

A smartphone-based ground magnetic survey for tracing the iron ore that crops out on NE Utö

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Abstract

The historical iron deposits at Utö have been significant during Utö's history, since exploitation began during the 12th century. Utö has a long interesting geological history and is important for understanding the geological evolution of the Bergslagen region. Likewise, the geology of Utö is best understood within the broader geological history of the Bergslagen region.

This study presents a ground magnetic survey of northeastern Utö with the aim of investigating the stratigraphic position of the iron ore that crops out on northeastern Utö. By mapping magnetic anomalies and comparing these with previous geological maps, structural geological maps and a magnetic anomaly map, it was possible to investigate and re-evaluate the previous geological interpretations. Magnetic field measurements were collected using the mobile phone application Physics Toolbox Sensor Suite and processed in QGIS to produce magnetic anomaly maps.

The survey identified several strong positive and negative magnetic anomalies associated with the historical mine sites of Nyköpingsgruvan, Långgruvan, Östra Brottet, Bykgruvan and Silvergruvan. Additional magnetic anomalies were identified both northwest and northeast of the known deposits. Comparisons with previous geological maps show that the anomalies are generally associated with the felsic metavolcanic and volcanoclastic succession, in the upper unit of the supracrustal rocks, although some anomalies also occur within adjacent lithological units depending on the geological interpretation adopted. The magnetic anomalies typically follow the structural synform. Several previously unmapped magnetic anomalies were identified.

This study proposes two alternative lithostratigraphic models for the Utö supracrustal succession, both consisting of a basal metasedimentary unit. They differ in whether the metavolcanic, volcanoclastic rocks and overlaying carbonates represent a single continuous succession or repeated volcanic and carbonate cycles. In both models, the iron oxide and sulphide mineralisation are interpreted as stratabound, occurring in the upper unit of the succession. The iron ore and sulphide deposits occur within felsic metavolcanic and volcanoclastic rocks, limited to VAS, at the same or closely related stratigraphic positions. They are not structurally controlled, which implies that the supracrustal rocks were deposited prior to deformation. This study cannot confirm whether the ore mineralisation is restricted to one ore body-unit that has been folded, or if there are several ore bodies in different strata that has been folded.

The results demonstrate that ground magnetic surveying using a smartphone-based magnetometer can be used to identify iron oxide and iron sulphide mineralisation and additional magnetic anomalies. The study further demonstrates that magnetic data can complement previous geological mapping and contribute to an improved understanding of the supracrustal rocks located on northeastern Utö.

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Content

1.0 Historical and geological significance of Utö	8
1.1 Aims and thesis question.....	9
1.2 Regional geology.....	10
1.2.1 Supracrustal rocks and their stratigraphic positions	10
1.2.2 Ore deposits.....	10
1.2.3 Intrusions	11
1.3 Local geology	11
1.3.1 Lithostratigraphic and structural model by Holmquist (1910)	11
1.3.2 Lithostratigraphic and structural model by Gavelin et al. (1976).....	12
1.3.3 Lithostratigraphic model by Stålhös (1982).....	12
1.3.4 Structural model by Stålhös (1982).....	12
1.3.5 Lithostratigraphic and structural model by Allen et al. (1996)	13
1.3.6 Lithostratigraphic model by Talbot (2008)	13
1.3.7 Structural model by Talbot (2008)	14
1.3.8 Lithostratigraphic model by Dunst et al. (manuscript).....	14
1.3.9 Iron ore deposits	15
2.0 Theoretical Background of Applied Geophysics within Magnetometry.....	15
2.1 Magnetic survey	15
2.2 The geomagnetic elements	15
2.3 Magnetic susceptibility.....	16
2.4 Magnetic anomalies.....	17
2.5 Magnetic data reduction	17
2.5.1 IGRF and DGRF	17
2.5.2 Diurnal variations	18
2.6 The Hall effect and the Hall-effect sensor.....	18
3.0 Methods and materials.....	19
3.1 Literature review	19
3.2 Field data acquisition.....	19
3.3 Data collection timeframe	20
3.4 Preliminary GIS Map	20
3.5 Data processing	21
3.6 GIS	21
3.6.1 DEM.....	21
3.6.2 Vector layers and CRS	21
3.6.3 IGRF and DGRF	21

3.6.4 IDW-Interpolation, buffer and clip raster by mask	21
3.6.5 Symbology & Classification of the Magnetic Anomaly Intensity Map	22
3.6.6 Symbology & Classification of the Magnetic Anomaly Vector Map	23
3.6.7 Finalizing map & map comparisons.....	24
4.0 Results	24
4.1 Profiles	24
4.2 Magnetic anomaly intensity and vector maps	25
4.2.1 Magnetic anomaly intensity and vector maps displayed on the geological map of Holmquist (1910)	26
4.2.2 Magnetic anomaly intensity and vector maps displayed on the geological map of Gavelin et al. (1976).	28
4.2.3 Magnetic anomaly intensity and vector maps displayed on the geological map of Stålhös (1982)	29
4.2.4 Magnetic anomaly intensity map displayed on the anomaly map of Stålhös (1982)	31
4.2.5 Magnetic anomaly intensity and vector maps displayed on the lineation map of Stålhös (1982)	32
4.2.6 Magnetic anomaly intensity and vector maps displayed on the geological map of Allen et al. (1996)	34
4.2.7 Magnetic anomaly and vector maps displayed on the geological map of Talbot (2008)	35
4.2.8 Magnetic anomaly and vector maps displayed on the lineation map of Talbot (2008)	37
4.2.9 Magnetic anomaly intensity and vector maps displayed on the geological map of Dunst et al. (manuscript).....	38
5.0 Discussion	40
5.1 Lithology, iron oxide and sulphide mineralisation, and the spatial relationship of the magnetic anomalies.....	40
5.1.1 Lithostratigraphic models in comparison with the magnetic anomaly map	40
5.1.2 This study's interpretation of the supracrustal rock succession and the stratigraphic position of the iron ore	41
5.3 Structural and spatial relationship with magnetic anomalies	42
5.4 Comparison of magnetic anomaly maps from this study and Stålhös (1982)	42
5.5 Limitations and error sources	43
5.5.1 Magnetic surveying	43
5.5.2 GPS and Magnetometer.....	44
5.5.3 Hall-effect sensor.....	44
5.5.4 Map interpretations.....	44
5.5.5 Interpolation	44
5.5.6 Symbology and classification:.....	45
5.5.7 Literature review	45

6.0 Conclusion.....	46
Reference list.....	47
Appendix	49
Appendix A	49
Appendix B	51
Appendix C	53
Appendix D	54

1.0 Historical and geological significance of Utö

Utö is an island located 40 km southeast of Stockholm, Sweden. It has a long history of mining and geological research, where mining has been active since the beginning of the 12th century, until 1879 (SGU, n.d.; Holmquist, 1910; Stålhös, 1982). The most abundant ore is BIF (Talbot, 2008), but sulphide mineralisations also occur (Stålhös, 1982; Talbot, 2008). Magnetic surveys over the area have been conducted to identify areas of significant mineralisations (Stålhös, 1982).

Between 1711 and 1878, 2 070 900 tons of iron ore were exploited (Holmquist, 1910). Several mines are located on the island, where the two northern, Nyköpingsgruvan and Finngruvan, have been mined to depths of c. 214 meters and 150 meters respectively (Stålhös, 1982). At the beginning of the 16th century native silver was found (Holmquist, 1910). Nevertheless, the mineral occurrences were too small for exploitation.

Several new rare minerals have been found at Utö, such as petalite, in which the element Lithium first was discovered during the 19th century (SGU, n.d.; Stålhös, 1982). Utö is internationally recognised for its natural resources of lithium, however not in mineable quantities (Stålhös, 1982). Several pegmatitic dikes with lithium occurrences have been identified, however, one that crosses through Nyköpingsgruvan is specifically famous for being lithium rich (Gavelin et al., 1976; Stålhös 1982). The mineral “Holmquistit” is another lithium rich mineral, that was discovered by professor P.J. Holmqvist, that occur among skarn layers adjacent to some of these dikes (Utö Hembygdsförening, n.d.; Stålhös, 1982).

1.1 Aims and thesis question

This thesis aims to conduct a magnetic survey of northeastern Utö, using the smartphone application “Physics toolbox Sensor Suite” (Vieyra Software, n.d.). The magnetic survey intends to trace the iron ore that crops out in the central part of northeastern Utö, beginning from the mines Nyköpingsgruvan, Långgruvan, Östra Brottet, Bykgruvan and Silvergruvan towards the northwest and east. The data from the magnetic survey will be used to construct a GIS map of the magnetic anomalies. By doing a literature review and comparing the GIS map to previous geological, structural and magnetic anomaly maps of the geological area, that has been produced by Allen et al. (1996), Dunst et al. (manuscript), Gavelin et al. (1976), Holmquist (1910), Stålhös (1982) and Talbot (2008) , the following question shall be answered:

- What is the stratigraphic position of the iron ore that crops out in the central part of NE Utö?

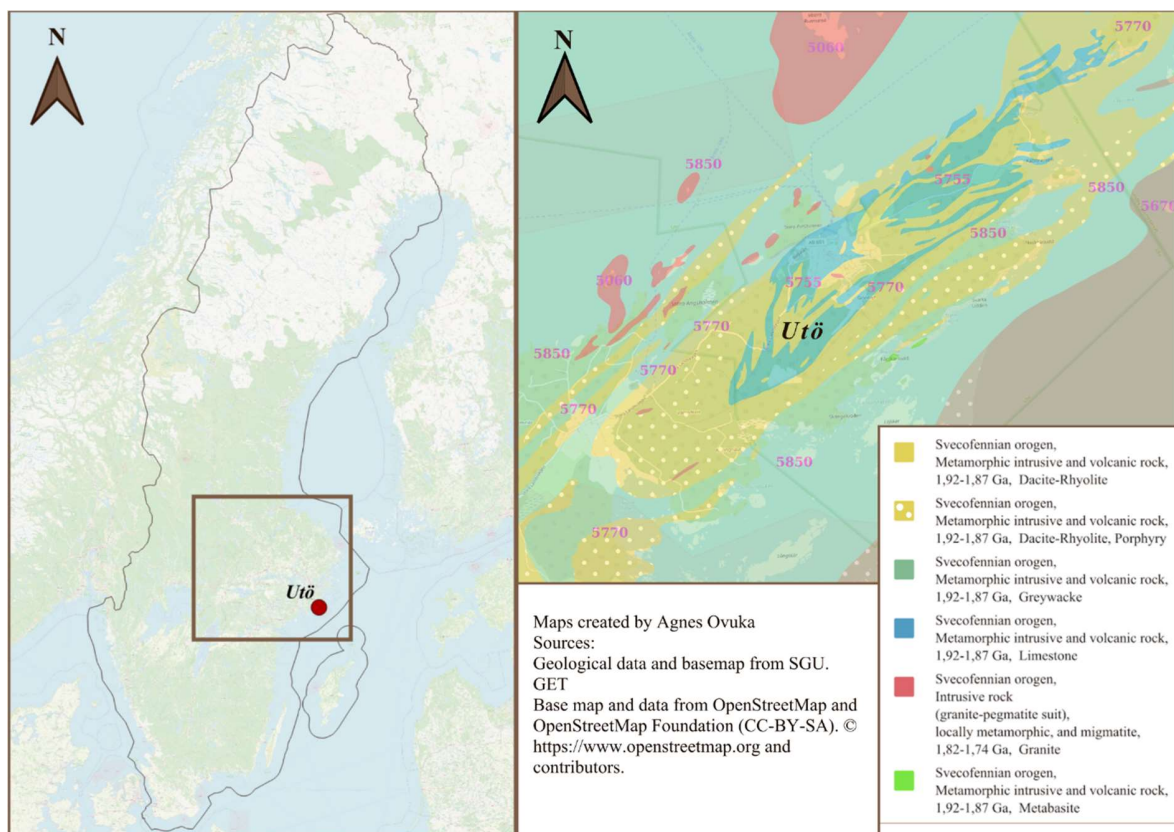


Figure 1. (1) Overview Map over Sweden and Utö, where Bergslagen is located within the brown box. (2) Geological map over Utö.

1.2 Regional geology

Utö is located within the Svecofennian province and is geologically associated with the Bergslagen region, which forms part of the Paleoproterozoic Baltic shield (Allen et al., 1996). The Bergslagen region has been interpreted as an extensional back-arc magmatic region near an active continental margin, which has significantly deformed the original stratigraphy. It is a felsic magmatic region that was affected by low pressure and high temperature metamorphism (Stålhös, 1982, p. 27). Generally the region is of lower to upper amphibolite facies metamorphic rocks, but there is a small area of greenschist facies in western Bergslagen, such as the area of Grythyttan (Stålhös, 1982, pp 27-28). However, prior to ductile deformation, the volcanic rocks were affected to variable extents by different types of regional hydrothermal alteration (Stephens, 2009, pp 9-10). The supracrustal rock succession was deposited between ca 1.90 and 1.87 Ga (Allen et al., 1996). Thick quartzites locally contain detrital zircons with ages ranging from 1.95 to 2.7 Ga, indicating that an older granitic basement underlies the region.

1.2.1 Supracrustal rocks and their stratigraphic positions

The supracrustal rock succession can be divided into four units. The basal part is composed of turbiditic metagreywacke. The lower part of this unit consists of poorly sorted sandstones, whereas the upper portion consists of sub-greywackes of quartz rich sandstone and quartzite, argillite, and conglomerates (Allen et al., 1996; Stephens, 2009).

The metavolcanic succession overlies the basal sedimentary unit (Stephens, 2009). It is of mainly rhyolitic character, including shallow subvolcanic intrusions. In the west there are characteristics of bimodal rhyolite-basalt composition. In the east, dacite and andesite are abundant (Allen et al., 1996). The upper part of the metavolcanics contains interbeds of pelitic sediments, limestones, graphitic pelite, and chemical sedimentary rocks, including marble, BIF and calc-silicate rock (Allen et al., 1996; Gavelin et al., 1976; Stålhös, 1982).

Above the volcanic rocks lie a younger sequence of clastic metasedimentary rocks, consisting of metargillite, sandy to muddy turbidities, and quartzite and metaconglomerates (Allen et al., 1996; Stephens, 2009).

The metavolcanic rocks in the region are known as the Leptite formation, however, traditionally there's a division between them, namely Hälleflintas and Leptites (Holmquist, 1910; Stålhös, 1982). Hälleflintas are characterized by fine recrystallised matrixes and correspond to greenschist facies, and the leptites are characterized by coarsely recrystallised matrices that correspond to amphibolite facies (Allen et al., 1996).

1.2.2 Ore deposits

The major part of the ore deposits is hosted as intercalations in metamorphosed and hydrothermally altered rhyolitic volcanic rocks, and the associated skarn or carbonate rock (Stephens, 2009). These include banded iron formation (BIF), magnetite calc-silicate skarn, manganiferous skarn- and carbonate-hosted iron ore, apatite bearing iron ore, stratiform and stratabound Zn-Pb-Ag-(Cu-Au) sulphide ores, and W skarn (Allen et al., 1996; Stephens,

2009). The majority of the major base metal sulphide deposits and iron ore deposits are located in the upper part of the volcanic succession, whereas the apatite bearing iron ores are an exception (Allen et al., 1996). The base metal sulphide deposits mainly formed slightly later than most iron ores. A general regional facies model is appropriate in the area, because several base metal sulphide deposits are located adjacent to iron ore deposits in the same stratigraphic unit.

1.2.3 Intrusions

The 1.91 - 1.89 Ga and older supracrustal rocks were intruded by three different compositional suites (Stephens, 2009, p. 10; Stålhös, 1982). The Granitoid-dioritoid-gabbroid (GDG) intrusive rock suite is the oldest intrusive rock suite in the Bergslagen region, and intruded between 1.90 -1.87 Ga. The GDG dominates the bedrock in the region. The Granite-syenitoid-dioritoid-gabbroid (GSDG) intrusive rock suite can be divided into two suites, where the first suite was between 1.87-1.84 Ga and the second one between 1.81-1.78 Ga. The Granite-pegmatite (GP) intrusive rock suite intruded between 1.85 - 1.75 Ga and overlaps with the late GSDG rocks.

1.3 Local geology

Several lithostratigraphic and structural models have been proposed for the supracrustal succession of Utö. This section presents the interpretations of Allen et al. (1996), Dunst et al. (manuscript), Gavelin et al. (1976), Holmquist (1910), Stålhös (1982) and Talbot (2008). The models are presented in chronological order according to their publication date, where the last by Dunst et al. (manuscript) has not yet been published. The results of this study will later be compared to the previous models and be further discussed.

1.3.1 Lithostratigraphic and structural model by Holmquist (1910)

Holmquist (1910) interpreted the coarse-bedded leptites as the oldest unit on Utö. These were intruded and partly uplifted by acid magmas, after which alternating lava and tuff, with ash material and volcanic muds were deposited on the porphyritic beds. Above these, limestone bearing sediments were later deposited. The northern part of Utö consists of alternating layers of limestone, hälleflinta, calcareous hälleflinta. The iron ore is predominantly of quartz banded hematite or grey quartzite banded magnetite, adjacent to coal bearing hälleflinta. These are followed by leptites, hälleflintas and amphibole bearing calcareous rocks. Holmquist (1910) believes the iron ore formed as a sediment together with the stratified leptites, hälleflintas and limestones. According to Holmquist (1910) sulphide minerals are associated with the iron ore. The sulphides mainly include chalcopyrite, pyrite, galena, blende and pyrrhotite, and are commonly followed by quartz and calcite and usually form tiny cementing masses in the iron ore and the surrounding rocks, particularly in the hälleflintas. These together with the porphyries form a near isoclinal fold, where the first unit fills the space between the limbs. This caused the strata to dip steeply and resulted in the northwestern and southeastern metasediments corresponding stratigraphically to each other.

1.3.2 Lithostratigraphic and structural model by Gavelin et al. (1976)

Gavelin et al. (1976) interpreted that the supracrustal rocks formed a monoclinial succession where the oldest rocks occur at the southeast and the youngest at the northwest. The succession is divided into four units, where the lower unit consists of greywackes and subgreywackes. Above this lies the hälleflinta and leptite-group with its limestones, skarn, iron ore and occasional sulphide mineralisation. The porphyry sheets might be of hypabyssal intrusions between the greywacke and the hälleflinta-leptite group. The upper, northwestern metasedimentary unit consists of dacitic tuffs and metasubgreywackes. They suggested that the supracrustal rocks were deposited prior to deformation and folding. Structurally, the most prominent structure on Utö is a major isoclinal fold, which is part of a large drag fold. Its northwestern limb is cut by a fault, going northeast to southwest through Kyrkviken on Utö. Bedding strikes mainly northeast and dips steeply to the northwest, while the axis of the great fold plunges steeply towards the southwest.

1.3.3 Lithostratigraphic model by Stålhös (1982)

Stålhös (1982) suggested that Utö is composed of a monoclinial succession, with the oldest rocks occurring in the southeast and the youngest in the northwest. The stratigraphic succession is divided into four units. The southeastern metasedimentary group consists of meta-argillite and meta-arenite with local intraformational conglomerates. This is overlain by a metavolcanic unit composed of hälleflinta and leptites associated with marble, skarn and iron ores. The upper metasedimentary group consists of banded metatuffitic formation of feldspar porphyry-porphyrityte with a rhyodacitic to quartz-andesitic composition. Subvolcanic intrusions of quartz porphyry and plagioclase porphyrites occur at different levels. The iron ore is a banded iron formation (BIF), consisting predominantly of quartz-banded hematite, which eventually transitions to quartz-banded magnetite. Several sulphide mineral deposits occur northeast of Bykgruvan within a zone approximately 300 m long. Stålhös (1982) suggests the sulfide mineralisation is occurring at a slightly higher structural level than the iron ore deposits. Stålhös (1982) interpreted that the iron ore deposit is hosted within the alkalic metatuffites (leptites) and hälleflintas, within the synformal structured part of Utö.

Stålhös (1982) presented a map of the total magnetic intensity, displaying the distribution of magnetite within the bedrock of the study area. According to Stålhös (1982), weaker magnetic sulfides have most likely caused several of the magnetic anomalies. A correlation, between lithological- and magnetic contour boundaries, can be expected to the extent where magnetite and magnetic sulfides are constantly associated with a specific rock type. This applies principally to the leptites, where a significant content of magnetite is expressed by strong magnetic anomalies around the mine localities.

1.3.4 Structural model by Stålhös (1982)

Stålhös (1982) proposed that the supracrustal rocks were lithified prior to deformation and folding. In northern Utö, the earliest tectonic event is interpreted to have been a southwest directed thrust movement. Evidence for this is preserved within the trough composed of limestone and leptite, where two southwest verging leptite fold arcs occur, located southwest and north of the mines. This was followed by northwest verging folding of the succession, resulting in a major synform with its adjoining antiform. The deformation resulted in axial planes that dip steeply towards the northwest. The steeply oriented axial planes hindered southwest directed thrust movement. Instead, the applied stress caused slip along the steep

axial planes that strike northeast to southwest, which formed upright folds. Associated fold axes and lineations show a maximum plunge of 85 degrees towards the northwest. Intense tectonic deformation is recorded in northern Utö, where Breccia formations consisting of fragmented hälleflinta interbedded within carbonates, where the carbonates display plastic behaviour of the carbonates.

1.3.5 Lithostratigraphic and structural model by Allen et al. (1996)

Allen et al. (1996) suggested that the base of the supracrustal succession consists of a thick metasedimentary succession, composed of quartz-rich turbidites, overlain by a metavolcanic succession associated with metalimestones and skarns. The upper part of the supracrustal sequence is deformed by a mylonite zone, leading to a change in metamorphic grade. As a result, the original thickness of the metavolcanic succession and/or the character of the original strata is uncertain. A metavolcanic unit, interpreted as an ignimbrite, is in the lower part of the metavolcanic succession. Allen et al. (1996) suggested that the Bergslagen region is an extensional back-arc magmatic region near an active continental margin, which has significantly altered the original stratigraphy.

According to Allen et al. (1996), most iron oxide and sulphide deposits are hosted in hydrothermally altered metavolcanic rocks and are associated with metalimestones and skarns in the Bergslagen region. Nevertheless, the BIFs are suggested to be a chemical suspension deposit, interlayered with rhyolitic ash siltstone. The sulphides include stratabound volcanic associated limestone-skarn-hosted Zn-Pb-Ag-Cu-Au deposits (SVALS) and stratiform ash-siltstone hosted Zn-Pb-Ag sulphide deposits (SAS).

However, Allen et al. (1996) believes the stratigraphic position of the Utö ore deposits is difficult to decide, due to the tops of the volcanic succession not being exposed. On northeastern Utö, the rhyolitic ash siltstone is in the upper part of the volcanic succession in the syncline. Allen et al. (1996) argued that due to the fairly old age of the lower part of the volcanic sequence at Utö, the overlying ash-siltstone, limestone and related ore deposits, could be correlates of the ash-siltstones in the rest of Bergslagen region. However, they could also represent a completely older cycle of intense volcanism, waning volcanism and ore formation.

1.3.6 Lithostratigraphic model by Talbot (2008)

Talbot (2008) interpreted the supracrustal succession to be part of an accretionary prism, where the magmatic arc activity began to convert the accretionary prism into a crystalline Svecofennia at about 1.904 Ga. The basal part of the stratigraphic succession consists of bedded and unbedded greywackes. According to Talbot (2008) the Utö greywackes were recycled by mass flows in the accretionary prism subducting the floor of an ocean open to what is now the east. The lower part of the greywackes is distinguished by frequent graded bedding, while the upper part may exhibit graded bedding, cross-bedding and conglomerates. The prism constructed a shelf of siliciclastic sediments, which were buried by deposits of silica-rich pyroclastic rocks. Towards the northeast along the axial trace of the synform, the pyroclastic deposits thin out among carbonate beds of variable purity. These were interlayered with individual eruptions of pyroclastics coming from a contemporaneous magmatic arc. Talbot (2008) positioned the BIF and sulphide mineralisation within the youngest supracrustal rocks, which are infolded into the core of the F2 synform. The BIF consists of beds of siliceous cherts interbedded with haematitic or magnetite-rich cherts, while the sulphides

occur within finegrained siltstones and pyroclastic deposits. According to Talbot, the BIF possibly reflects calm water deposition of chemical sediments that were furnished by the magmatic arc (Talbot, 2008). Sheets of granitoids crop out in the south among the migmatites, and these are approximately at the same structural level as the porphyry sheets within the greywackes and shelf sediments. Talbot (2008) interpreted the tectonic evolution of Utö to involve two deformation phases, D1 and D2, and two metamorphic phases, M1 and M2.

1.3.7 Structural model by Talbot (2008)

During D1, tight to isoclinal F1 folds formed. The F1 folds verged west, and their fold axes now trend approximately north to northwest and are large enough to be called nappes (Talbot, 2008). A penetrative grain-shape fabric (S1 fabrics) is axial planar to F1 folds, developed simultaneously in most rocks of Utö. D2 overprinted most D1 structures. During D2, F2 folds with steep southwest to northeast trending axial surfaces were formed. The most dominant structure on Utö is the F2 synform, along the centerline of Utö. Its northwestern limb was sheared by the Utö Shear Zone, also called USZ. A steep foliation (S2 fabrics) that are axial planar to F2 folds, are absent from the cherts, BIF and volcanic rocks. However, these are formed in the migmatites and carbonates, as well as refolding the S1 in the sandstones, older granite and quartz porphyries. One siliceous bed, exposed on the northwest coast, is brecciated and record shelf instability.

Talbot (2008) interpreted two metamorphic phases, M1 and M2, which most likely correspond to the two phases of regional metamorphism dated in the Bergslagen region at c. 1.87 and 1.78 Ga (or younger). According to Talbot (2008), macroscopic zoning of the porphyroblasts of andalusite $\pm$ cordierite $\pm$ garnet in the mudstones of the greywackes can be seen in the field to record two phases of growth. He argues that most porphyroblasts preserve evidence of both M1 + M2, where they have a macroscopic impure margin around a cleaner core. Talbot (2008) noted macroscopic strain shadows or deformed inclusion trails associated with any of the garnets are absent, which he interpreted to indicate that their growth phases outlived both D1 and D2.

1.3.8 Lithostratigraphic model by Dunst et al. (manuscript)

Dunst et al. (manuscript) suggests Utö preserves a shallow marine-felsic volcano-sedimentary system and represents a small-scale example of stratiform mineral systems in Bergslagen. The basal unit of the supracrustal succession consists of interbedded sandstones and siltstones, local conglomerates. Within the upper part of the lower unit, crossbedded sandstone units and minor ignimbrites are present. The upper unit of the succession is mainly composed of volcanic ash siltstone, with an increasing abundance of carbonate layers further up in the sequence, which Dunst et al. (manuscript) interpreted as deposition below the wave base in a shallow marine basin. In the upper part of the upper unit, coarser volcanoclastic interlayers occur, but are rare. They argue that early volcanism included both rhyolitic and dacitic compositions. However, later input was mainly of highly evolved rhyolites. Dunst et al. (manuscript) proposes that wavy carbonate-ash interfaces are possible stromatolitic growth surfaces. These are in the middle upper unit, indicating deposition in the photic zone. Similar structures occur in the Bergslagen region, where they have been suggested to represent draped stromatolites.

According to Dunst et al. (manuscript) the Fe-oxide and Zn-Pb-Ag mineralisation are limited to a single, restricted, stratigraphic section within the upper ash-siltstone-carbonate

succession. This can be followed by approximately one kilometer along strike. The iron oxides mineralisation is in the upper part of the upper unit and lie within a section dominated by siltstones with only thin carbonate interbeds. The main sulphide mineralisation occurs within volcanic ash siltstone (VAS) on the northeastern continuation of the iron oxide mineralisation. These are polymetallic and occur mainly as thin layers of pyrrhotite with some galena, sphalerite pyrite and chalcopyrite. Minor sulphides occur as veinlets crosscutting the Fe-oxide mineralisations and its host rock, across the principal ore horizon.

1.3.9 Iron ore deposits

The primary iron ore is banded iron formation, consisting of quartz banded, with magnetite and/or hematite mineralisations (Allen et al., 1996; Dunst et al., manuscript; Gavelin et al., 1976; Holmquist, 1910; Stålhös, 1982; Talbot, 2008). The ore body has an extension of approximately 700 meters, is about 70 m thick on the hinge and up to 25 m thick on the F2 synform limbs (Gavelin et al., 1976; Holmquist, 1910; Talbot, 2008).

As mentioned previously mentioned, sulphide deposits occur at Utö (Allen et al., 1996; Dunst et al., manuscript; Gavelin et al., 1976; Holmquist, 1910; Stålhös, 1982; Talbot, 2008). The main sulphide deposits continue northeast of the BIF, occurring in Bykgruvan and Silvergruvan (Dunst et al., manuscript; Gavelin et al., 1976; Holmquist, 1910). These are polymetallic, according to Dunst et al. (manuscript), Holmquist (1910) and Stålhös (1982). The different authors broadly agree regarding the lithostratigraphic framework of the supracrustal succession. However, the stratigraphic position of the Fe-oxide and sulphide mineralisation is being debated.

2.0 Theoretical Background of Applied Geophysics within Magnetometry

2.1 Magnetic survey

Magnetic surveying is a geophysical method used in the exploration of economically valuable minerals and other resources that are of economic significance, as well as planetary studies, geological mapping, archaeological surveys, the detection of old mines and objects distributed by human activity (Mussett & Khan, 2000, p. 162). A magnetic survey's intention is to identify and characterize regions that exhibit anomalous magnetization of the Earth's crust (Lowrie, 2007, p. 324). A magnetometer is needed when executing a magnetic survey, which is an instrument that measures the terrestrial magnetic field at a specific locality (Mussett & Khan, 2000, p.162; Lowrie, 2007, p.324).

2.2 The geomagnetic elements

The geomagnetic field can be explained with the cartesian sets of geomagnetic elements X (north), Y (east), Z (vertically downward) or by the angles I (Inclination), D (Declination) and F (total field intensity), which are the spherical polar geomagnetic elements (Lowrie, 2007, p. 306) . These relate to one another as follows:

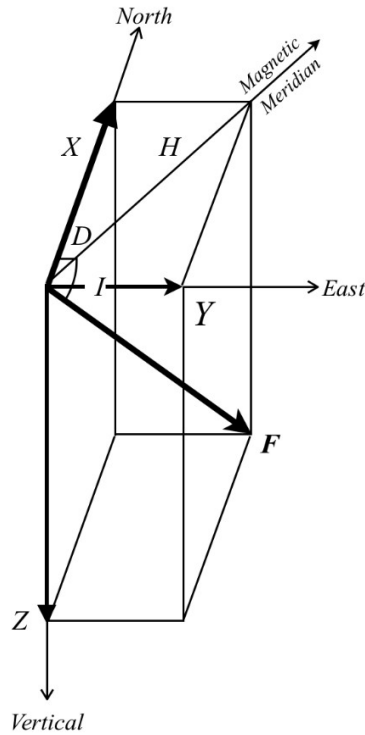


Fig. 2 An illustration of the geomagnetic elements created by Agnes Ovuka based on Lowrie's figure (2007, p. 306).

To calculate the total field intensity, the angles and vectors are used. The magnitude of the total field intensity is given by the field strength F and its direction is specified by two angles. It is calculated as follows (Lowrie, 2007, p. 306):

$$F = \sqrt{X^2 + Y^2 + Z^2}$$

2.3 Magnetic susceptibility

Magnetic behaviour of minerals and rocks by the magnetization by an external field is called magnetic susceptibility and is measured in SI-units (dimensionless) (EPA, 2026). The following magnetic behaviour will be described: Diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism and antiferromagnetism (EPA, 2026).

Diamagnetic minerals exhibit a reversible, weak and negative susceptibility that is independent of temperature, due to the magnetic moment that opposes the applied field, such as the Earth's magnetic field. These are often masked by stronger paramagnetic or ferromagnetic properties. Calcite and quartz are diamagnetic minerals. (Lowrie, 2007, p. 289)

Paramagnetism is when the magnetic moments align slightly with an applied field, resulting in a weak induced magnetization (Mussett & Khan, 2000, p. 146). Paramagnetic susceptibility is reversible, small and positive, and decreases with increasing temperature (Lowrie, p. 289).

When the external magnetic field is removed, the magnetization will disappear. Amphibole and olivine are typical paramagnetic minerals (Lowrie, 2007, p. 290).

Ferromagnetism is when the magnetic moments align exactly parallel within a rock sample containing ferromagnetic minerals, generating a spontaneous magnetization (Lowrie, 2007, p. 290; Mussett & Khan, 2000, p. 147). The magnetic moments respond collectively to the external magnetic field, resulting in strong positive susceptibility (Lowrie, 2007, p. 290). Susceptibility decreases with increasing temperature (Lowrie, 2007, p. 291). Due to magnetic hysteresis, ferromagnetic minerals will retain remanent magnetization when an external magnetic field is removed. (Mussett & Khan, 2000, p. 147; Lowrie, 2007, p. 290). An example is iron, which is a ferromagnetic mineral.

Ferrimagnetic minerals (ferrites), such as magnetite, maghemite, pyrrhoite and goethite, exhibit magnetic hysteresis and have strong positive susceptibility. This is due to an indirect exchange process involving antiparallel and unequal magnetizations of the sublattices, leading to a net spontaneous magnetization. (Lowrie, 2007, p. 291)

Antiferromagnetic minerals, such as Ilmenite (FeTiO_3) and Hematite, have a weak positive susceptibility due to equally strong magnetization in opposing directions and no net magnetization (Lowrie, 2007, p. 291).

2.4 Magnetic anomalies

A magnetic body becomes magnetized and generates its own magnetic field, which can be described as a dipole consisting of a positive and negative pole (Mussett & Khan, 2000, p. 168). The dipole field interacts with earth's magnetic field. A magnetic anomaly results from the contrast in magnetization between rocks with different magnetic properties, and depends on the direction of magnetization and the Earth's field (Lowrie, 2007, p. 327; Mussett & Khan, 2000, p. 162). The shape of the anomaly depends on the shape and depth of the magnetic body, as well as its orientation to the profile and to the inducing magnetic field (Lowrie, 2007, p. 327). The anomaly's direction and intensity vary depending on where it is located geographically. Earth's magnetic field varies with latitude, and consequently the intensity of magnetic anomalies varies (Mussett & Khan, 2000, p. 168).

Negative magnetic anomaly occurs at locations where the field of the dipole is opposite in direction of the Earth's field, resulting in a total field intensity being less than expected. A positive magnetic anomaly occurs where the field of the dipole reinforces earth's magnetic field, resulting in a total field intensity being higher than expected (Mussett & Khan, 2000, p. 162). The stray magnetic field from a magnetized rock disturbs the geomagnetic field locally and can be measured with magnetometers (Lowrie, 2007, p. 320).

2.5 Magnetic data reduction

2.5.1 IGRF and DGRF

The Earth's magnetic field varies very much over Earth's surface (Mussett & Khan, 2000, p. 167). The total field strength varies from roughly about 30 000 nT at the equator to 60 000

nT near the magnetic poles (Mussett & Khan, 2000, p140). The magnetic poles of the Earth are defined as the locations where the inclination of the magnetic field is ± 90 degrees, it is where Earth's magnetic field is vertically upward or downward (Lowrie, 2007, p. 311). The Earth's magnetic field is constantly changing ("secular changes"), and because of this it is necessary to correct the measurements. The geomagnetic correction removes the background geomagnetic field component from the data, so that only the magnetic anomaly resulting from the geomagnetic field's interaction with the magnetic body remains. (Lowrie, 2007, p. 324)

When a magnetic survey has been conducted, it is important to compare the results with the expected value at each measurement station (Lowrie, 2007, p. 324). This is done through the International Geomagnetic Reference Field (IGRF), which is a standard mathematical description of the Earth's main magnetic field (Lowrie, 2007, p. 324; NCEI, 2025). It is revised every five years to take account of secular variation (Mussett & Khan, 2000, p. 167).

DGRF 1965 represents the average of the IGRF over a five year period starting 1960, (SGU, 2024). It is used to relate the measurements of the magnetic field to a fixed set of reference values, and to study how the Earth's magnetic field changes on a global scale. The difference between the measured value at a locality and the expected value from the DGRF is resulting in a magnetic anomaly (SGU, 2024; Lowrie, 2007, p. 324).

2.5.2 Diurnal variations

The change of the Earth's magnetic field changes during the day, however, its variation is barely as much as 100 nT over the 24 hours and is due to electrical currents and solar activity (Lowrie, 2007, p.307; Mussett & Khan, 2000, p. 167). However, occasionally "magnetic" storms occur which can reach amplitudes of up to 1000 nT (Mussett & Khan, 2000, p. 167). These give rise to rapidly varying, anomalously strong magnetic fields at the Earth's surface (Lowrie, 2007, p. 309). These can last for hours to days, and magnetic surveys cannot be executed because of this.

2.6 The Hall effect and the Hall-effect sensor

The basic principle force underlying the Hall effect is the Lorentz force, which is a combination of the electrical force and the magnetic force (NIST, 2026). When an electron on a sample moves along the electric field direction perpendicular to an applied magnetic field, it experiences a magnetic force. When electrons move from the left, x-axis, in the presence of a z-directed magnetic field, the electrons will eventually move sideways towards the y-axis due to the magnetic field. In the end there will be more electrons towards the y-axis, leading to an electrical current with an excess negative surface charge resulting in Hall voltage (Texas Instruments, 2021). Hall voltage is the difference in distribution of the electrons, and its magnitude and duality is based on the orientation and strength of the magnetic field (ITG Linear Motor, 2025).

The Hall-effect sensor is based on the Hall effect, which turns the magnetic field into voltage, which is converted to a measurable signal (Texas Instruments, 2021). The voltage output is very small and therefore both analog and digital processing circuitry are important and work as amplifiers. The Hall-effect sensors are used within the automotive industry, renewable

energy and power systems, and consumer electronics such as smartphones (ITG Linear Motor, 2025). The smartphone-based ground magnetic survey uses the Hall-effect sensor for measuring the magnetic field, which it measures in three directions (Bosch Sensortec GmbH, 2020).

3.0 Methods and materials

3.1 Literature review

A literature review of six articles was carried out to better understand the geological area and history of Utö and the Svecofennian region (Allen et al., 1996; Dunst et al., manuscript; Gavelin et al., 1976; Holmquist, 1910; Stålhös, 1982; Talbot, 2008). These studies present their fieldwork, data acquisition, results and interpretations at both regional and local scales within the study area.

3.2 Field data acquisition

Magnetic field data were collected using the magnetometer from the smartphone application Physics Toolbox Sensor Suite (Vieyra Software, n.d.), where it is possible to record GPS coordinates and magnetic field intensity using the devices built-in sensors. The sampling frequencies varied between campaign 1 and campaigns 2/3 (see section 3.3).

The mobile devices used in this study were iPhones of different editions, in which their geomagnetic sensors were compared to each other to evaluate their alignment in magnetic measurements. Apple does not publicly specify which geomagnetic sensor is used in its devices. However, many Android phone devices are using BMM150 geomagnetic sensors manufactured by Bosch (Bosch Sensortec GmbH, 2020). This includes a 3-axis magnetometer integrated into motion sensor chips. It has a magnetic field resolution of approximately ± 300 nT, and a magnetic field range of about $\pm 1\,300\,000$ nT (x-, y-axis) and $\pm 2\,500\,000$ nT (z-axis). The BMM150 geomagnetic sensor is based on the Hall-effect sensor, which calculates the total magnetic field automatically (Bosch Sensortec GmbH, 2020).

Flanders (2023) has previously done a magnetic ground survey on Utö, using a SCINTREX MP-2, a portable proton-precession magnetometer. When executing a profile crossing Nyköpingsgruvan, the instrument cut off when it reached a maximum of 92 000 nT. This study did therefore not use a proton-precession magnetometer, because the magnetic field on Utö is stronger than the measurement range of a proton-precession magnetometer.

No specifications for the GPS accuracy of an iPhone or Android are available. However, Jeff Shaner (ESRI, 2013) has conducted tests with different smartphones in the open sky, where 90% of all collected positions fell within 3m of their baseline.

The study area focused on the iron oxide and sulphide deposits that are part of the associated mine sites: Nyköpingsgruvan, Långgruvan, Östra Brottet, Bykgruvan and Silvergruvan.

The survey was conducted along a series of profiles oriented approximately southeast to northwest or in the opposite direction, depending on the starting position. Each profile ranged

from approximately 600 to 800 meters in length, with a spacing of 50 meters between adjacent profiles. The beginning and end of each survey profile were mapped in Google Earth, helping the survey team to keep track of the profiles that had already been surveyed. Colored strings acted as a back-up, which also were tied at these locations.

Data was collected by two persons walking each profile. It was technically possible for one person to record the GPS and magnetic measurements at the same time. However, in this case the total field intensity would not be calculated automatically in Physics Toolbox Sensor Suite (Vieyra Software, n.d.). Each profile contained between approximately 25 000 to 200 000 values, making it impractical to calculate every magnetic measurement's total field intensity manually.

Person number 1 and 2 will in the following text be declared as P1 and P2. P1 recorded the GPS tracks and navigated the team along the profile by using a compass. In addition to using a compass, Google Earth was sometimes used as an extra reference when the compass readings were uncertain. P2 followed approximately 2-3 meters behind and recorded the magnetic field measurements. This was to minimize magnetic interference between the two smartphones. Additionally, the magnetometer was intended to be held at a fixed height from the ground to keep the magnetic measurements consistent. When each profile was done, the data were sent to the team's email addresses.

3.3 Data collection timeframe

The work was carried out during three field campaigns:

- Campaign 1: 29 July - 2 August 2024
- Campaign 2: 20 April - 24 April 2026
- Campaign 3: 27 April - 1 May 2026

During the first campaign, an earlier version of Physics Toolbox Sensor Suite (Vieyra Software, n.d.) was used. It had a GPS sampling rate of 1 Hz and a magnetometer sampling rate of 100 Hz. During the second and third campaign, the software was updated and a newer version had to be used. This resulted in both the GPS and magnetometer being recorded with a sampling rate of 100 Hz.

3.4 Preliminary GIS Map

During the beginning of the third campaign, all magnetic survey profiles were imported into QGIS for visualising each profile and their data. A preliminary map was constructed for comparisons with existing geological maps of this study area and to identify gaps in the dataset, leading to further data acquisition to improve study area coverage.

3.5 Data processing

Microsoft Excel was used for structuring and processing the datasets containing the each recorded GPS coordinates and magnetic measurements. The data processing for campaign two and three differed slightly from the first campaign. Both the GPS coordinates and the magnetic measurements were recorded at a sampling rate of 100 Hz. The entire dataset would technically be possible to retain as it is. However, it would be extremely large and difficult to manage, especially when processing and gridding in QGIS. Therefore, the columns for longitude, latitude and the magnetic data were resampled to 1 Hz and stored in their new respective columns.

3.6 GIS

3.6.1 DEM

GeoTIFF rasters, based on LiDAR, 2 m DEM from Lantmäteriet, were downloaded using the Geodata Extraction Tool (GET) provided by Sveriges lantbruksuniversitet (SLU) (n.d.). The TIFF files were merged by using the GDALS “Raster Miscellaneous- Merge” creating a merged raster layer. This layer was later used to created into a DEM, with pixel size of x=2 and y=2, through “Raster Analysis- Hillshade”.

3.6.2 Vector layers and CRS

The programme QGIS was used to visualise the acquired field data using coordinate reference system SWEREF 99 TM (EPSG: 3006). All 89 profiles, from campaign 1, 2 and 3, were converted to CSV files, readable by QGIS profile as individual vector layers. Each profile is given automatically in WGS 84 (EPSG: 4326) and had to be converted to SWEREF 99TM (EPSG: 3006). All 89 vector layers were subsequently merged into a single layer.

3.6.3 IGRF and DGRF

The 1965 DGRF values along the profiles exhibit only minor variations of approximately 1 nT between the locations, with a mean value of 49 900 nT (NCEI, 2025). Because of the small variation and the large sized dataset, the mean DGRF value of 49 900 nT was subtracted from each magnetic measurement, using the QGIS field calculator in the attribute table. This resulted in the creation of a new attribute column containing the calculated magnetic anomalies.

3.6.4 IDW-Interpolation, buffer and clip raster by mask

An interpolation was produced of the merged vector layer, by using QGIS algorithm “Inverse Distance Weighted” (IDW). The sample points are weighted throughout interpolation, the influence of one point relative to another declines with distance from the unknown point that is intended to be estimated (QGIS Documentation, 2025). When the merged vector layer with its great number of input values are incorporated into the gridded dataset, a broader extent is

covered, which increases its reliability. The IDW-raster layer was buffered by a distance of 100 meters, to cover at least two profiles. This was later used as a mask layer in GDAL'S "clip raster by mask"-tool to clip the raster, so it would not show extrapolated values beyond the typical profile distance.

3.6.5 Symbolology & Classification of the Magnetic Anomaly Intensity Map

After subtracting the DGRF value of 49 900 nT, magnetic anomaly values around 0 nT show bedrock with low susceptibility. Values below 0 nT are negative magnetic anomalies and values above 0 nT are positive magnetic anomalies. Based on magnetic measurements around Nyköpingsgruvan, Långgruvan and Östra Bröttet, where both outcrops of BIF and high magnetic values occur, a level of magnetic response could be defined. Carbonate rocks and metagreywackes showed a weak magnetic response.

A distinct difference in intensity can be observed around the mine pits. Displaying all positive and negative magnetic anomalies on the map would reduce the contrast between the neutral ground and the significant magnetic anomalies. A transition zone was defined at 6000 nT, where significant magnetic anomalies range from 8000 nT to 207 000 nT. A transition zone was defined at 2000 nT, where the significant negative anomalies range from - 3000 nT to - 9100 nT. Magnetic values ranging from -2000 nT to 6000 nT are included into the background (neutral ground category).

The symbolology is designed to represent the magnetic anomalies ranging from negative from - 9 100 nT to 207 000 nT. The strongest negative magnetic anomalies are represented by the darkest shades of purple, which gradually transition to cerise with decreasing anomaly intensity before reaching the transparent neutral ground category. The strongest positive magnetic anomalies are represented by dark red, which gradually transitions through neon red, orange, yellow, neon green and neon turquoise with decreasing anomaly intensity before reaching transparent neutral ground (See fig. 3). When ground-truthing, the magnetic values around the mine were ranging from at least 76 000 nT (36 000 nT when subtracting the DGRF). Values exceeding this threshold are visualized using different intensities of red. The diagram is not linear, the purpose is to demonstrate the differences in magnetic anomaly intensity.

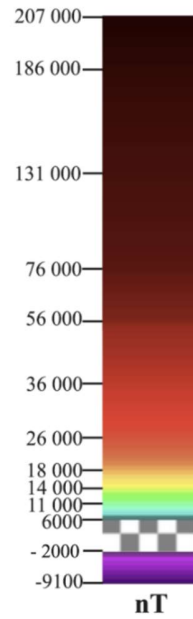


Fig. 3 Magnetic anomaly values (nT)

3.6.6 Symbology & Classification of the Magnetic Anomaly Vector Map

The merged vector layer is used for demonstrating the localities of the magnetic anomalies, facilitating the interpretation of the results. Blue dots are classified as negative magnetic anomalies and red dots as positive magnetic anomalies. The values range between - 32 000nT to 269 000 nT, where the neutral ground is positioned between -3000nT and 8000 nT. No transition zones are included. The vector data is not generalised by gridding and does not display magnetic anomaly intensities (see [fig.4](#)).

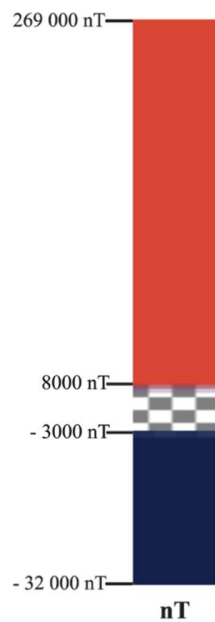


Fig. 4 Magnetic anomaly values (nT)

3.6.7 Finalizing map & map comparisons

The final step was the completion of two magnetic anomaly maps, which later shall be used for comparisons between geological maps, structural geological and a magnetic anomaly map (Allen et al., 1996; Dunst et al., manuscript; Gavelin et al., 1976; Holmquist, 1910; Stålhös, 1982; Talbot, 2008).

4.0 Results

4.1 Profiles

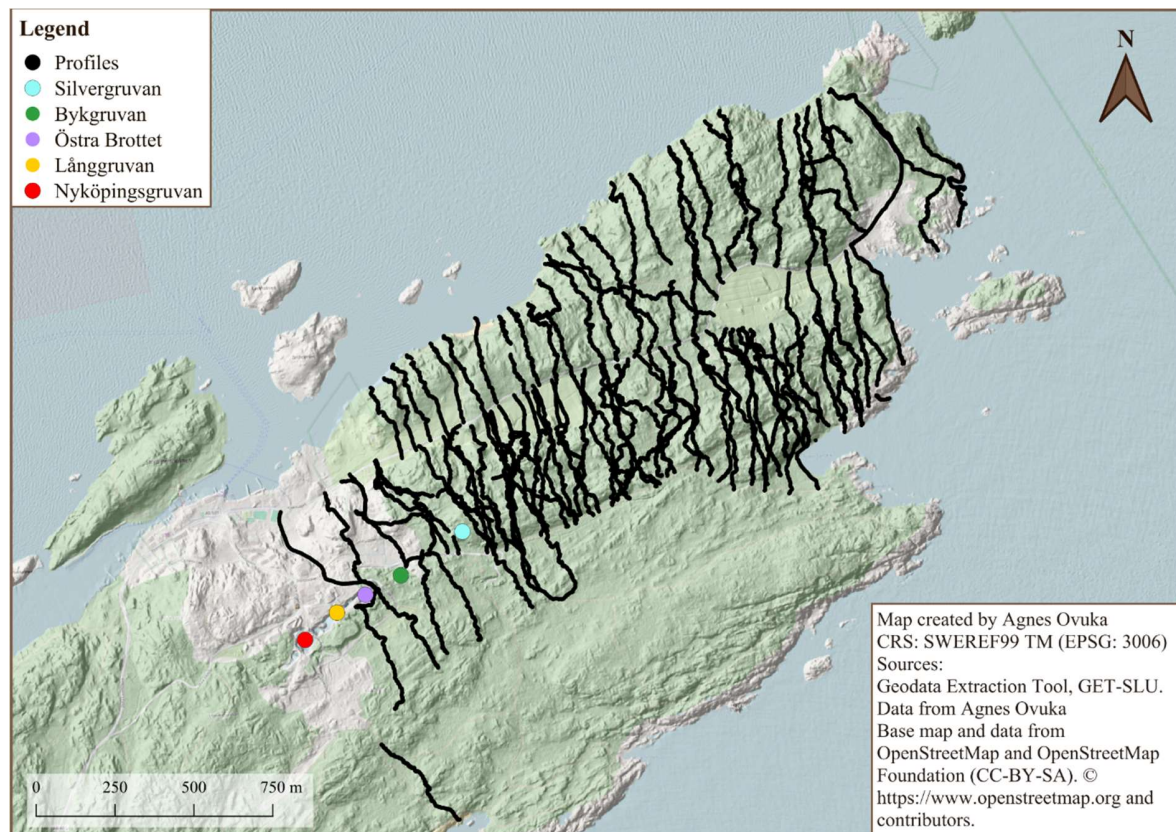


Fig. 5 Recorded GPS coordinates for all 89 profiles across the study area.

A total of 89 profiles were completed across the study area, during which both the magnetic measurements and the GPS coordinates were recorded (see fig. 5). Each profile was oriented along a southeast to northwest axis, and vice versa. As planned, the survey followed the mine sites of Nyköpingsgruvan, Långgruvan, Östra Brottgruvan, Bykgruvan and Silvergruvan.

4.2 Magnetic anomaly intensity and vector maps

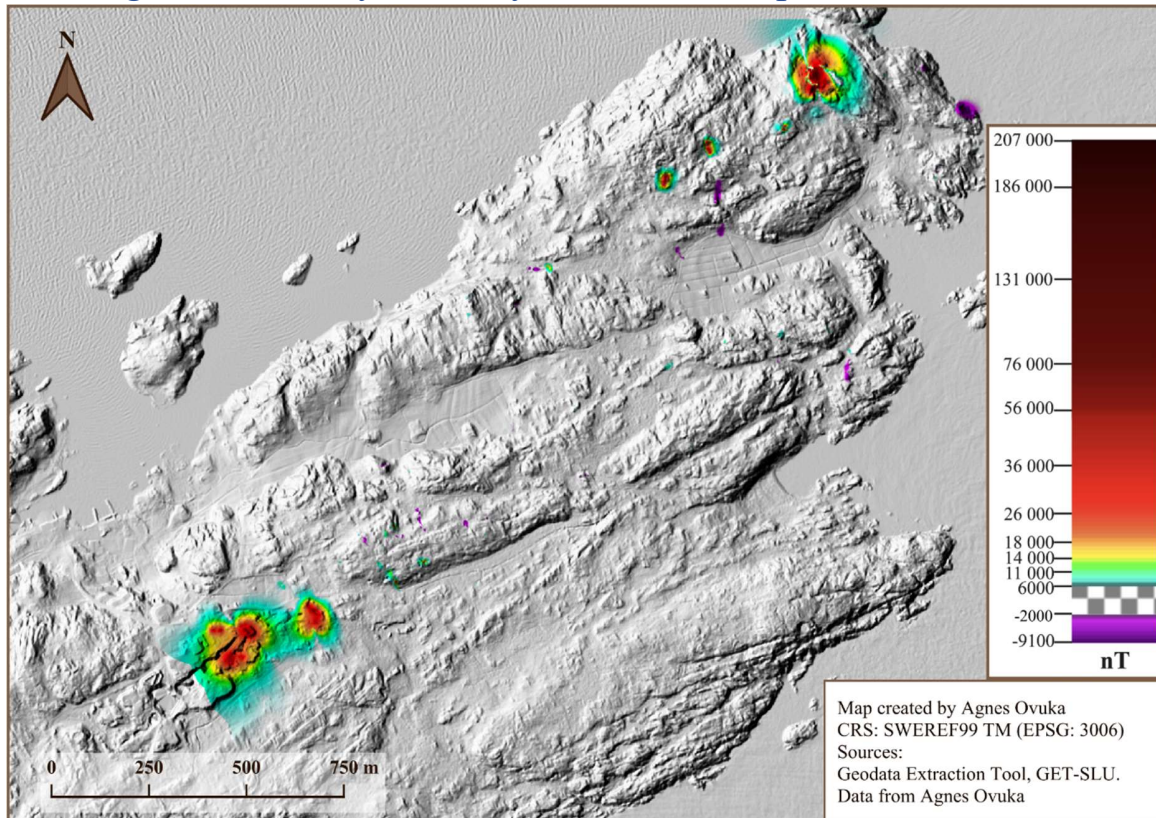


Fig. 6 Magnetic anomaly intensity map

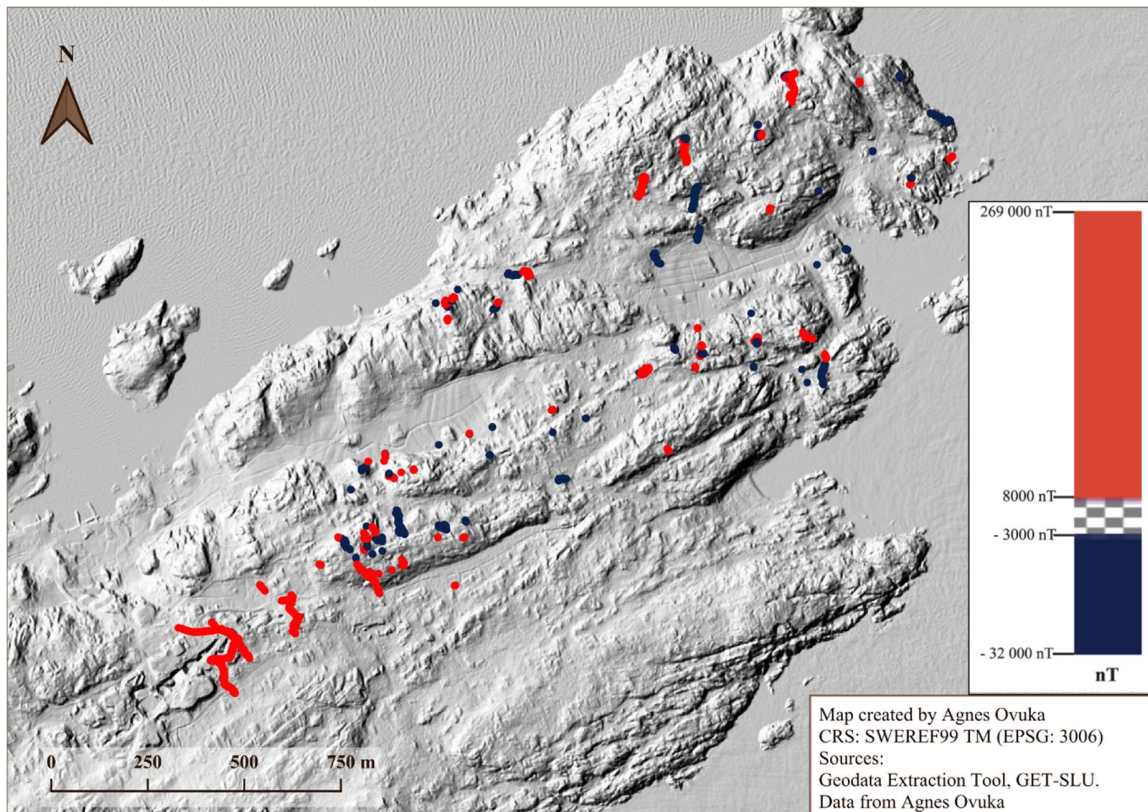


Fig. 7 Magnetic anomaly vector map

The magnetic anomalies are concentrated around the mine site localities Nyköpingsgruvan, Långgruvan, Östra Brottet, Silvergruvan and Bykgruvan, where very high peaks occur (see fig. 6). The peaks are distributed towards the northeast and northwest with very high values over 100 000 nT. The highest anomaly, located in the northwestern area, reaches a peak of approximately 206 756 nT and is associated with the lowest negative anomaly of approximately -9 100 nT.

It is important to keep in mind that these values have been gridded using IDW interpolation, which smoothed the data. In the raw dataset, the highest peak recorded was approximately 318 700 nT and lowest trough 17 900 nT, which corresponds to anomalies approximately 268 800 nT and -32 000 nT after the subtraction of the DGRF.

4.2.1 Magnetic anomaly intensity and vector maps displayed on the geological map of Holmquist (1910)

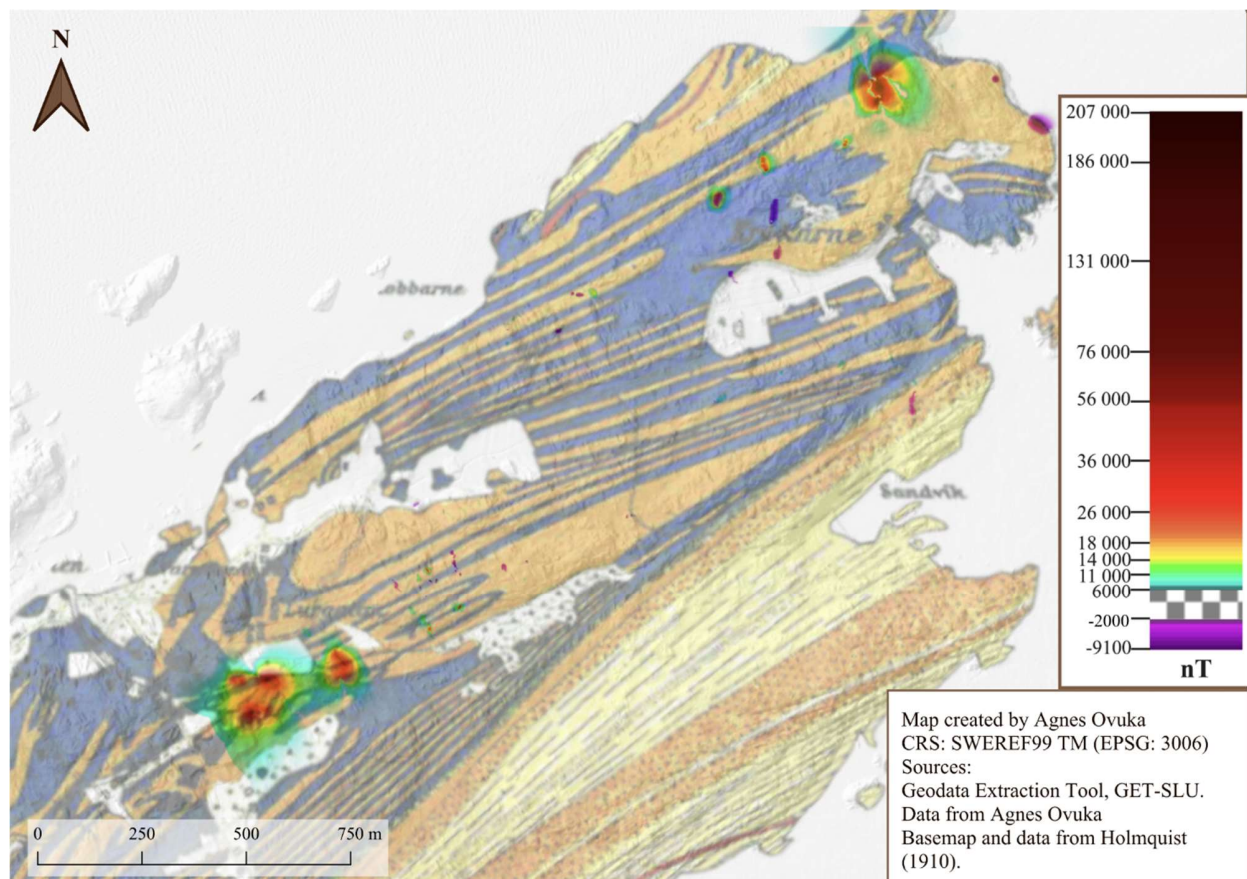


Fig. 8 Magnetic anomaly intensity map displayed on the geological map of Holmquist (1910).

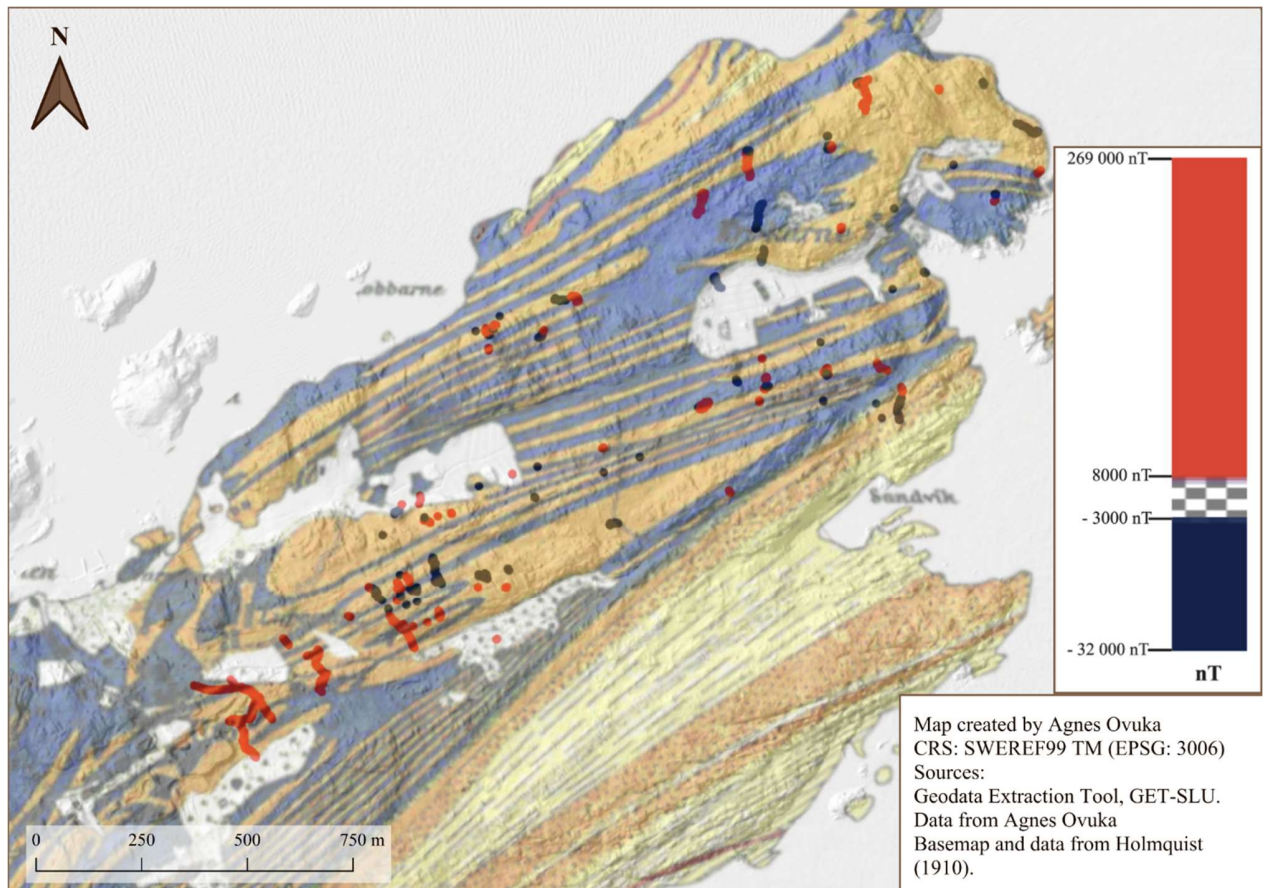


Fig. 8 Magnetic anomaly vector map displayed on the geological map of Holmquist (1910).

Holmquist (1910) described the northern part of Utö consists of alternating layers of limestone, hälleflinta, calcareous hälleflinta. Although a legend for this map could not be found, later studies which have partly based their interpretations on Holmquist (1910) discoveries, identified the area as consisting of interlayers of marble and hälleflinta-leptites, represented as blue and yellow respectively. It can therefore be inferred that the blue represents limestone and the yellow hälleflinta on Holmquist's geological map (1910).

Most vector anomaly points, including positive and negative anomalies, seem to be located within the leptites and hälleflintas. The strongest positive anomalies located around the mines and on the northwestern part of northeastern Utö, are included in these. There are few positive and negative anomalies that either occur outside or on the contact of this rock unit.

4.2.2 Magnetic anomaly intensity and vector maps displayed on the geological map of Gavelin et al. (1976).



Fig. 9 Magnetic anomaly intensity map displayed on the geological map of Gavelin et al. (1976).

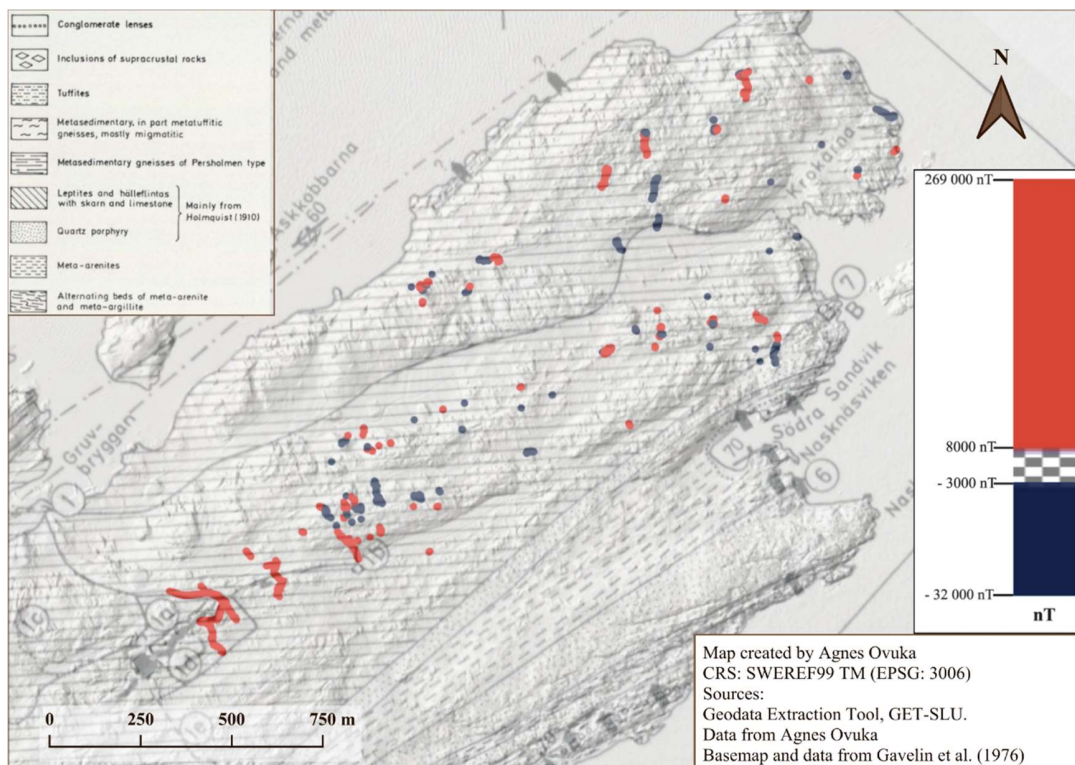


Fig. 10 Magnetic anomaly vector map displayed on the geological map of Gavelin et al. (1976).

When comparing the geological map of Gavelin et al. (1976), the magnetic anomalies are associated with the leptites and hälleflintas, with skarn and limestones (see fig. 9). However, a distinct negative anomaly is observed within the porphyry sheet northwest of Södrasandviken. According to Gavelin et al. (1976) most of the interpretations connected to this rock unit are based on Holmquist's (1910) earlier work.

4.2.3 Magnetic anomaly intensity and vector maps displayed on the geological map of Stålhös (1982)

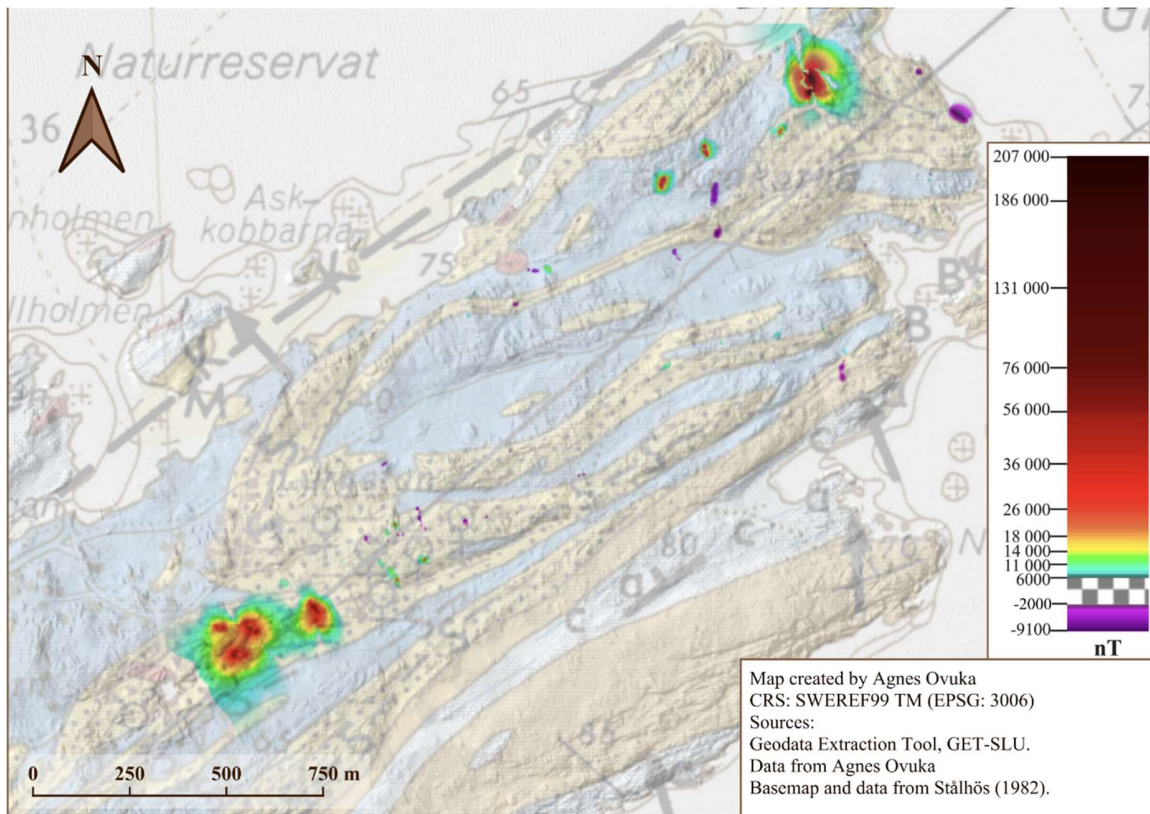


Fig. 11 Magnetic anomaly intensity map displayed on the geological map of Stålhös (1982).

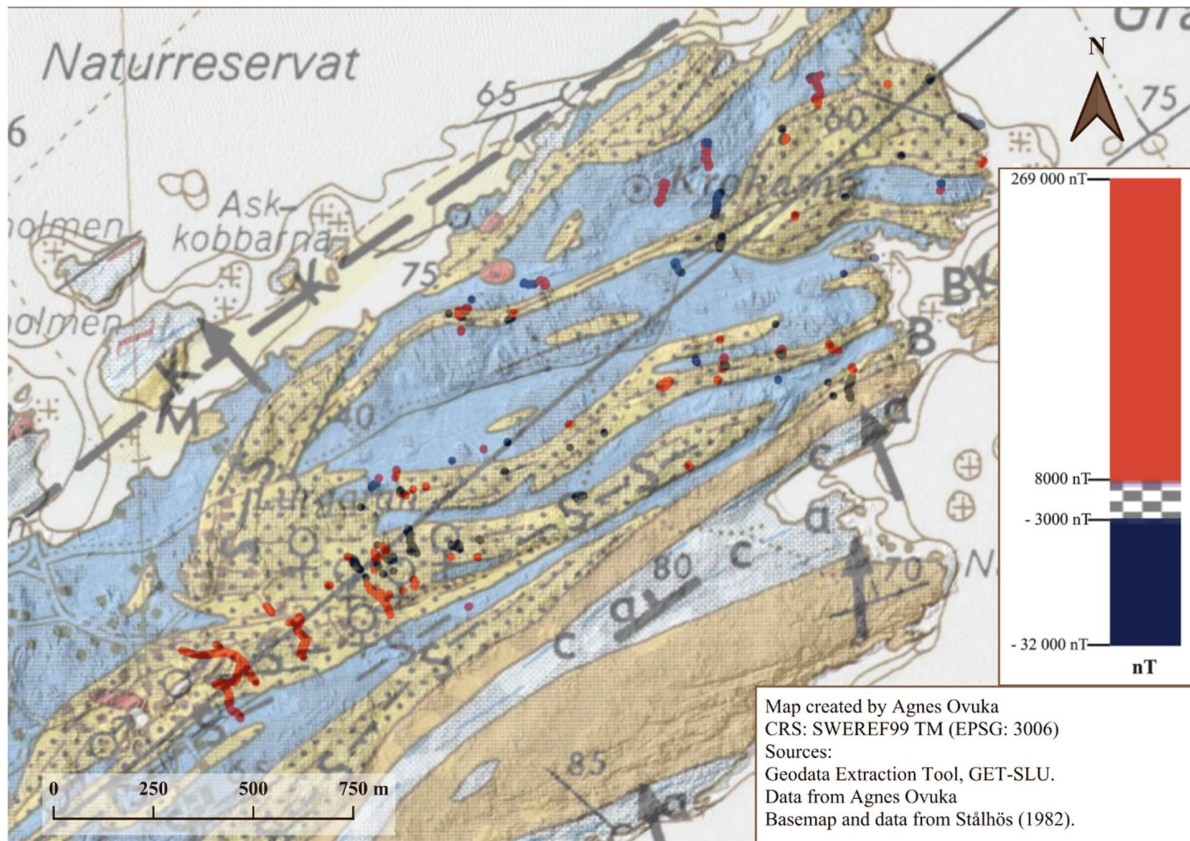


Fig. 12 Magnetic anomaly vector map displayed on the geological map of Stålhös (1982).

When compared to the geological map of Stålhös (1982) (see geological legend in appendix B), the magnetic anomalies are located within the alkaline metatuffites (sodic), and the marble/dolomites, with one negative anomaly occurring along the contact between the quartz-plagioclase porphyry and alkaline metatuffites.

The magnetic anomalies in the area of Nyköpingsgruvan, Långgruvan, Östra Brottet, Byggruvan and Silvergruvan, are located within the alkaline metatuffite unit. Here, BIFs are mapped within Nyköpingsgruvan, Långgruvan and Östra Brottet, whereas sulphide deposits occur within Byggruvan and Silvergruvan. Farther northeast, the magnetic anomalies occur mostly within the alkaline metatuffites, nevertheless, some occur within the marble/skarn.

On the western and northwestern part of Utö, positive and negative magnetic anomalies are scattered within both alkaline metatuffites and the marble and/or dolomite. The most prominent positive magnetic anomaly is located within the marble and/or dolomite.

4.2.4 Magnetic anomaly intensity map displayed on the anomaly map of Stålhös (1982)

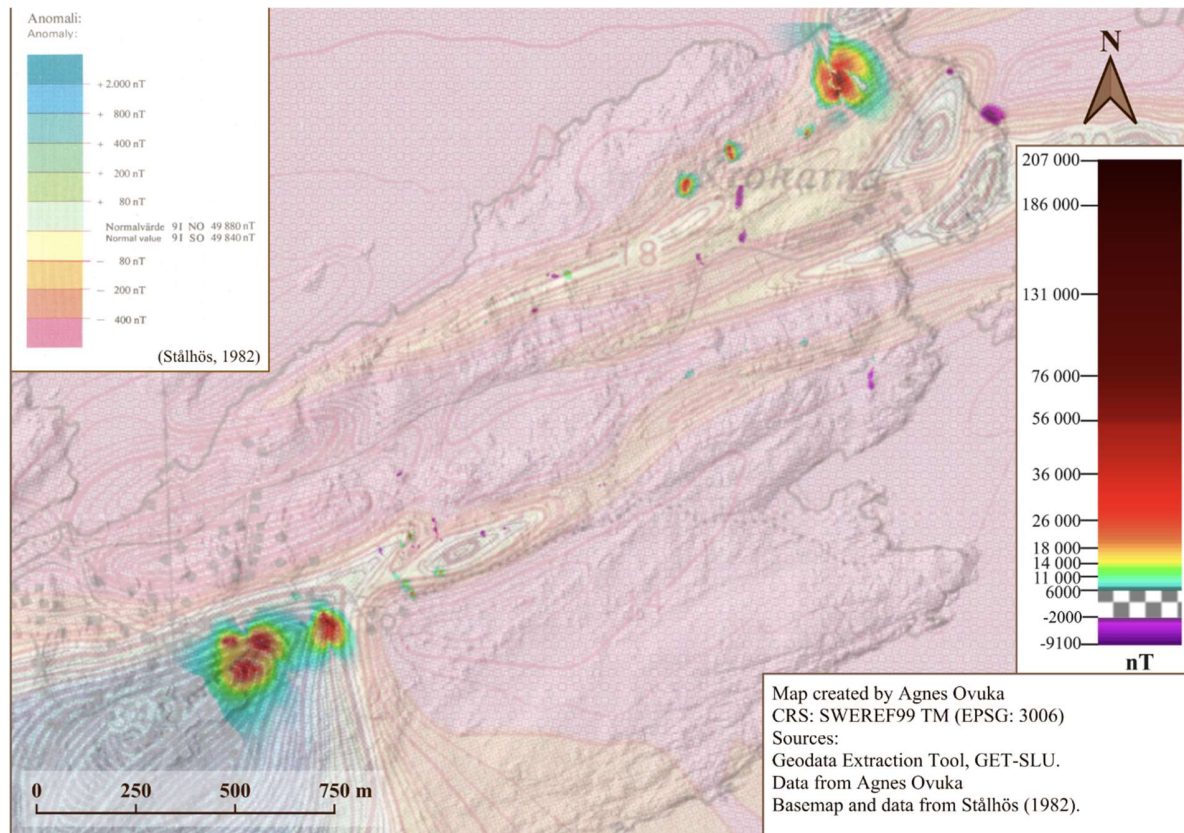


Fig. 13 Magnetic anomaly intensity map displayed on the magnetic anomaly map of Stålhös (1982).

Comparing the magnetic anomaly map with the magnetic anomaly map of Stålhös (1982) demonstrates that both maps show similar peaks, however, there are some differences (see magnetic anomaly legend in appendix C).

The normal value of the map of Stålhös (1982) is 91 NO 49 880 nT, whereas the map for this study has an almost identical normal value of 49 900 nT. As mentioned, by subtracting the DGRF, it results in magnetic anomaly values. In this case, the map of Stålhös is ranging between < -400 nT to > 2000 nT. In the following section the map of Stålhös (1982) will be referred to as M1, while the map of this study will be referred to as M2.

On M1 the magnetic anomaly values range between -80 nT to > 2000 nT within the mine localities. On M2, the magnetic anomaly values range between approximately 6000 nT to $> 76\,000$ nT. Both maps show strong magnetic anomalies.

Continuing northeastward to Bykgruvan and Silvergruvan, the magnetic anomalies range from approximately -200 nT to $+200$ nT on M1, whereas on M2, the magnetic anomalies are ranging from -9100 nT to above 26 000 nT.

Continuing northeastward, positive magnetic anomalies around 6000 to 11 000 nT are laying within the orange approximate -400 nT band of M2. Few negative and positive anomalies

from Map 2 lie within the area assigned to be <-400 nT on M1. These are either negative anomalies <1100 nT or positive anomalies between 6000 nT and $18\,000$ nT.

At the western part of Utö, the anomalies from M2 range from -9100 nT to $20\,000$ nT, whereas at M1 the anomalies range between -400 nT to its normal value. On northwestern Utö, four intense positive anomalies from M2 are located within the orange band on M1, that is between -200 nT to 400 nT. The strongest positive anomaly on M1 is located within this area, which has a trough of -9100 nT and a peak of $207\,000$ nT.

Northeast of the peak magnetic anomaly from M1, two negative anomalies of -9100 nT are located within the colour bands orange and yellow ranging from -400 nT to the normal value of M2.

Southeast of the two negative anomalies, small clusters of positive and negative anomalies from M2, ranging between -9100 nT to approximately $16\,000$ nT, occur between the pink to light green bands, ranging from <-400 nT to $+80$ nT on M1.

Three negative anomalies from M2 are located south of the cluster of the four intense anomalies. These have magnetic anomaly values down to -9100 nT and are located within a light orange band ranging between -400 nT to 80 nT according to M1.

4.2.5 Magnetic anomaly intensity and vector maps displayed on the lination map of Stålhös (1982)

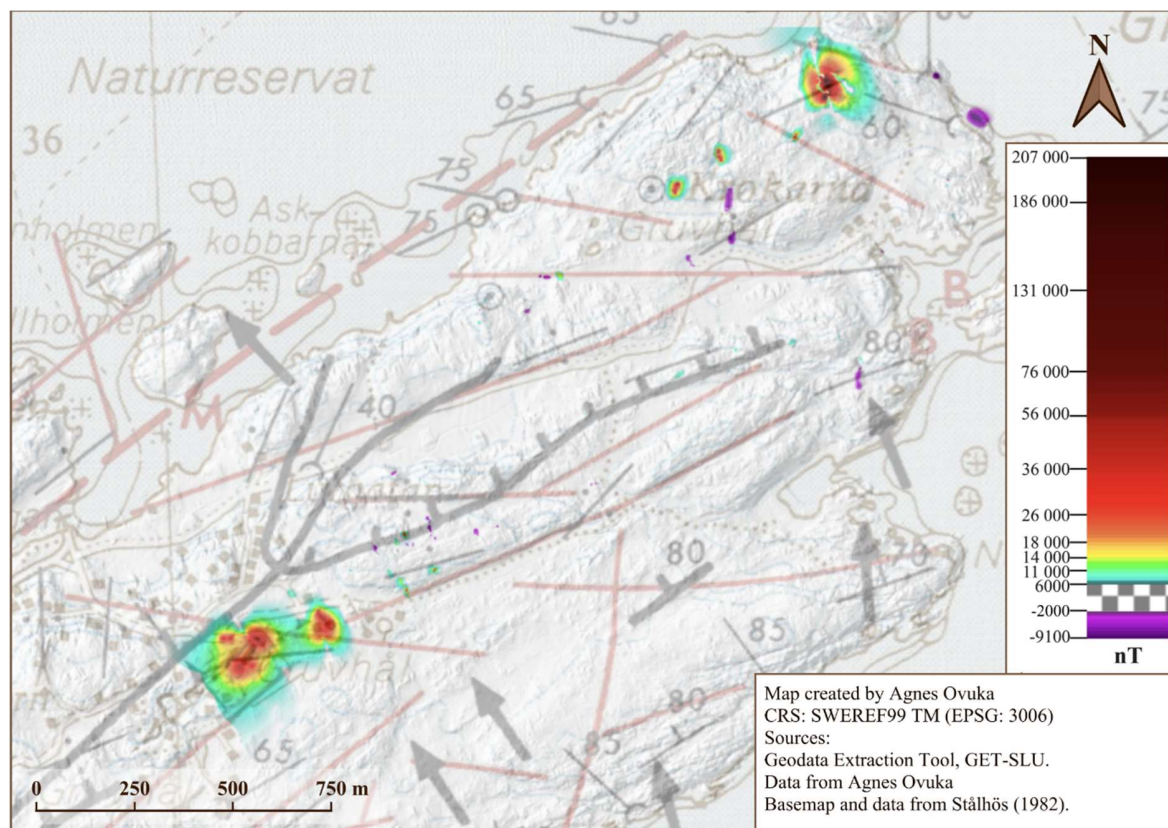


Fig. 14 Magnetic anomaly intensity map displayed on the lination map of Stålhös (1982).

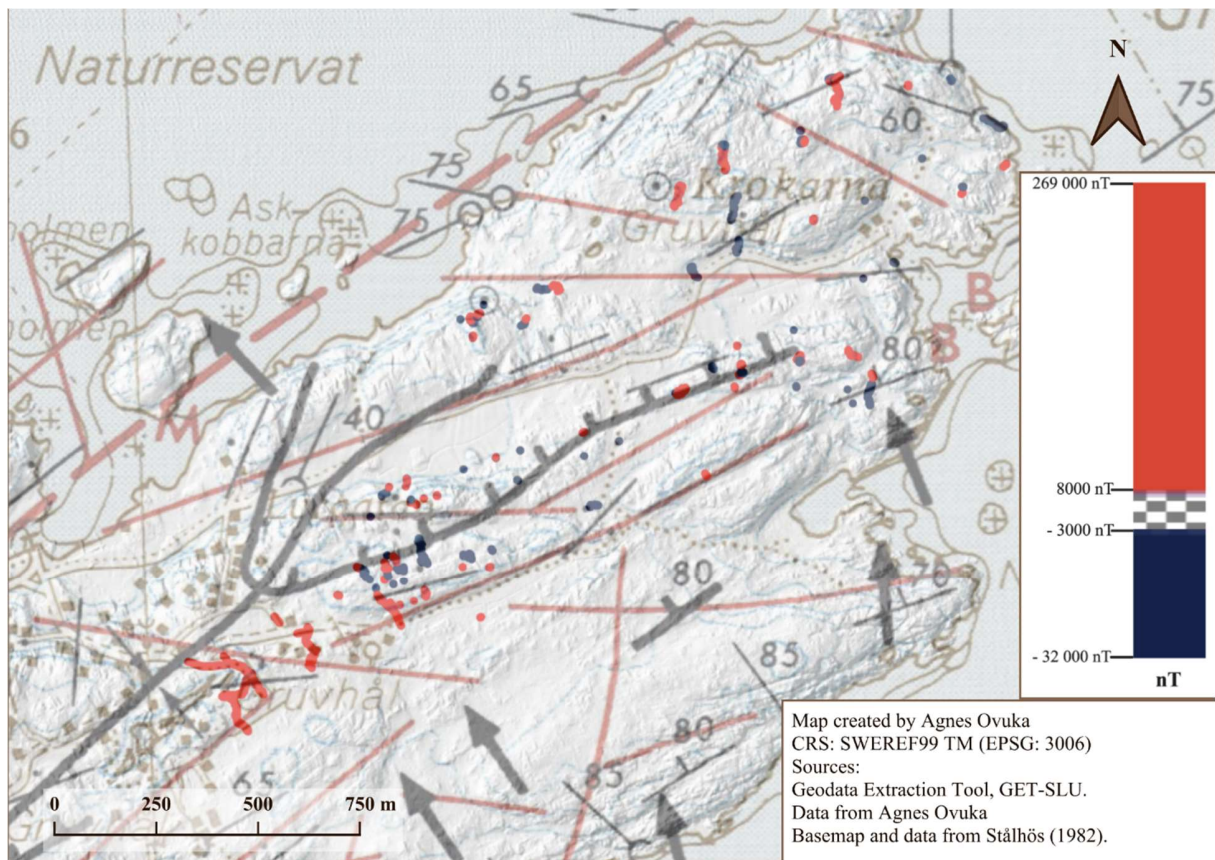


Fig. 15 Magnetic anomaly vector map displayed on the lineation map of Stålhös (1982).

Stålhös lineation map (1982) shows a major synform, with an axial plane striking southwest to northeast (see lineation legend in appendix D). The magnetic anomalies surrounding the mine localities are located southeast of the synform. The western and eastern limbs are mapped as fold fronts on either side of the fold. The scattered anomalies surrounding Bykgruvan and Silvergruvan are slightly east and approximately aligned with the eastern fold front, while the anomalies to the west and northwest appear to follow the trend of synform the synforms axial plane.

4.2.6 Magnetic anomaly intensity and vector maps displayed on the geological map of Allen et al. (1996)

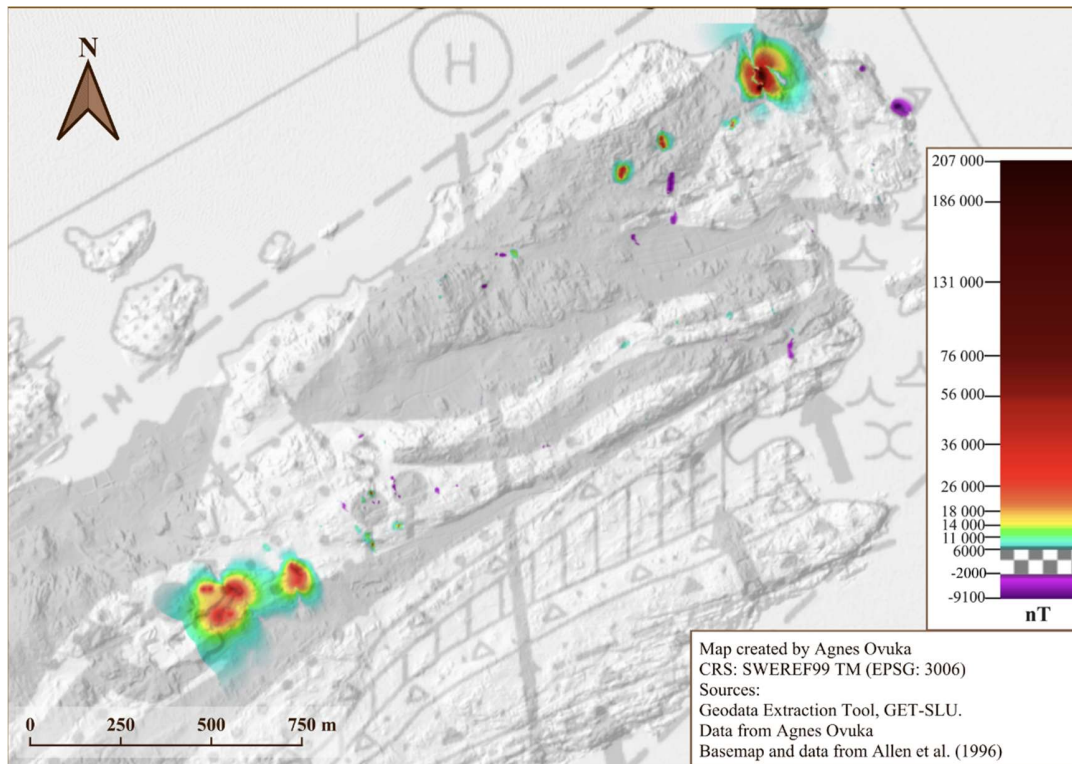


Fig. 16 Magnetic anomaly intensity map displayed on the geological map of Allen et al. (1996).

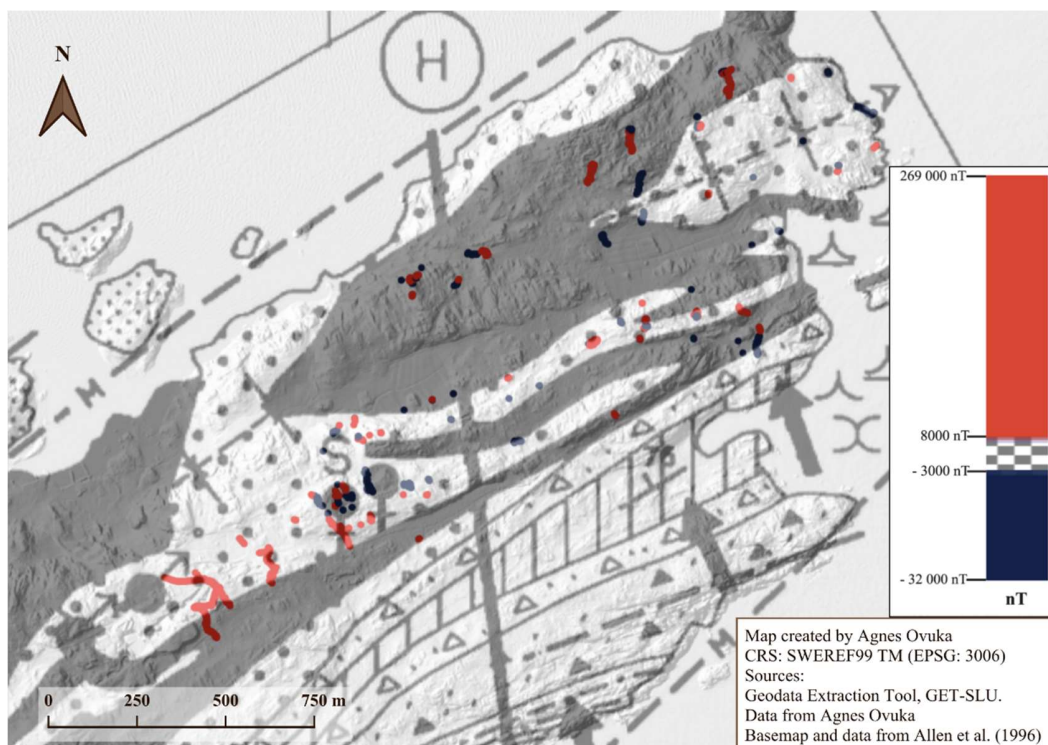


Fig. 17 Magnetic anomaly vector map displayed on the geological map of Allen et al. (1996).

The magnetic anomalies that are concentrated along Nyköpingsgruvan, Långgruvan and Östra Brottet, are mapped as Quartz-rich iron deposits by Allen et al. (1996) (see geological and structural legend in appendix A). Further positive and negative anomalies occur northeastward in relation to Silver and Bykgruvan, where SAS hosted Zn-Pb-Cu-Ag occur. These anomalies are mostly distributed within the Rhyolitic ash-siltstone unit, with up to 50% interbedded volcanic sandstones, marbles and skarn.

Continuing northeast, negative and positive magnetic anomalies are present within the same lithology, however, as well as within marble (larger limestones and dolomite). One prominent negative anomaly located on the northeastern part close to Kroka, is located at the contact between the thick, poorly stratified rhyolitic, syn-eruptive massflows and the marble.

In the northwestern part of Utö, most positive and negative anomalies are associated with marble, including the peak anomaly. However, there are anomalies also located within the rhyolitic ash-siltstone unit.

4.2.7 Magnetic anomaly and vector maps displayed on the geological map of Talbot (2008)

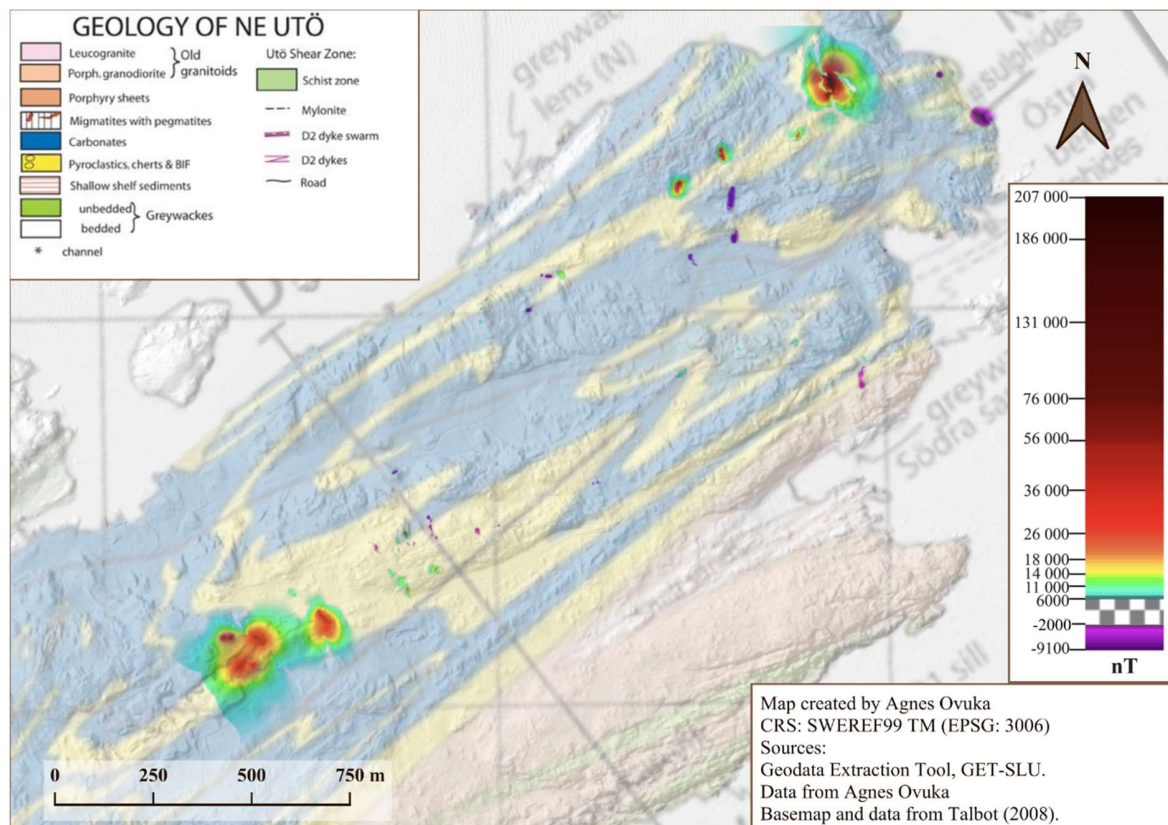


Fig. 18 Magnetic anomaly intensity map displayed on the geological map of Talbot (2008).

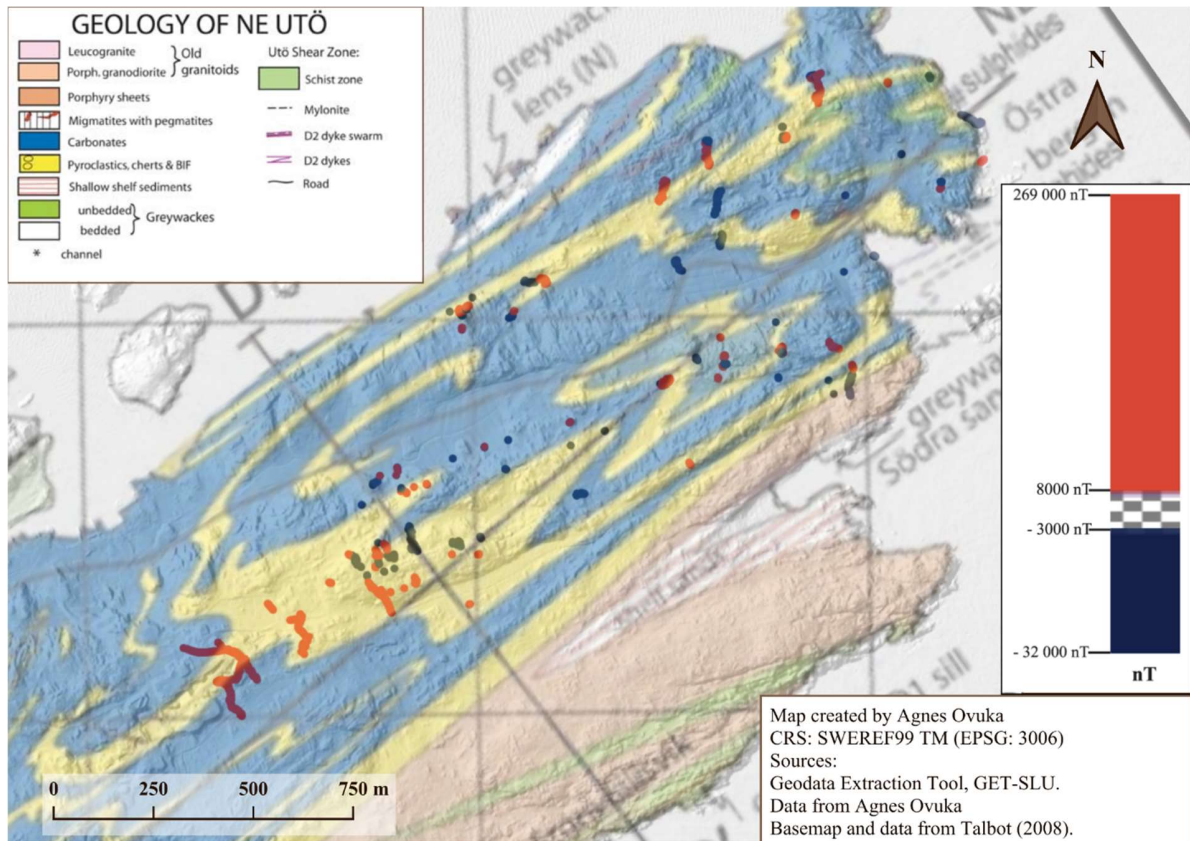


Fig. 19 Magnetic anomaly vector map displayed on the geological map of Talbot (2008).

When compared with the geological map of Talbot (2008), the magnetic anomalies are predominantly associated with the pyroclastics, cherts and BIF-unit. Relatively few are present within the carbonate unit. The most intense magnetic anomalies occur around the mine localities, which Talbot (2008) maps within the pyroclastic, cherts and BIF. Four additional strong positive magnetic anomalies occur on the northwestern part of the island, also mapped within the pyroclastic, cherts and BIF, and can be compared to the magnetic anomalies around the mine localities. One of them, the most northwesterly located anomaly, has magnetic anomaly values ranging from -9100 nT to 270 000nT. One negative anomaly is located within the unbedded greywacke unit, northeast of the highest positive anomaly and another one intersects with the porphyry sheet on the geological map of Talbot (2008).

4.2.8 Magnetic anomaly and vector maps displayed on the lineation map of Talbot (2008)

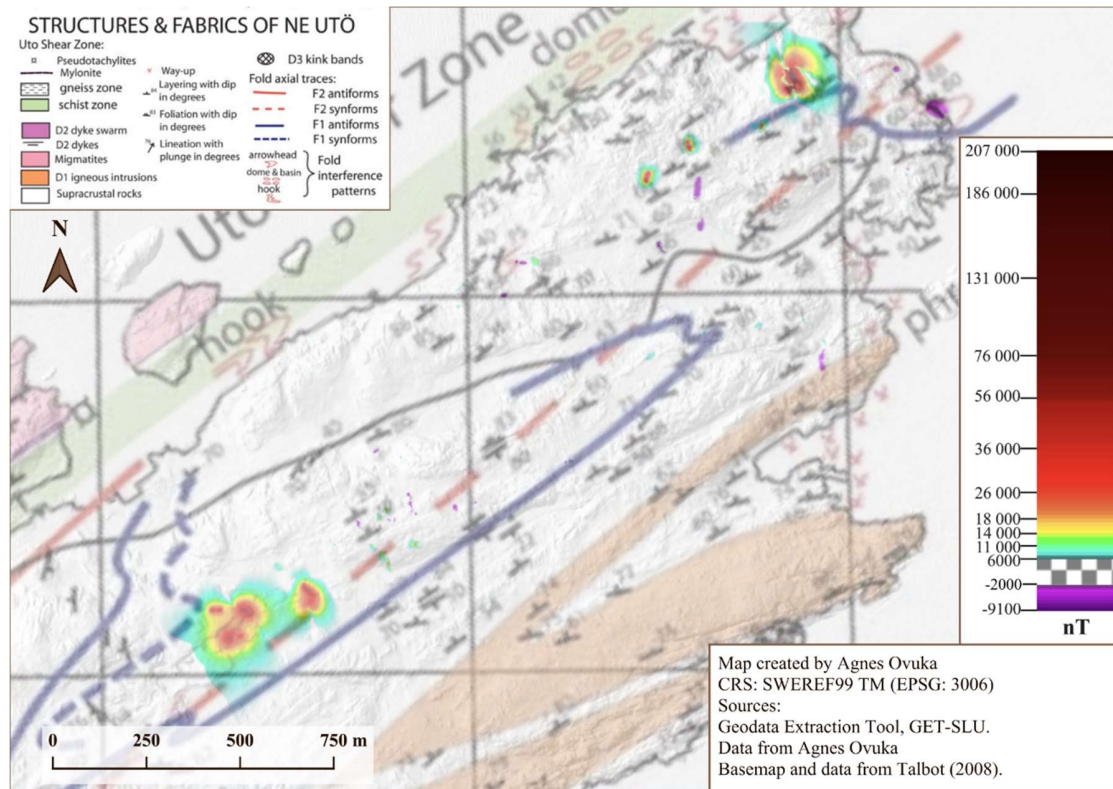


Fig. 20 Magnetic anomaly intensity map displayed on the lineation map of Talbot (2008).

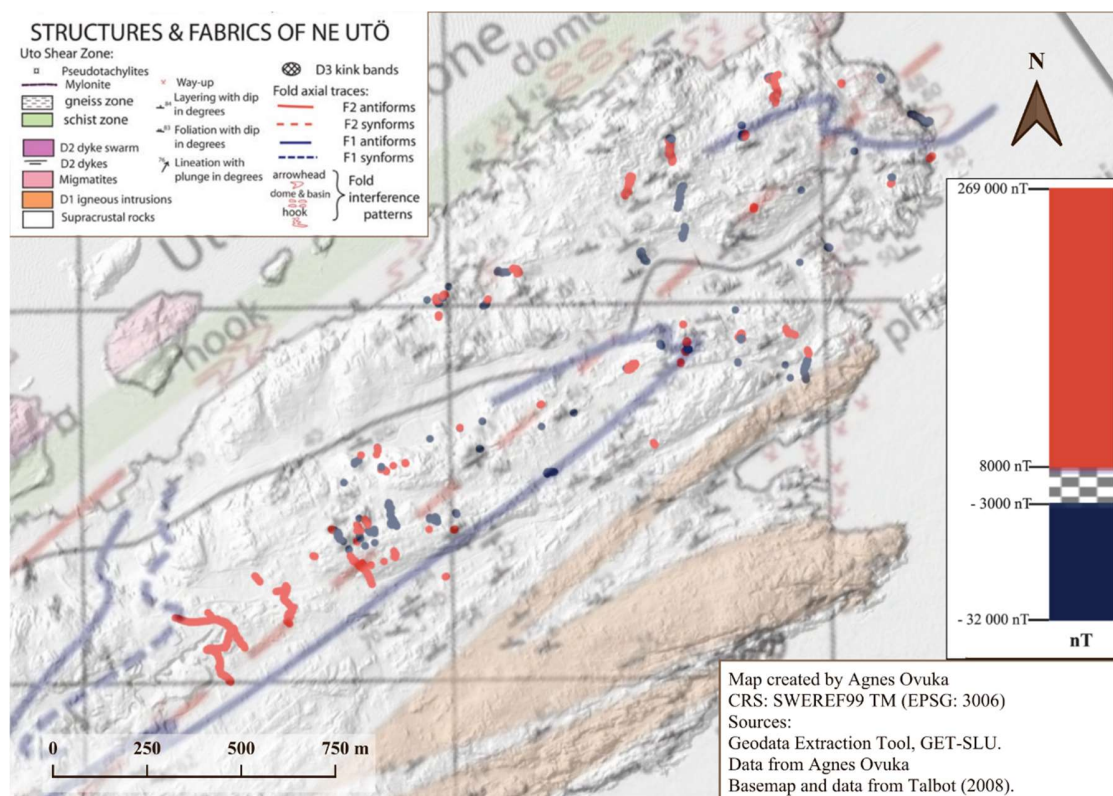


Fig. 21 Magnetic anomaly vector map displayed on the lineation map of Talbot (2008).

The red dashed line going through northeastern Utö, is mapped as a great synform on the map of Talbot map (2008). The blue lines are older antiforms that became overprinted by the F2 synform. The magnetic anomalies around the mine localities occur either slightly northwest or along the synforms axial trace. The anomalies surrounding Silvergruvan are clustered around the hinge. The anomalies west and northwestern of the northeastern Utö, appear to be located on the northwestern limb of the synform. The strongest positive magnetic anomaly and nearby anomalies, almost seem to follow the northernmost F1 antiform. On the eastern and northeastern part of the island, the anomalies also appear on the eastern limb of the synform. The magnetic anomalies generally follow the synforms axial trace in the southwest, but are randomly scattered farther northeast.

4.2.9 Magnetic anomaly intensity and vector maps displayed on the geological map of Dunst et al. (manuscript)

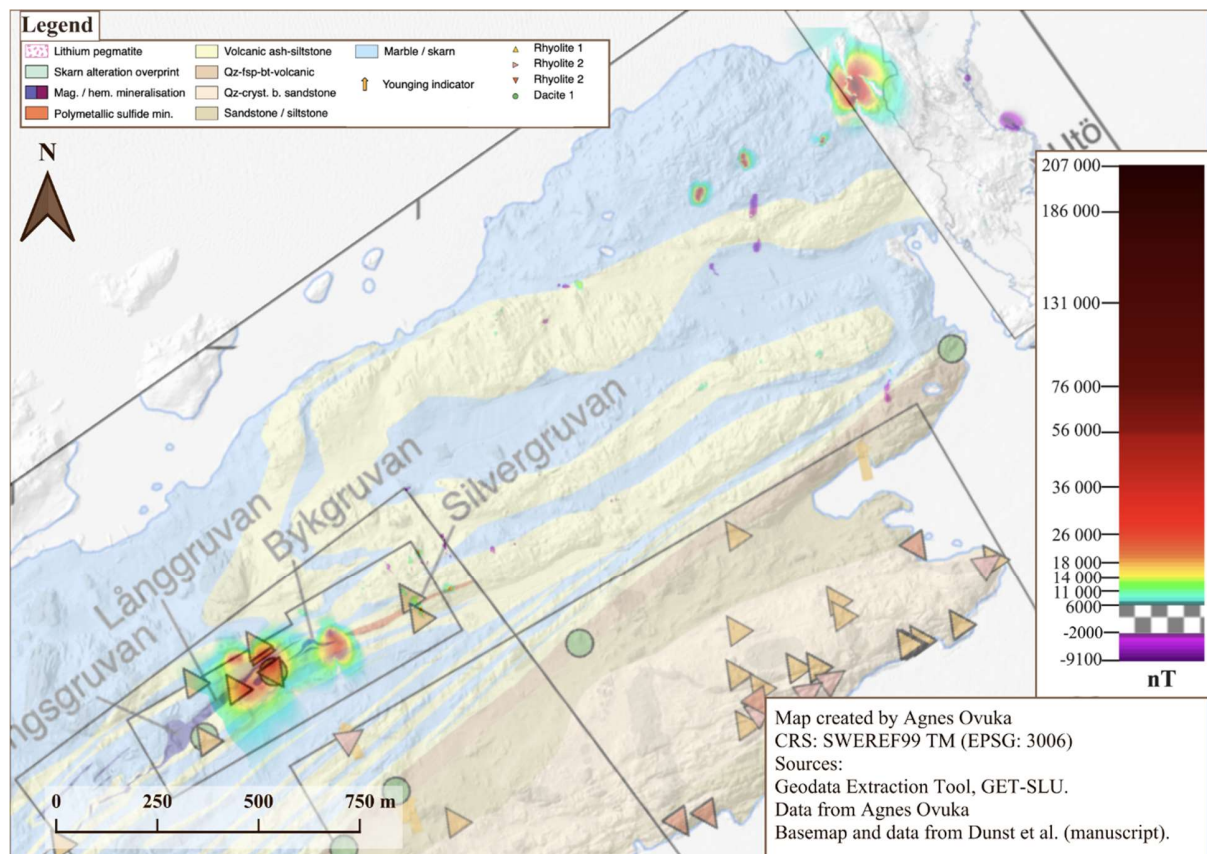


Fig. 22 Magnetic anomaly intensity map displayed on the geological map of Dunst et al. (manuscript).

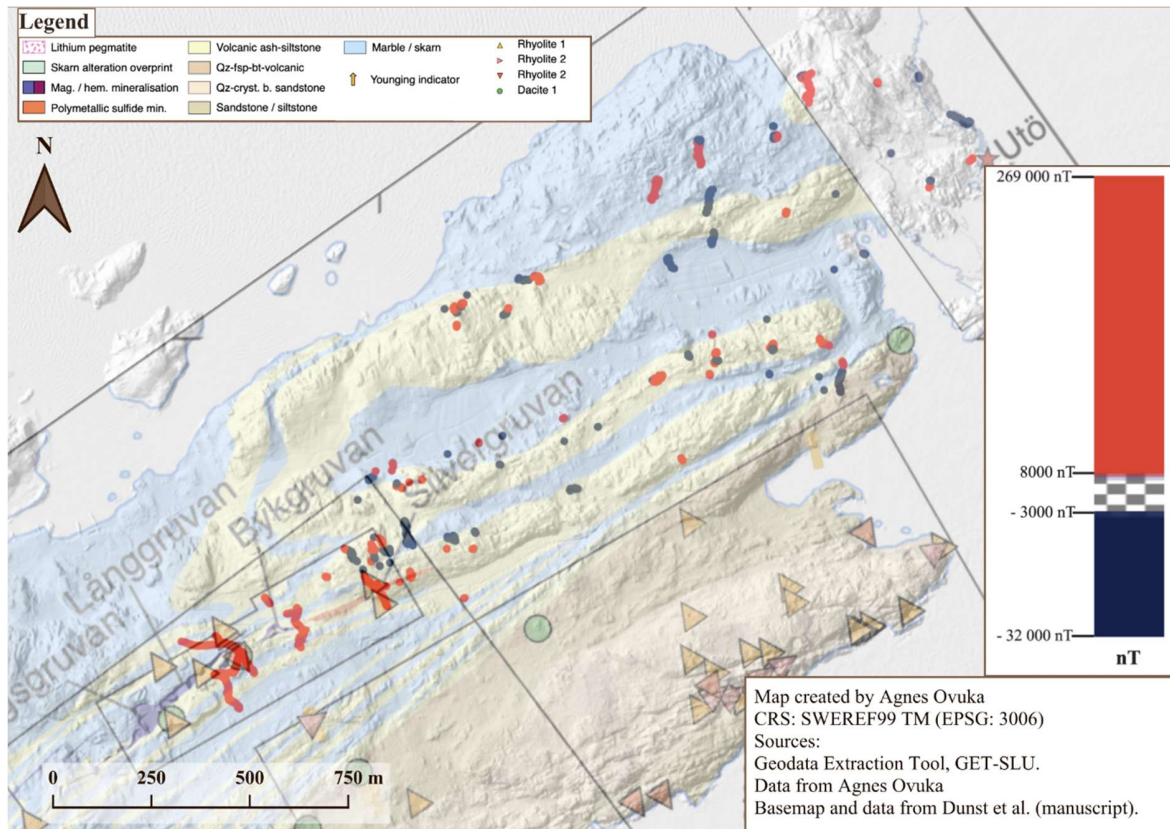


Fig. 23 Magnetic anomaly vector map displayed on the geological map of Dunst et al. (manuscript).

When compared with the geological map by Dunst et al. (manuscript), the magnetic anomalies occur within both the volcanic ash-siltstone unit and the marble/skarn unit. However, in the northeastern part of Utö, one negative anomaly occurs within the Qz-fsp-bt-volcanic.

Most of the magnetic anomalies occur within the volcanic ash-siltstone unit including the anomalies associated with the mine localities, Nyköpingsgruvan, Långgruvan, Bykgruvan and Silvergruvan. The strongest positive anomaly is located northwest and within the ash-siltstone unit.

On the western and northwestern part of northeastern Utö, the magnetic anomalies of varying intensities are randomly distributed within the volcanic ash siltstone and the marble/skarn. Three positive anomalies, <76 000 nT are located within the marble/skarn, as well as negative anomalies of magnetic anomaly values -9100 nT.

The two negative anomalies located northeast are excluded in this comparison, because the full geological map could not be displayed in QGIS due to technical issues. The magnetic anomaly map was therefore compared to the final map by Dunst et al. (manuscript).

5.0 Discussion

5.1 Lithology, iron oxide and sulphide mineralisation, and the spatial relationship of the magnetic anomalies

There is a broad agreement between lithostratigraphic frameworks of the authors. Although, the authors sometimes use different lithographic terminology and propose different structural models. Holmquist (1910), Gavelin et al. (1976), Stålhös (1982), Allen et al. (1996), Dunst et al. (manuscript) and Talbot (2008) place the iron ore and sulphide deposits within the upper part of the supracrustal rock succession. The main differences between these authors are the interpretation regarding the surrounding rock sequences, the lower southeastern metasedimentary group, the northwestern metasedimentary group, and the position of the porphyry sheets.

Most authors proposed that iron ore mineralisation occur within the felsic metavolcanic and volcanoclastic rocks. However, the spatial relationship between the magnetic anomalies from this study's magnetic anomaly map and the mapped lithological units from the different geological maps differ considerably among the suggested models.

5.1.1 Lithostratigraphic models in comparison with the magnetic anomaly map

Holmquist (1910) interpreted the iron ore as its own sedimentary unit that formed together with the stratified leptites, hälleflintas and limestones. He describes the sulphides as being followed by quartz and calcite and usually form tiny cementing masses in the iron ore and the hälleflintas. Comparison with the geological map of Holmquist (1910) shows that the magnetic anomalies almost entirely occur within the leptites and hälleflintas. Magnetic anomalies do not seem to support the idea that the iron ore occurs as its own sedimentary unit, nor does it appear within the carbonates.

Gavelin et al. (1976), positioned the iron ore deposit within the hälleflinta and leptite-group with its limestones and skarn. Magnetic anomalies are located within this unit.

Stålhös (1982) interpreted the iron ore deposit to be hosted within the alkalic metatuffites (leptites) and hälleflintas, with the sulfide mineralisation occurring at a slightly higher structural level. In this case, the magnetic anomalies are located within the leptites and hälleflintas, as well as the carbonates.

Allen et al. (1996) proposed that most iron oxide and sulphide deposits are hosted by metavolcanic rocks and associated with metalimestones and skarns. According to Allen et al. (1996), they have encountered both SVALS and SAS sulphide mineral deposits. This study's comparison displays that the magnetic anomalies occur within the metavolcanic rocks and the carbonates.

Talbot (2008) interpreted that the BIF and sulphide mineralisations lie within the pyroclastics and cherts. Comparing this study's magnetic anomaly map with Talbot's geological map (2008), shows that the magnetic anomalies are almost exclusively associated with the pyroclastics-cherts-BIF-unit and not the carbonates, just as he proposed.

Dunst et al. (manuscript) suggested the iron oxides lie within a section dominated by siltstones with only thin carbonate interbeds. The main sulphide mineralisations occur within

VAS. Both mineralisations are limited to a single stratigraphic section within the upper ash-siltstone-carbonate succession. According to Dunst et al. (manuscript) limited stratabound carbonate alteration or carbonate replacement sulphide mineralisation may have occurred, but these were difficult to recognise due to deformation, metamorphism and recrystallisation. Comparing this study's magnetic anomaly map with the geological map of Dunst et al. (manuscript), shows that the magnetic anomalies occurred within both the VAS and the marble beds.

According to Dunst et al. (manuscript) and Holmquist (1910) pyrrhotite is one of the main sulfides in the sulfide mineralisations, which is a magnetic sulphide mineral (Mussett & Khan, 2000, p. 152). Stålhös (1982) argues that weaker magnetic sulfides have most likely caused several of the magnetic anomalies on his magnetic anomaly map. This means that the magnetic anomaly map of this study most likely demonstrates magnetic anomalies originating from both ore types.

5.1.2 This study's interpretation of the supracrustal rock succession and the stratigraphic position of the iron ore

This study proposes that both ore types are stratabound and occur within the felsic metavolcanic and volcanoclastic rocks, limited to VAS, at the same or closely related stratigraphic positions. Pure carbonate rocks generally display diamagnetism (Lowrie, 2007, p. 289). However, due to deformation, metamorphism and alteration, many of the carbonates may not be pure. Therefore, this indication may not be entirely reliable.

Nevertheless, Dunst et al. (manuscript) argues that both mineralisations share a stratigraphic position. However, they are laterally and vertically separated, which they interpreted to indicate spatial variations in redox conditions, sulphur availability, and fluid chemistry within the basin. Dunst et al. (manuscript) does not consider these as separate mineralising events, which is considered a reasonable interpretation in the present study.

While not definitive, this study suggests two primary interpretations of the lithostratigraphy of the supracrustal rocks of Utö. The first interpretation proposes that the supracrustal succession's basal part consists of (1) metagreywackes and subgreywackes, which are overlain by (2) rhyolitic tuffs and associated metavolcanic and volcanoclastic deposits, including VAS, which hosts the Fe-oxide and sulfide mineralisation. The succession records a continuous sequence from rhyolitic to dacitic deposits. These units are overlain by (3) carbonates, possibly containing with its possible stromatolites, as suggested by Dunst et al. (manuscript). The uppermost unit reflects a shallow calm depositional environment. The iron ore and sulphide deposits are positioned in the lower to middle part of the upper unit in the stratigraphy. This interpretation suggests that it is one ore unit that has been folded.

The second interpretation proposes that the basal part of the supracrustal succession consists of (1) metagreywackes and subgreywackes. However, in this case there would be a cycle from intense volcanism to waning volcanism, as suggested by Allen et al. (1996). As a result, there would be a cycle between the (2) rhyolitic tuffs and metavolcanic and volcanoclastic deposits, including VAS, which hosts the Fe-oxide and sulfide mineralisation, and the (3) carbonate deposits. The third unit possibly contains stromatolites (Dunst et al., manuscript). The iron ore and sulphide deposits are positioned in the lower to upper part of the upper unit in the stratigraphy. This implies that there are separate ore bodies, in different strata.

However, further investigation is needed in the anomalous areas that indicate disagreement with the mapped lithological interpretations, including core drill, petrography and mineral identification, geochemistry analysis and sulphur isotope analysis.

5.3 Structural and spatial relationship with magnetic anomalies

The distribution of the magnetic anomalies is quite compatible with the synformal structural models of Stålhös (1982) and Talbot (2008). However, neither of the maps can fully explain the anomaly pattern.

On the map of Stålhös (1982), the magnetic anomalies are generally located slightly southeast of the mapped synform. However, when the trend of the axial trace of the synform is projected, the anomalies in the northwestern part of Utö concur with the hinge. On the northeastern part of the study area, the anomalies are located on the eastern limb.

On the map of Talbot (2008) the magnetic anomalies are concentrated near the hinge of the synform and mostly follow its mapped axial trace from the southeast to the center part of northeastern Utö. Exceptions occur on the northwestern and northeastern part of the study area, where the anomalies are located on the northwestern and northeastern limbs of the synform.

On both lineation maps, the magnetic anomalies commonly follow the hinge and the limbs of the synform located in the study area. Gavelin et al. (1976), Holmquist (1910), Stålhös (1982) and Talbot (2008) proposed that the supracrustal rocks were deposited prior to deformation. The fold axes and lineations show a maximum plunge of 85 degrees towards the northwest (Stålhös, 1982).

Based on the previous observations and interpretations, together with the spatial relationship between the structural and the magnetic anomalies of this study, their relationship indicates that the supracrustal rocks were deposited prior to deformation. This study argues that the ore deposits are not structurally controlled. Instead, they are stratabound deposits, that were deformed with the rest of the supracrustal rocks. This interpretation is based solely on the spatial relationships of the magnetic anomalies compared to the structural and geological maps, derived from magnetic survey data and GIS analysis. No geological mapping and structural measurements were undertaken during this study.

5.4 Comparison of magnetic anomaly maps from this study and Stålhös (1982)

The two maps broadly agree despite using completely different magnetic survey methods. The map of Stålhös (1982) is based on an airborne survey, using a fluxgate magnetometer (1971), while this study is done through ground magnetic surveying, using the Physics Toolbox magnetometer from Vieyra Software (n.d.). The magnetic anomaly values are not directly comparable, however, the spatial patterns, geometry and connection to geology are important indicators.

The magnetic anomaly map produced in this study agrees with Stålhös (1982) in the southeastern part of the study area (mine localities), where both show strong positive anomalies. The anomalies from both magnetic anomaly maps occur within the alkalic metatuffites on Stålhös geological map (1982).

In contrast to the map of Stålhös (1982), intense positive anomalies are identified on the northwestern part of Utö. Where the anomaly that's ranging between -9100 nT to 207 000 nT lies between the interval - 400 nT to -80 nT on the map of Stålhös (1982). This anomalous area on his map is interpreted as negative. However, according to this study it should imitate the anomalous area around the mines on his map. The reason this anomaly might not be included on the map of Stålhös, can be because the anomaly is very thin and not having been covered in the profiles of the airborne survey. These had a spacing of 200 meters. Field observations indicated that the anomaly originated from exposed bedrock, there was no visible evidence of buried magnetic objects. The similarities between these and the anomalies within the mine localities, suggest that the northwestern area should be investigated further.

According to Stålhös (1982), the sulphide mineralisations, that is of a weaker magnetic susceptibility, have contributed to several areas on the map. A certain correspondence can be expected if the iron oxide and sulphide mineralisations are consistent with particular geological and magnetic contour boundaries. The mapped leptites contain an abundance of magnetite and show themselves through strong anomalies (Stålhös, 1982).

However, the northwestern intense positive anomalies are located within the mapped marble (Stålhös, 1982). This may indicate that the marble contains minerals with high magnetic susceptibility, and/or be interlayered with skarn bearing such minerals. The contact between the alkalic metatuffites and the marble could be inaccurately mapped, but it is also possible that the source rock is of iron oxide and sulphide rich alkalic metatuffites, such as in the southeastern part of the study area.

This study identified numerous small local variations that are absent from Stålhös magnetic survey (1982). This could either be because they did not obtain data of these variations or because these variations were smoothed out during data processing. Negative and positive anomalies occurred in close association. In the field, the presence of a positive anomaly was often followed by a negative anomaly, and vice versa, along the survey profiles.

5.5 Limitations and error sources

5.5.1 Magnetic surveying

The field terrain was intense, with dense forest, swampy or rocky environments. This made it difficult to execute survey profiles with an exact southeast to northwest direction. Narrower or wider spacing between each profile was sometimes necessary. Consequently, significant magnetic measurements might have been missed. Occasionally, it was difficult to maintain a constant sensor height, which required the phone to be held closer or placed on the ground.

Magnetized objects such as fences, cars and tools, may influence magnetic measurements. To minimize the interference between the smartphones, the instruments were carried with adequate spacing. Tests showed that when the devices were held close to each other, without contact, the effect on the magnetic measurements was tiny (<1 nT).

5.5.2 GPS and Magnetometer

Cellular enabled smartphones include an integrated GPS-chip-set manufactured by companies such as Qualcomm, Broadcom and CSR (ESRI, 2013). Between these, the locational accuracy is almost the same. These chip-sets are predominantly designed for power consumption, second for time to fix and lastly for locational accuracy. However, the difficult terrain could potentially affect the ± 3 m resolution when magnetic surveying.

During magnetic surveying, minor timing differences when starting and stopping recording the instruments, occasionally resulted in a minor offset between the datasets. This may have shifted magnetic measurements marginally along the survey profiles (<1 m).

5.5.3 Hall-effect sensor

Temperature fluctuations can affect the geomagnetic sensor, causing changes in its sensitivity including: (1) Sensitivity temperature drift where the typical change is ± 0.01 and the max ± 0.3 %/K between -40°C to 85°C , (2) the resolution that is 300 nT at 25°C , and (3) the zero-B offset that is ± 2000 nT between -40°C to 85°C (Bosch Sensortec GmbH, 2020). The zero-B offset means that the magnetic field values may be indicated in the measurements even if the external magnetic field is absent. These effects are considered to only have had a minor influence on the data.

5.5.4 Map interpretations

The maps used for comparisons in this study did not align perfectly with the GIS magnetic anomaly map created in this study, except for Dunst et al. (manuscript). Although the spatial differences were minor, they should be included as a source of uncertainty.

5.5.5 Interpolation

Different interpolation methods can produce different shapes of the data. Several methods were tried, including GDAL's Grid (IDW with nearest neighbour searching) and Grid (Inverse distance to a power), as well as QGIS IDW interpolation, which was used for this study. The major difference between (1) "IDW with nearest neighbour searching" and (2) "Inverse distance to a power" is when the sample points are weighted throughout interpolation, the influence of one point relative to another declines with distance from the unknown point that is intended to be estimated (QGIS Documentation, 2025).

For this study, the second method was selected because it made the magnetic anomaly intensity and distribution clear. The QGIS IDW interpolation exhibited a high resolution and continuous surface when demonstrating the anomalies. However, it is crucial to acknowledge that no measurements were collected between the profiles. This means that the values are interpolated estimates and represent an interpretation, rather than real field observations. The interpolation smoothes the data, which can lead to the body of the anomaly being distorted, and slightly shift its position.

There are disadvantages with interpolation and this method specifically. If the data points are unevenly distributed, which is the case for this study, the quality of the interpolation can decrease (QGIS Documentation, 2025). The data density was reduced significantly to improve processing and quality, while preserving the distribution of the magnetic values. The data-set could potentially be further reduced. However, too much data reduction may remove significant variations and weaken the interpretation. Whereas, keeping too many data points unlikely improves the interpretation either. Despite this limitation, the interpolation successfully highlighted the spatial distribution and intensities of the magnetic anomalies.

5.5.6 Symbology and classification:

The classifications were developed to guide and facilitate the interpretation of the magnetic data, by emphasising significant positive and negative magnetic anomalies. They are based on ground-truth observations, together with GIS-based analysis. Nevertheless, the classifications are simplified and may be partly subjective. Alternative threshold values may slightly change the appearance of the magnetic anomalies, however the geographical distribution and geometry would remain the same.

5.5.7 Literature review

The literature review has been crucial for interpreting the data of this study. Earlier studies may rely on more traditional approaches regarding data acquisition, whereas more recent work includes advanced analytical tools and models. This does not imply that the earlier studies produced are of less valuable results, it does only imply that the studies had varying opportunities when acquiring data. For example, prior to 1974 it was possible to collect samples by breaking rock in the field on Utö, whereas these activities are no longer permitted due to the status as a nature reserve (Länsstyrelsen Stockholm, 2025). It was also noticeable that later studies build their observations on previous studies.

6.0 Conclusion

This study shows ground magnetic surveying can be done using a smartphone magnetometer. In this case, a smartphone equipped with the application Physics Toolbox magnetometer from Vieyra Software (n.d.), successfully identified magnetic variations, which could be used to map the iron ore formation on northeastern Utö. The resulting GIS-based magnetic anomaly maps clearly display the strong magnetic anomalies around the mines. Nevertheless, strong magnetic anomalies are identified further northwest and east, including an exceptionally strong positive magnetic anomaly.

Comparison with previous studies and maps shows that the magnetic anomalies are spatially connected to the felsic metavolcanics and metatuffites, and the carbonates. Even though the different authors use slightly different lithological terminology and structural interpretations, all agree that the stratigraphic position of the iron ore is positioned within the upper unit of the supracrustal rocks. The magnetic data align with these interpretations and provide additional indications on the distribution of the iron mineralisations within the lithological units.

Based on the combined interpretation of previous studies and magnetic data presented within this study, it is suggested that the iron ore is hosted within or occurs along the contacts of the felsic metavolcanic and volcanoclastic rocks, limited to VAS, at the same or closely related stratigraphic positions.

This study proposes two alternative lithostratigraphic models for the Utö supracrustal succession, where both consists of a basal metasedimentary unit. They differ principally in whether the metavolcanic and volcanoclastic rocks, with their overlaying carbonates, represent a single continuous succession or repeated cycles of volcanic and carbonate deposition. Both interpretations position the iron oxide and sulphide mineralisation within the upper unit. This study proposes that iron oxide and sulphide mineralisation are stratabound and occur within the felsic metavolcanic and volcanoclastic rocks, limited to VAS, at the same or closely related stratigraphic positions. They are not structurally controlled, which means that the supracrustal rocks were deposited prior to deformation. This study cannot confirm whether the ore mineralisation is restricted to one ore body-unit that has been folded, or if there are several ore bodies in different strata that has been folded.

The comparison with the airborne magnetic survey mapped by Stålhös (1982) demonstrates a general agreement in the magnetic anomaly geometry and intensity pattern, despite using different survey methods. In addition, this study identifies several previously unrecognised magnetic anomalies that may represent areas of geological interest and therefore warrant further investigation. One example is the extremely strong positive magnetic anomaly in the northwestern part of northeastern Utö.

The results show that magnetic surveying done by a smartphone provides an easy and cost-effective method of geological investigations. It is a useful complement for geological and educational field investigations.

Further investigations, such as magnetic surveying, core drilling, petrography and mineral identification, geochemistry analysis and sulphur isotope analysis, are required to determine the origin of the newly identified magnetic anomalies and their relationship to the iron oxide and sulphide mineralisations.

Reference list

- Allen, R.L., Simeonov, A. and Christofferson, H. (1996) 'Facies Analysis of a 1.9 Ga Continental Margin, Back-Arc, Felsic Caldera Province with Diverse Zn-Pb-Ag-(Cu-Au) Sulfide and Fe Oxide Deposits, Bergslagen Region, Sweden', *Economic Geology*, 91, pp. 979–1008.
- Bosch Sensortec GmbH. (2020). *BMM150 geomagnetic sensor: Datasheet*. Available at: <https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bmm150-ds001.pdf> (Accessed: 21 July 2026).
- Dunst, R., Pitcairn, I. and Jansson, N.F. *Hydrothermal alteration and the formation of Fe-oxide and sulphide mineral deposits on Northeastern Utö, eastern Bergslagen, Sweden*. Manuscript (preprint), Department of Geological Sciences, Stockholm University. Registered in DiVA; full text not publicly available.
- Flanders, N. C. (2023). *A Geophysical Survey of Northern Utö*. Master's thesis, Department of Geological Sciences, Stockholm University. Available at: <https://www.diva-portal.org/smash/get/diva2:1847470/FULLTEXT01.pdf> (Accessed: 21 July 2026).
- Gavelin, S., Lundström, I. and Norström, S. (1976) 'Svecofennian Stratigraphy on Utö, Stockholm archipelago', *Sveriges Geologiska Undersökning*, C719, pp. 1–44.
- Holmquist, P.J. (1910) 'The Archaean geology of the coast-regions of Stockholm', *Geologiska Föreningens i Stockholm Förhandlingar*, 32, pp. 798–908.
- ITG Linear Motor. (2025). *What Is the Hall Effect Sensor and How Does It Work?* Available at: [ITG Linear Motor – What Is the Hall Effect Sensor and How Does It Work?](#) (Accessed: 21 July 2026).
- Länsstyrelsen Stockholm (2025) *Utö naturreservat*. Available at: <https://www.lansstyrelsen.se/stockholm/besoksmal/naturreservat/uto.html> (Accessed: 3 June 2026).
- Lowrie, W. (2007) *Fundamentals of Geophysics*. 2nd edn. Cambridge: Cambridge University Press.
- National Centers for Environmental Information (NCEI). (2025) *International Geomagnetic Reference Field (IGRF)*. Available at: <https://www.ncei.noaa.gov/products/international-geomagnetic-reference-field> (Accessed: 3 June 2026).
- National Geophysical Data Center (2025) *Magnetic Field Calculator*. Available at: <https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml> (Accessed: 3 June 2026).
- National Institute of Standards and Technology (NIST). (2026). *Hall Effect*. Available at: <https://www.nist.gov/pml/nanoscale-device-characterization-division/popular-links/hall-effect> (Accessed: 21 July 2026).
- Shaner, J. (2013) *Smartphones, Tablets and GPS Accuracy*. Esri ArcGIS Blog. Available at: <https://www.esri.com/arcgis-blog/products/field-mobility/field-mobility/smartphones-tablets-and-gps-accuracy/> (Accessed: 21 July 2026).

Stephens, M.B., Ripa, M., Lundström, I., Persson, L., Bergman, T., Ahl, M., Wahlgren, C.-H., Persson, P.-O. and Wickström, L. (2009) *Synthesis of the bedrock geology in the Bergslagen region, Fennoscandian Shield, south-central Sweden*. Sveriges geologiska undersökning, Ba 58. Uppsala: SGU.

Stålhös, G. (1982) *Beskrivning till berggrundskartan Nynäshamn NO/SO: Utö med omgivande skärgård*. Sveriges geologiska undersökning, Af 138.

Sveriges geologiska undersökning (SGU) (n.d.) *Berggrund 1:50 000–1:250 000, WMS-tjänst*. Available at: <https://resource.sgu.se/service/wms/130/berggrund-50-250-tusen> (Accessed: 4 June 2026).

Sveriges geologiska undersökning (SGU) (2025) *Magnetfält*. Available at: <https://www.sgu.se/produkter-och-tjanster/geologiska-data/geofysik--geologiska-data/magnetfalt/> (Accessed: 3 June 2026).

Sveriges geologiska undersökning (SGU) (n.d.). *Utö*. Tillgänglig på: [SGU – Utö](#) (Accessed: 22 July 2026).

Sveriges lantbruksuniversitet (SLU). (n.d.). *GET – Geological Exploration Tools*. Available at: <https://maps.slu.se/get/> (Accessed: 4 April 2026).

Talbot, C.J. (2008) 'Palaeoproterozoic crustal building in NW Utö, southern Svecofennides, Sweden', *GFF*, 130, pp. 49–70.

Texas Instruments. (2021). *What Is a Hall-effect Sensor?* Technical Article SSZT164. Available at: [Texas Instruments – What Is a Hall-effect Sensor? \(SSZT164\)](#) (Accessed: 21 July 2026).

United States Environmental Protection Agency (EPA). (2026). *Magnetic Susceptibility*. Environmental Geophysics. Available at: <https://www.epa.gov/environmental-geophysics/magnetic-susceptibility> (Accessed: 21 July 2026).

Utö Hembygdsförening (n.d.). *Utö gruvor*. Tillgänglig på: <https://www.hembygd.se/uto/besoksmal-pa-uto/uto-gruvor> (Accessed: 22 July 2026).

Vieyra Software LLC. (n.d.). *Physics Toolbox Sensor Suite*. Available at: <https://www.vieyrasoftware.net/> (Accessed: 21 July 2026).

QGIS Documentation (2025). *Interpolation – IDW Interpolation*. Available at: https://docs.qgis.org/3.44/en/docs/user_manual/processing_algs/qgis/interpolation.html#qgisidwinterpolation (Accessed: 22 July 2026).

QGIS Documentation (2025). *Raster analysis (GDAL)*. Available at: https://docs.qgis.org/3.44/en/docs/user_manual/processing_algs/gdal/rasteranalysis.html (Accessed: 22 July 2026).

Appendix

The following appendices contain maps and legends referred to in this thesis. They are included to facilitate comparison between the magnetic survey results and previously published geological interpretations of the study area. Original sources are cited in the reference list, and direct links to publicly available maps are provided in the appendix.

Appendix A

Geological map legend of Allen et al. (1996)

Figure A1. Geological legend used by Allen et al. (1996).

Rock or facies	
	Post-Svecofennian rocks, younger than 1850 Ma
	Synvolcanic "Svecofennian" or pre-tectonic "Svecokarelian" granitoids, 1870-1890 Ma
	Argillite, slate and rhyolitic, volcanoclastic turbidites (facies nr 16)
	Fine-medium grained, quartz rich sandstone (facies nr 17)
	Marble (limestone and dolomite, large ones only, facies nr 15)
	Conglomerate (polymictic), arenite (facies nr 18)
	Ash-siltstone, rhyolitic, with up to 50% interbedded volcanic sandstones, marbles and skarn (facies nr 6, 7a, 8)
	Stratified successions of rhyolitic, syn-eruptive massflows and post-eruptive, reworked volcanoclastic rocks, with or without limestone (facies nr 1a, 2, 3a, 4, 5a) Includes some dacitic units in Garpenberg
	Stratified successions of post-eruptive, rhyolitic volcanoclastic rocks, with or without limestones and ash-siltstone (facies nr 2, 4)
	Very thick, poorly stratified rhyolitic, syn-eruptive massflow (facies nr 1a, 3a, 5a)
	Very thick, poorly stratified dacitic, syn-eruptive massflow (facies nr 1b, 3b, 5b)
	Mafic lavas (facies nr 13, 14)
	Mafic sills and dykes (large ones only, facies nr 12)
	Intrusive and extrusive rhyolitic porphyries (facies nr 9a, 10)
	Intrusive (and extrusive?) dacitic porphyries (facies nr 9b)
	Metavolcanic rocks, undifferentiated, (facies nr 11a, 11b)
	Lavas and shallow intrusions, small occurrences (facies nr 9a, 9b)

Fig. A1 Geological legend used by Allen et al. (1996).

Figure A2. Geological-, facies-, depositional environment- and structure legend used by Allen et al. (1996).

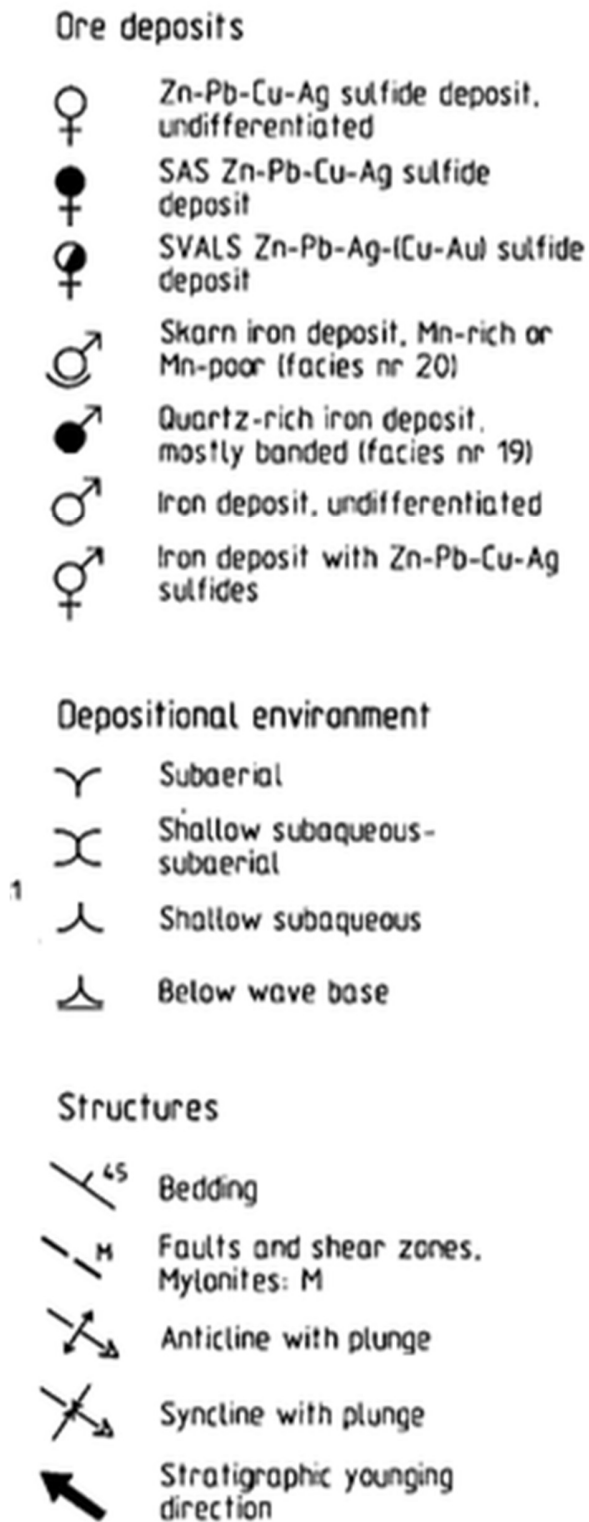


Fig. A2 Geological-, facies-, depositional environment- and structure legend used by Allen et al. (1996).

Appendix B

Geological legend of Stålhös geological map (1982).

Figure B1. Geological legend used by Stålhös (1982).

	Häll Outcrop
	Gruva, järnmalm, nedlagd Iron mine, abandoned
	Sulfidmalm Sulfide ore
	Fältspatbrott (nedlagt) Quarry for feldspar (abandoned)
	Stänglighet med gradtal för stupning Lineation, plunge in degrees
	Stänglighet med vertikal stupning Lineation, plunge vertical
	Veckaxel med gradtal för stupning Fold axis, plunge in degrees
	Skiffrighet med gradtal för stupning Foliation, dip in degrees
	Skiffrighet med brant stupning (86–89°) Foliation with high dip
	Skiffrighet med vertikal stupning Foliation, dip vertical
	Skiffrighet med okänd eller starkt varierande stupning Foliation, dip unknown or highly variable
	Lagerföljd. Pilen pekar mot yngre skikt Way-up determination. Younger beds in direction of arrow
	Lagring med gradtal för stupning Bedding, dip in degrees
	Lagring med vertikal stupning Bedding, dip vertical
	Lagring med okänd eller starkt varierande stupning Bedding, dip unknown or highly variable
	Lagring med vindlande strykning och gradtal för stupning Bedding, strike highly variable, dip in degrees
	Tektonisk zon, B = breccia, M = mylonit Tectonic zone, B = breccia, M = mylonite
	Förkastning genom väsentligen vertikala rörelser. Pilarna pekar mot det sänkta blocket Dip-slip fault. Arrows indicate down-faulted block
	Diabasgång. Dbs = gångsvärm. Dolerite dike. Dbs = swarm of dikes.
	Inneslutna partier av 1, sedimentgnejs, 2, leptit, 3, gnejsgranit Xenoliths of 1, metasediment, 2, leptite, 3, gneissose plutonics

Fig. B1 Geological legend used by Stålhös (1982).

Figure B2. Geological legend used by Stålhös (1982).

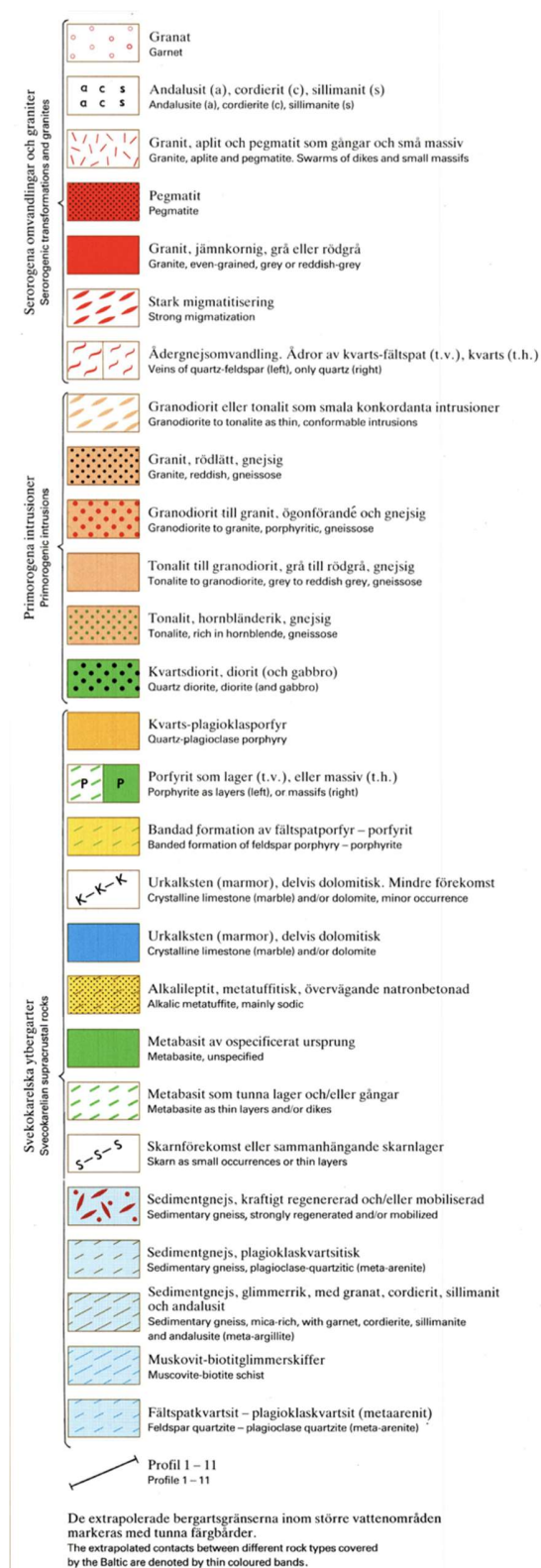


Fig. B2 Geological legend used by Stålhös (1982).

Original map available from the Geological Survey of Sweden (SGU):

<https://resource.sgu.se/dokument/publikation/af/af138karta/af138-karta.pdf>

Appendix C

Magnetic anomaly map after Stålhös (1982)

Figure C1. Magnetic anomaly map after Stålhös (1982).

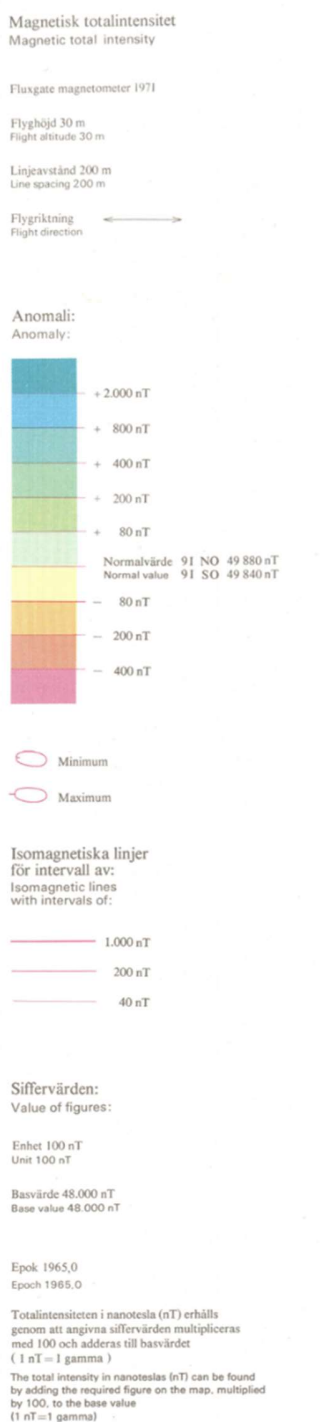


Fig. C1 Magnetic anomaly legend used by Stålhös (1982).

Original map (Stålhös, 1982) available from the Geological Survey of Sweden (SGU):

<https://resource.sgu.se/dokument/publikation/af/af138karta/af138-2-karta.pdf>

Appendix D

Lineation legend used by Stålhös (1982).

Figure D1. Lineation legend used by Stålhös (1982).

	Stänglighet med gradtal för stupning Lineation, plunge in degrees
	Stänglighet med vertikal stupning Lineation, plunge vertical
	Veckaxel med gradtal för stupning Fold axis, plunge in degrees
	Skiffrighet med gradtal för stupning Foliation, dip in degrees
	Skiffrighet med brant stupning (86 – 89°) Foliation with high dip
	Skiffrighet med vertikal stupning Foliation, dip vertical
	Skiffrighet med okänd eller starkt varierande stupning Foliation, dip unknown or highly variable
	Lagerföljd. Pilen pekar mot yngre skikt Way-up determination. Younger beds in direction of arrow
	Lagring med gradtal för stupning Bedding, dip in degrees
	Lagring med vertikal stupning Bedding, dip vertical
	Lagring med okänd eller starkt varierande stupning Bedding, dip unknown or highly variable
	Lagring med vindlande strykning och gradtal för stupning Bedding, strike highly variable, dip in degrees
	Synform Synform
	Synform, överstjälpt och stupande Synform, overturned and plunging
	Antiform Antiform
	Antiform, överstjälpt och stupande Antiform, overturned and plunging
	Veckfront Fold front
	Sprickzon, smal Fracture zone, narrow
	Sprickzon, morfologiskt väl framträdande Fracture zone, morphologically prominent
	Förkastning genom väsentligen vertikala rörelser. Pilarna pekar mot det sänkta blocket Dip-slip fault. Arrows indicate down-faulted block
	Förkastning genom väsentligen horisontella rörelser Strike-slip or oblique-slip fault
	B = tektonisk breccia, M = mylonit B = tectonic breccia, M = mylonite
	Diabasgång. Dbs = gångsvärm Dolerite dike. Dbs = swarm of dikes
	Höjd över havet i meter Height in metres above sea level
	Höjdkurvor (ekvidistans 5 meter) Contour lines (interval 5 metres)

Fig. D1 Lineation legend used by Stålhös (1982).

Original map (Stålhös, 1982) available from the Geological Survey of Sweden (SGU):

<https://resource.sgu.se/dokument/publikation/af/af138karta/af138-3-karta.pdf>