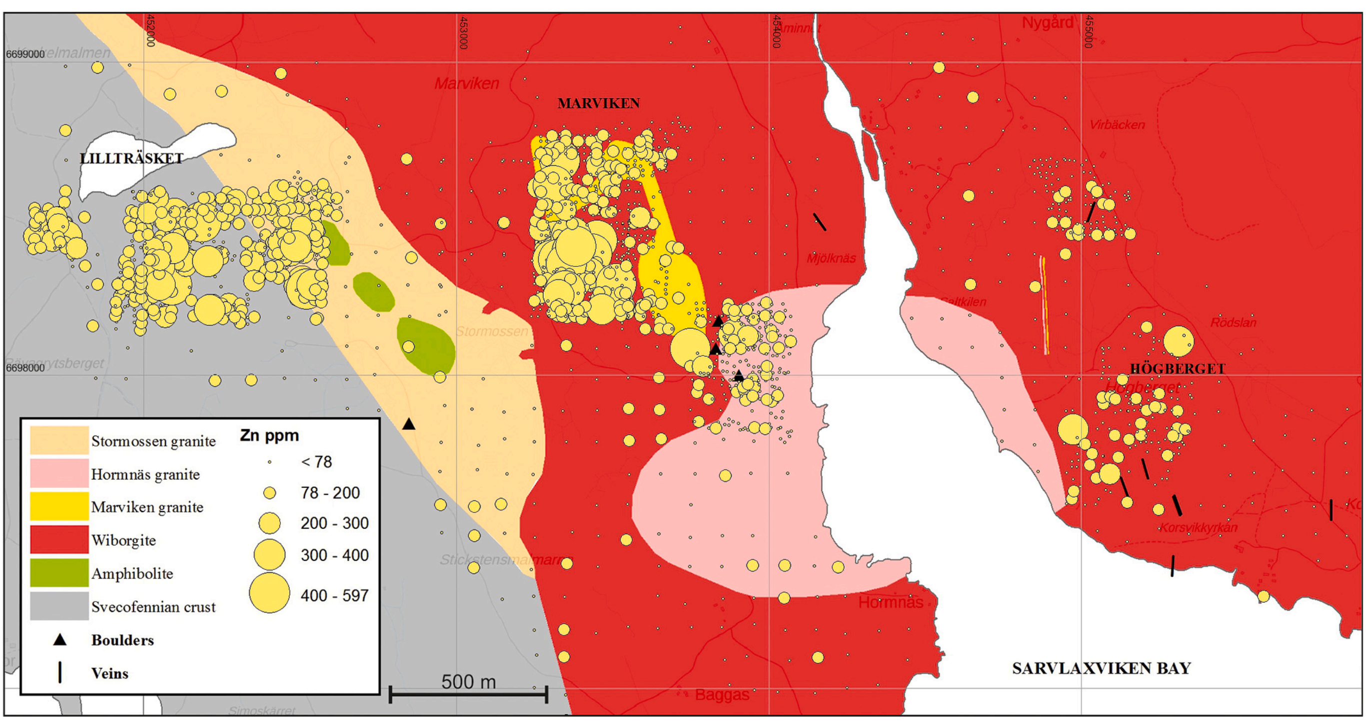

Fig. 16. Proportional symbol map displaying the Zn contents in till in the Högberget, Marviken and Lillträsket areas.

material becomes higher the closer the samples are taken to the bedrock, either by deeper digging or in areas with thin till cover (Drake, 1983; Dreimanis, 1956; Hirvas et al., 1977; McClenaghan et al., 2000). Since the till cover in the sampling sites in the Sarvlaxviken area commonly is 0–1 m thick, it is logical that the metal anomalies in the till must be derived from nearby bedrock sources.

5.2. *The eastern side of Sarvlaxviken*

Cluster analysis can be applied to geochemical data when the aim is to classify elements into meaningful and distinguishable groups (Zhou et al., 2018). In this study, the K-mean cluster analyses has provided information about a large set of data and revealed several areas of strong anomalies. Till samples were collected in an area of <1 km^2 on the eastern side of the Sarvlaxviken area, where polymetallic quartz veins

Table 2
Descriptive statistics of selected elements for clusters 1 (n = 1999) and 2 (n = 168).

	N	Min	Max	Mean	Std. deviation
Cluster 1					
Ag ppm	1999	0	4.14	0.21	0.23
As ppm	1999	0	153.0	4.3	5.7
Ba ppm	1999	45	1630	531	99
Be ppm	1999	1.0	86.9	3.7	3.1
Bi ppm	1999	0	5.45	0.44	0.43
Cd ppm	1999	0	1.6	0.1	0.1
Co ppm	1999	0.4	22.2	3.6	2.3
Cu ppm	1999	0.2	182.0	9.1	9.1
Fe wt%	1999	0.41	13.60	2.61	1.49
Ga ppm	1999	10.4	65.1	19.7	5.5
In ppm	1999	0.1	0.7	0.1	0.1
Li ppm	1999	3.3	114.0	18.8	11.9
Mn ppm	1999	39	830	347	131
Mo ppm	1999	0.1	29.0	1.4	2.0
Ni ppm	1999	1.1	80.3	6.5	5.3
Pb ppm	1999	14.8	284.0	31.3	13.1
Sn ppm	1999	1	53	2	3
Te ppm	1999	0.1	4.3	0.1	0.2
U ppm	1999	1.0	111.0	6.3	7.7
Zn ppm	1999	10.4	367.0	65.6	40.4
Valid N (listwise)	1999				
Cluster 2					
Ag ppm	168	0.03	2.86	0.32	0.34
As ppm	168	0.1	27.7	5.8	5.2
Ba ppm	168	143	655	423	90
Be ppm	168	2.6	11.8	6.3	1.9
Bi ppm	168	0.16	3.24	0.93	0.52
Cd ppm	168	0.1	0.9	0.4	0.2
Co ppm	168	3.7	73.8	10.8	7.9
Cu ppm	168	0.2	117.0	14.6	13.4
Fe wt%	168	1.79	17.30	8.02	3.23
Ga ppm	168	12.0	52.4	29.2	7.5
In ppm	168	0.1	0.7	0.3	0.1
Li ppm	168	7.4	137.0	41.7	26.3
Mn ppm	168	767	4500	1240	508
Mo ppm	168	0.1	23.2	2.6	3.3
Ni ppm	168	2.2	36.6	7.5	5.7
Pb ppm	168	21.9	212.0	53.6	24.4
Sn ppm	168	1	21	6	5
Te ppm	168	0.1	2.8	0.4	0.5
U ppm	168	2.9	49.1	11.2	6.6
Zn ppm	168	37.9	597.0	226.7	122.0
Valid N (listwise)	168				

were known (Valkama et al., 2016). Many of the metals enriched in the veins (Zn, In, Sn, Bi, Fe, Be, As, Mo, Cu, Ag and Cd) are also enriched in the overlying till, in the adjacent ground- and surface waters as well as in berries (Myllymäki, 2014). In this area, the strongest cluster of anomalous samples is located N-NW of where sulphide-bearing veins have been discovered. In detailed investigations of specific element maps, the area has several indications of anomalous samples that are enriched in the same metals as veins in generation 2b (K1–K3, KB). Especially, several of the In-bearing samples occur within a rather restricted area (approximately 500 m^2). However, these veins are unlikely the source of the anomalies. The local ice-movement direction (320°–330°) would have placed the anomaly SE of the veins, not NE or NW of the veins. Therefore, many of these anomalous samples strongly indicate that numerous veins of this type exist in the area.

The K-mean cluster plot detects a few anomalous samples at sites where detailed plots of specific elements display strong and clear anomalies. The K-mean cluster plot can, thus, be considered to indicate anomalous areas, but for proper prospecting in this kind of area where vein generation is enriched with certain metal associations, specific plots for different elements is also needed.

5.3. *The western side of the Sarvlaxviken*

Several metals are enriched in the till in extensive areas south of the Marviken farm field (Figs. 5–17). Some of these anomalies are likely related to sulphide-bearing veins but some may also be related to metal enrichments in the granites themselves. The background contents for Li (approx. 125 ppm) in the unmineralised Marviken granite explain most of the high Li contents in the till in that area. Furthermore, the background contents for Mo in the unmineralised rapakivi granite varieties in the Sarvlaxviken area can be up to 1.5–2 ppm which may explain some of the weakest Mo enrichments in the till. However, when the Mo contents exceed 4–5 ppm they would likely be related to molybdenite-bearing parts of the bedrock (Fig. 13). A majority of the elevated metal contents estimated for the till in the Marviken area should reflect the presence of proper metal sulphides (as has been demonstrated in the metal-rich boulders southeast of the Marviken farm field).

The most realistic source region for NNW-trending polymetallic boulder train must be somewhere to the NNW, partly based on the transport direction documented by Punakivi et al. (1977) and partly based on the fact that the boulder train itself has a NNW-trending extension. Based on the anomaly plots for Sn, As and Mo, the best estimate is that the source(s) for these boulders is immediately south of the Marviken farm field, close to the NE corner of the Marviken granite, which implies transport distances between 500 and 800 m for the individual boulders.

Even if the most likely sources for the metal-rich boulders at Marviken are located close to the NE corner of the Marviken granite, many tens of metal-anomalous samples have been collected from the till further to the west, where two types of metal signatures can be identified. One element association is Mo-Be-Sn-W-Be which follows the distribution of the northern limb of the Marviken granite and another association is characterized by Fe-Zn-Cd-In-Sn which occurs in till overlying wiborgite along respective margin of the northern limb of the Marviken granite.

The Lillträsket area includes two significant cluster of anomalous samples occurring 540 m and 680 m NNW (325° and 328° respectively) of the Zn-Cd-rich boulder discovered in 2009 (Figs. 5–17). These anomalies are located in till overlying the Stormossen rapakivi granite at distances of 40–50 m respective c. 100 m from the border to the Late Svecofennian granite and are highly probable sources for the Zn-rich boulder, with respect to transport directions, transport distances and type of host rock in the Zn-Cd-rich boulder. It is, however, also noted that several other metals (e.g. In, Fe, Cu, Bi, Ag, Bi and Sn) are enriched in the till at the assumed source rock sites for this boulder. Of even higher interestingly most of the till in the entire region south of the Lillträsket lake is anomalous with respect to metals. The strongest anomalies (with respect to Zn, Cd, Fe and In) are recorded 250–350 m south of the lake centre, all in the Late Svecofennian granite, but Zn-Cd-Fe-In-anomalies also occur SW of the lake, 600 m from the border to the Wiborg rapakivi granite.

In parallel with the analytical work to determine the metal contents in the till samples, Vind (2014) made systematic determinations of the mass susceptibility in the same samples and could demonstrate a close correlation between high mass susceptibility values and high contents of iron (and other metals like Zn, Cd, Sn and In). The coincidence between these two parameters was further matched with magnetometry anomalies at the same sites as where the magnetic Fe-rich till samples had been collected. This demonstrates an important link between a magnetometry anomaly (in the bedrock), an overlying till cover with high mass susceptibility values and high Fe-Zn-Cd contents. All this provides strong evidence for very short (<20 m) glacial transport of the magnetic material in the bedrock to the Fe-Zn-Cd-bearing till anomaly.

5.4. *Prospecting potential*

The discovery of In-bearing quartz veins east of the Sarvlaxviken bay

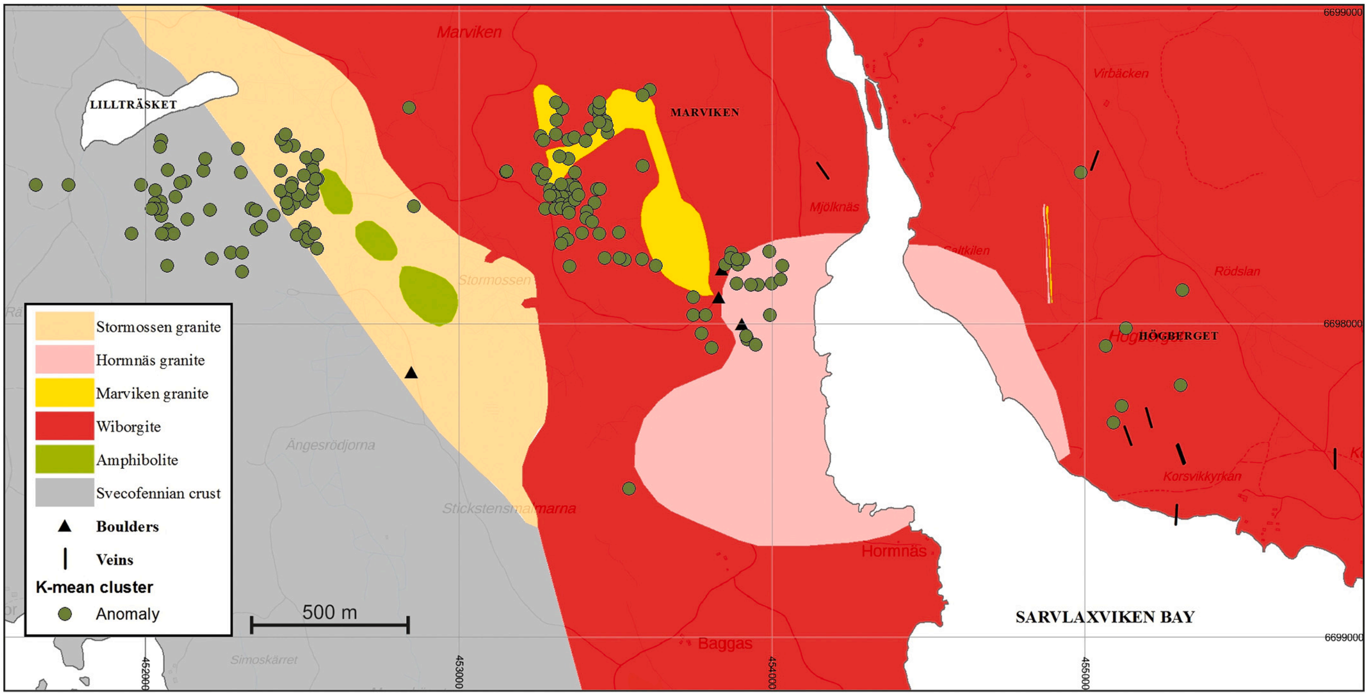

Fig. 17. Distribution of cluster 2 sample points in the Högberget, Marviken and Lillträsket areas.

(Cook et al., 2011) and ore-bearing boulders west of the same bay (Valkama et al., 2016) were the first signs to initiate systematic exploration for indium in that area. After recognizing c. 200 metal anomalous till samples in the same area, the potential for finding more veins in the Sarvlaxviken region has increased considerably.

It may be argued that the hitherto discovered cm-wide veins are far too narrow (although locally very metal-rich), but the fact that significantly thicker veins are observed in boulders, and not the least that intense and extensive till anomalies exist west of the Sarvlaxviken bay indicate that these areas are interesting from an exploration point of view.

The knowledge obtained from Cook et al. (2011), Valkama et al. (2016), Broman et al. (2018) and this study also provides scientifically important data, which can be used for exploration elsewhere where the geology is similar to the Sarvlaxviken area. As a consequence, by using the results from this study, it may be possible in the future to find economically viable, polymetallic, In-bearing ore deposits elsewhere in the Wiborg Batholith or in other similar anorogenic granites.

6. Conclusions

Based on more than 2000 till samples, collected within 20 km^2 in the Sarvlaxviken area, southeastern Finland, numerous anomalies of Ag, As, Be, Bi, Cd, Cu, Fe, In, Mo, Pb, Sn and Zn have been recognized.

The metal anomalies occur in till overlying bedrock consisting of the westernmost parts of the Wiborg Batholith and its immediate surroundings of Late Svecofennian granites.

Each metal anomaly is considered to be located at a relatively short (<50 m) distance from the bedrock source, which is in agreement with glacial transport distances of till matrix (<100 m) reported from elsewhere in southern Finland by Kokko (1988).

Several In-bearing polymetallic veins have been identified in the Sarvlaxviken area (Cook et al., 2011; Valkama et al., 2016; Broman et al., 2018) but their spatial relations to the till anomalies are such that none of them can represent the metal source for any of the till anomalies. Instead, the till anomalies can only be explained by undiscovered polymetallic veins, but before such veins are proven, by e.g. digging or drilling into the bedrock, their presence will remain uncertain. If this could be demonstrated, this till geochemistry survey would be a valuable example of a powerful exploration tool in regions with few bedrock out-crops, where till is common and where the glacial transport distance of the till matrix has been short.

CRediT authorship contribution statement

Mira Valkama: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Krister Sundblad:** Conceptualization, Supervision, Writing - original draft, Writing – review & editing. **Kirsti Korkka-Niemi:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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