2.5D geophysical model of the Gällivare mining area: An integrated study to model the top 4 km of the subsurface and guide for future exploration activities

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ABSTRACT

Potential field and Slingram data alongside rock physical properties, drill-core information and results from geological field mapping were used to investigate the geometry of the geological structures in the Gällivare area in regional scale. The main purpose of this study was to delineate the vertical and lateral extension of the Malmberget felsic volcanic rocks, the Dundret and Vassaravaara units as well as geological structures related to the crustal-scale Nautanen deformation zone. Furthermore, we aimed at identifying new magnetite-hematite and sulphide mineralizations and lithologies related to the mineralizations based on the results from regional-scale potential field modelling which are delineated with rock physical properties and borehole data. The study result indicated that the dome-shaped Dundret gabbro extends downwards to ~4 km depth and has its maximum depth at its centre. Hematite and magnetite assemblages occur within the top 2 km of the Dundret complex. Felsic volcanic rocks in the Malmberget area extend vertically down to a maximum depth of ~3 km and get considerably thinner towards the west. The model for the known magnetite-rich mineralizations in Malmberget was inferred from earlier drilling activities and was integrated into the profile models, which indicates a reasonable fit to the measured data, in particular on the magnetic anomaly; whereas the small dimensions of the modelled structures make them invisible on the Bouguer anomaly data. Additional magnetite-rich mineralizations are suggested within the Malmberget felsic rocks. High real component and low imaginary response of the Slingram data suggests conductive zones within the Nautanen deformation zone towards the NE, which given the geology of the area in the high strain zone can indicate disseminated sulphide mineralizations. Drill-hole data at the eastern parts of W-E profiles agreed well with the suggested model inferred from potential field data, suggesting presence of mafic intrusions within the ~top 1 km of the subsurface. The integrated model based on geophysical, petrophysical and geological data improved earlier understanding about the regional geometry of the key structures in the Gällivare area and indicates new

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magnetite-rich and sulphide mineralization prospects which can be used as a guide for future exploration activities in the area.

1   INTRODUCTION

1.1   History and economical importance of the Gällivare mining region

The Gällivare mining district located in Northern Sweden hosts some of Europe's largest ore deposits, such as the Malmberget apatite iron (Kiruna type) deposit and the Aitik Cu–Au–Ag (–Mo) deposit (Fig. 1).

The economic significance of the Gällivare area in terms of mineral potential was first discovered in the 18th century by exploration of iron deposits. In 1900, a mining company named Aktiebolaget Nautanens Kopparfalt started its exploration activities, which led to building the mining village, ropeway to Koskullskulle and a small smelter for producing blister copper. However, the low grade of the copper ore in addition to a lack of ore extraction technology made it non-economical, and therefore the company was bankrupted, which caused substantial failure for the investor, that is, the north-Swedish bank (Malmqvist and Parasnis, 1972).

1.2   The Malmberget, Aitik and Nautanen deposits

The Malmberget and Aitik deposits are located ∼15 km apart to the N and SE of the Gällivare town, respectively, in the southernmost part of the Northern Norrbotten ore district. These deposits contain more than 2000 Mt of Fe and more than 1000 Mt of Cu–Au–Ag ore. Additionally, 17 smaller mineralizations related to ferrous and base metal deposits occur in this area, among them the currently developed Nautanen Cu–Au deposit (Fig. 1).

Malmberget is the second largest underground iron mine in the world with an annual production of 16 Mt, and reserves are estimated to be ∼300 Mt of ore (LKAB, 2019). There are more than 20 identified tabular to stock shaped ore bodies in the Malmberget (Lund, 2009; Bauer *et al.*, 2018) with active underground mining restricted only to 13 ore bodies each with 5–245 Mt ore.

The Aitik deposit was discovered in 1932 by drilling a geophysical anomaly, and the deposit was further delineated by additional drilling which resulted in identifying a large volume of the low-grade copper ore. The base metal mineralization has been proven down to a depth between 400 and 800 m. Known as the largest open-pit mine in Europe, the Aitik deposit extends over 3 km in length, 1.1 km in width and ∼435 m in depth (Wanhainen *et al.*, 2014) with an annual production of ∼40 Mt (Boliden, 2019). The Nautanen deposit is suggested as an iron oxide copper–gold (IOCG) deposit, and most of the sulphide mineralizations are epigenetic and vary from disseminated to vein style which are hosted within Paleoproterozoic volcanosedimentary units of the Nautanen deformation zone (NDZ; Zweifel, 1976; Martinsson and Wanhainen, 2004a; Wanhainen *et al.*, 2006, 2012).

1.3   Earlier geophysical investigations

Due to the economic importance of the region, geophysical investigations have a long history as a major mean of ore prospecting. Various geophysical methods were employed to discover and locate ores at different depths. These methods include electromagnetic (airborne and surface), direct current (DC) resistivity, induced polarization, surface and borehole self-potential, airborne, surface and borehole magnetic, and ground gravity. In addition, geochemical moraine sampling as well as temperature measurements in drill-holes and isotopic determinations of ore content was conducted in certain areas, for example, Aitik, which is unique for such a large-scale deposit. The ore in the Aitik deposit is mostly of disseminated type with mostly weak impregnations of pyrite and chalcopyrite in a gneissic host rock. The electrical conductivity of this ore is generally low (o.1–1 mS/m); hence, the contrast in conductivity between the ore and the country rock is less than what is common in many other areas in Northern Sweden, which complicates geoelectrical interpretations (Malmqvist and Parasnis, 1972).

1.4   What is the significance of the present study?

Surprisingly, despite being one of the Europe's major ore districts, only a few regional-scale geophysical studies were
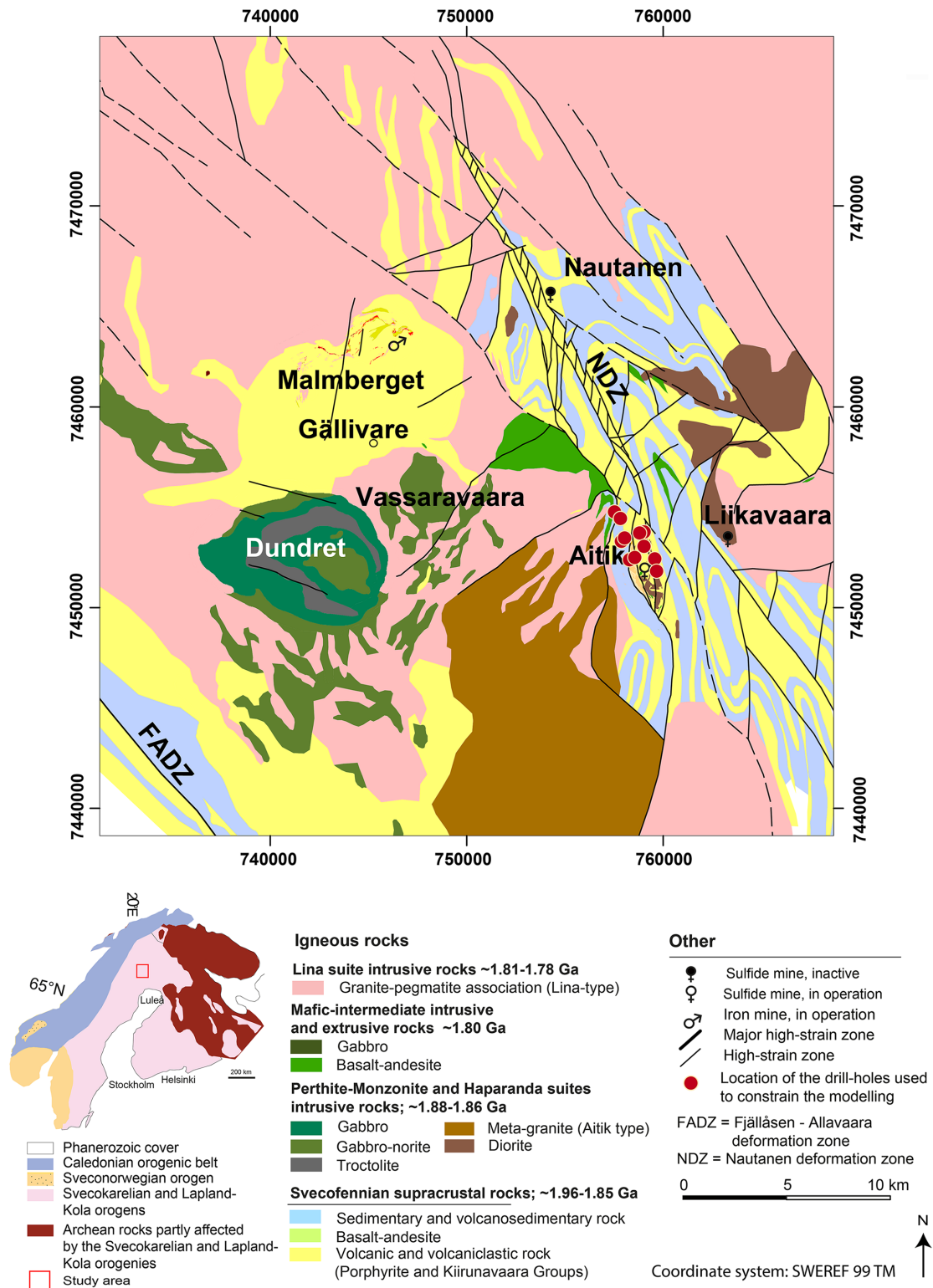
Figure 1 Simplified geological map of the Gällivare area and the Nautanen deformation zone (NDZ). Modified after Bauer *et al.* (2017) and Koistinen *et al.* (2001).

conducted in the Gällivare area. Although the study area in this paper benefits from ample and diverse integration of the geophysical and geological data, yet there is no explicit study that summarizes the regional-scale structure of the Gällivare area to the extent of this study.

This study aims at delineating the vertical and lateral extents of the dominant magmatic rock types in the study area including Malmberget felsic volcanic units, the Dundret and Vassaravaara gabbroic units as well as additional minor lithologies located in between the two major crustal structures; the NDZ in the east and the Fjällåsen–Allavaara deformation zone (FADZ) in the SW, down to a depth of ∼4 km. The result from this study provides basis for future mineral exploration activities and aids in the predictability of new discoveries combining 2.5D potential field modelling delineated with rock physical properties, borehole and Slingram data.

2 GENERAL GEOLOGY OF THE AREA

The bedrock in the Gällivare area comprises Paleoproterozoic volcanic, volcaniclastic and epiclastic rocks deformed and metamorphosed up to amphibolite facies conditions during the Svecokarelian orogeny (Fig. 1; Witschard, 1975; Zweifel, 1976; Bergman *et al.*, 2001; Tollefsen, 2014). These rocks are suggested to have been formed in a volcanic back-arc environment related to the subduction of Paleoproterozoic oceanic plate beneath an old Archaean craton at 1.90 Ga (Zweifel, 1976; Mellqvist *et al.*, 1999; Sarlus *et al.*, 2019). The meta-volcanosedimentary rocks occur in a 40-km-long zone parallel to the general N 20° W strike with an average width of 5 km forming an approximately rectangular zone centring the Gällivare area (Zweifel, 1976; Lynch *et al.*, 2015). Most of the ore deposits and mineralizations in the Gällivare area are hosted within these meta-volcanosedimentary rocks (Fig. 1). Rocks in the Gällivare area have been subject to at least two separate deformation phases. A first, N-S–directed compressional phase around 1.88 Ga (D1) is suggested to represent a regional-scale metamorphosis and resulted in the formation of a distinct tectonic fabric (Bauer *et al.*, 2017). The second deformation phase (D2) was suggested to represent an E-W-compressional folding and shearing phase with intense hydrothermal activity and the formation of iron oxide copper-gold (IOCG)-style mineralizations (Bauer *et al.*, 2017). The regional-scale Nautanen deformation zone (NDZ) located in the east of the Gällivare area cuts through these meta-volcanosedimentary rocks in the north–north–west direction (Fig. 1). The NDZ represents the most conspicuous structural feature in the area and is clearly delineated on magnetic anomaly maps (Lynch *et al.*, 2015). Meta-volcanosedimentary rocks adjacent to the NDZ host several Cu–Au ± Fe deposits and prospects, few example, include Nautanen, Liikavaara and Ferrum (see reviews by Martinsson and Wanhainen, 2004a, 2004b, 2013). The meta-volcanosedimentary rocks are surrounded and intruded by two major generations of igneous intrusive suites ranging in composition from granite to ultramafic-mafic gabbroic units. The ultramafic-mafic intrusive rocks are found mainly in the western part of the Gällivare area and occur as rounded to sub-rounded bodies. Most prominent is the Dundret intrusive layered complex rising to ∼825 m above sea level and exceeds approximately 10 km in the east–west and 8 km in the north–south directions (Fig. 1). To the east of the Dundret, a smaller 3×3 km sub-rounded intrusive body, the Vassaravaara intrusive complex, is found. Both layered complexes are prominent features on the magnetic maps. To the north of Dundret, felsic volcanic rocks form a ∼10 × 10 km sub-rounded body hosting the Malmberget Fe deposit (Fig. 1). Adjacent to the NDZ, mafic-intermediate plutonic rocks are found with composition varying from dioritic to gabbroic. Some of these dioritic rocks have played a significant role in the ore formation process, such as the quartz-monzodiorite found in the footwall of the Aitik deposit (Wanhainen *et al.*, 2006, 2012). Other common bodies found in the Gällivare area are the dolerites occurring in the form of dykes and sills. They occur as solitary bodies as well as clusters usually ranging in width from 1 to 10 m and are mafic to intermediate in composition (Sarlus, 2016; Sarlus *et al.*, 2019). Felsic plutonic rocks cover a large part of the Gällivare map sheet and include granitoids and syenitoids. Deformed and undeformed varieties of these granitoids and syenitoids are found ranging in age from 1.88 to 1.78 Ga (Sarlus *et al.*, 2018). Felsic plutonic rocks in the Gällivare area occur as voluminous as well as smaller sheet-like bodies, the latter occur especially within the 1.78 Ga granitic rocks belonging to the Lina suite described by Bergman *et al.* (2001). A second regional crustal structure i.e. FADZ, is found to the west of the Gällivare area and strikes parallel to the NDZ (Bergman *et al.*, 2001; Andersson *et al.*, 2020). The FADZ to the west and the NDZ in the east segment the Gällivare area into specific structural domains (Bauer *et al.*, 2017). The Gällivare area located between these two major crustal structures (Fig. 1) is regarded as a relatively low strain block during the D2 deformation phase. Second-order structures and locally high strain zones are associated with these major crustal structures (Bauer *et al.*, 2017). Intense

hydrothermal alteration is often observed with increasing intensity in conjunction with these major crustal structures especially the NDZ (Lynch *et al.*, 2015) as well as second-order structures and high strain zones (Martinsson and Wanhainen, 2004a). Alteration mineral assemblage comprise magnetite–biotite–amphibole–garnet–K-feldspar–tourmaline, epidote, sericite, scapolite and albite (Martinsson and Wanhainen, 2004a; Wanhainen *et al.*, 2012; Martinsson *et al.*, 2013).

3 GEOPHYSICAL AND PETROPHYSICAL DATA

A large set of geophysical data were compiled to study the regional structural geometry of the major geological structures in the Gällivare area. These geophysical data were collected at different times and for various purposes and include both airborne and ground-based data. A brief description of the geophysical data used in this study is summarized below.

3.1 Aeromagnetic and ground-based gravity data

Aeromagnetic data in this study have been utilized as one of the key geophysical methods (Fig. 2a1). The majority of the data were collected between 1980 and 2012 by the Swedish Geological Survey (SGU) from 60 to 200 m altitude; however, all aeromagnetic data used in this study were measured during 1984. The line spacing was 200 m and data were collected along the lines every 7 to 40 m. The instrument used was CS2 SENSOR with the DAARC500 electric control system.

Ground gravity data were provided by SGU and cover the entire study area (Fig. 2a2). The data were collected sparsely with changing station spacing of 500 to 700 m, depending on the natural barriers and exploration targets. The gravity data were collected from as early as 1901 and continued to 2008 in the entire Gällivare area. Complementary local measurements were conducted even after 2008 to provide denser data set for specific exploration purposes. The data have been corrected for latitude variation, tidal and instrumental drifts, free air, instrument height, Bouguer plate effects and terrain variation up to 50 m.

3.2 Ground-based Slingram data

Slingram consists of a pair of moving transmitter and receiver coils connected by a cable at a fixed distance, normally 40 or 60 m, with penetration depths corresponding to half the coil spacing. The measured data consist of two components, that is, real and imaginary parts and a high real component and low imaginary part can signify presence of a conductor. The Slingram data presented in this study were measured and provided by SGU with 18kHz frequency and using 60m coil separation. Slingram data in this study cover the eastern parts of the study area, only in a few spots along the Nautanen deformation zone (NDZ; Fig. 2b1).

3.3 Rock physical properties and drill-hole data

Around 6300 outcrop samples were collected by SGU from the Gällivare area and surroundings to determine the magnetic properties and density of the samples. Remnant magnetization and Q values (Königsberger ratio) were measured only on a few samples. A summary of the selected petrophysical data from SGU is listed in Table 1. In general, mean magnetic susceptibility values indicate high, compared with the common values of the corresponding rock types for most of the rocks, which can be explained by high magnetite content in the rocks within large parts of the study area. The median Q values indicated highest for the basalt/andesite and lowest for the felsic volcanic rocks (Table 1). Magnetite is of metamorphic and metasomatic-hydrothermal origin within the volcanosedimentary rocks as described by Lynch *et al.* (2015) and Bauer *et al.* (2018) and is mainly focused to major fluid conduit zones such as NDZ and related second-order structures. These crustal weak zones/fluid pathway with alteration assemblage including magnetite can explain the variation in the magnetic susceptibility. Boliden Mineral AB has conducted density measurements on ~3700 rock samples from the Aitik mine which are listed in Table 2.

Information from ~1350 drill-holes in the study area was integrated into the ArcMap database (Fig. 2b2). These boreholes were drilled by SGU and Boliden Mineral AB mainly between 1950 and 2005. A part of drill-holes lacks lithology description, which make them of no use. Boliden data contain additional information on metal grades. Most of the drill-holes are located within the eastern parts of the study area (Fig. 2b2). The selected drill-holes were integrated to constrain the potential field modelling when they met at least one of the following conditions: (a) located within maximum 1 km proximity from the modelled profiles and (b) were minimum 500 m deep, enough to correlate with the regional-scale models. The uppermost parts of the profiles that coincided with occurrences of the boreholes benefitted from detailed lithology descriptions inferred from borehole data.

(a) Aeromagnetic and Bouguer anomaly maps
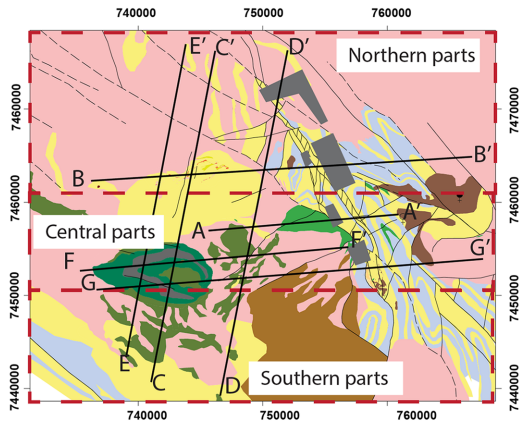
(a1) Aeromagnetic anomaly map
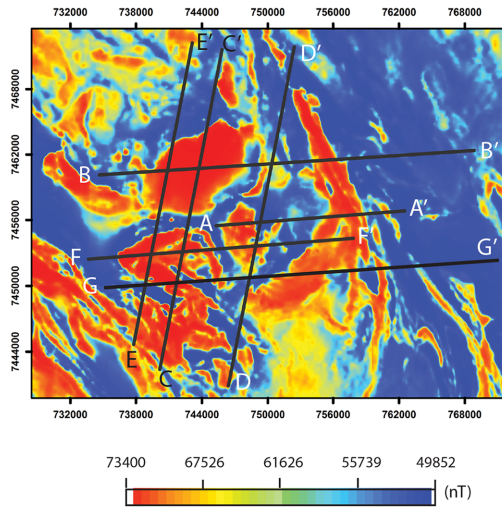
(a2) Bouguer anomaly map
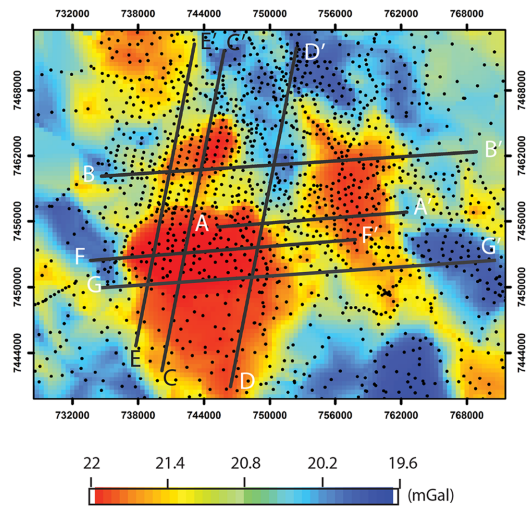
(b) Study zones, study profiles, slingram data coverage and location of the drill-holes in the study area

(b1) Study zones and regional-scale profiles

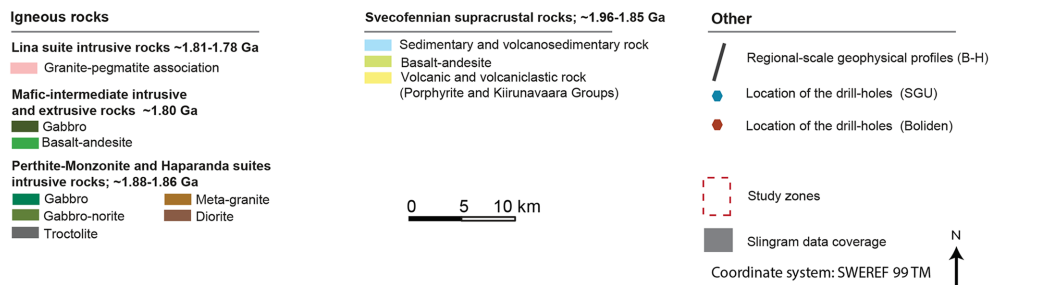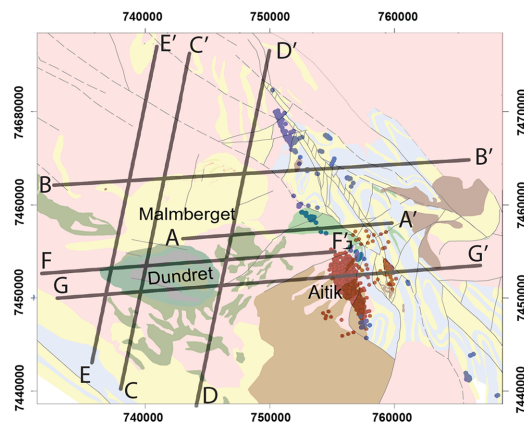(b2) Distribution of the of drill-holes

Igneous rocks

Lina suite intrusive rocks ~1.81-1.78 Ga

Granite-pegmatite association

Mafic-intermediate intrusive and extrusive rocks ~1.80 Ga

Gabbro
Basalt-andesite

Perthite-Monzonite and Haparanda suites intrusive rocks; ~1.88-1.86 Ga

Gabbro
Gabbro-norite
Troctolite
Meta-granite
Diorite

Svecofennian supracrustal rocks; ~1.96-1.85 Ga

Sedimentary and volcanosedimentary rock
Basalt-andesite
Volcanic and volcaniclastic rock (Porphyrite and Kiirunavaara Groups)

Other

Regional-scale geophysical profiles (B-H)
Location of the drill-holes (SGU)
Location of the drill-holes (Boliden)

Study zones

Slingram data coverage

Coordinate system: SWEREF 99 TM

0   5   10 km

N

Figure 2 Overview of the geophysical data and studied profiles (a1) aeromagnetic anomaly map, (a2) Bouguer anomaly map and distribution of the measured gravity stations in the study area. b1) study zones, studied profiles and Slingram data coverage and (b2) drill-hole data distribution.

Table 1 Physical properties of the key lithologies in SI units around the studied profiles measured on outcrop samples (SGU). The number of the samples is indicted by # and σ denotes the standard deviation

Rock type	#	Density (kg/m^3) and (σ)	Magn.susc (μ) $\times 10^{-3}$ SI	Q value	# Q values
Gabbro/diorite	60	3018 (140)	77	5.13	49
Rhyolite/dacite	17	2626 (140)	16	0.26	7
Basalt/andesite	55	2805 (101)	110	13.43	6
Sandstone/greywacke	10	2810 (79)	45	4.56	6
Granite	62	2689 (132)	51	2.19	12

Table 2 Density of the rock samples in SI units from Aitik mine (Boliden Mineral AB). The number of the samples is indicted by # and σ denotes the standard deviation

Rock type	#	Mean density (kg/m^3)
Feldspar epidote	31	2820
Muscovite schist	77	2920
Pegmatite	60	2690
Biotite schist	20	2890
Amphibole-biotite gneiss	2173	2910
Hornblende-banded gneiss	62	2880
Biotite gneiss	200	2870
Diorite	1009	2770

4 MODELLING SCHEME AND DATA PROCESSING

To study the key lithological units distinctly, the study area was divided into three parts, namely northern, central and southern parts. Each study part encompasses either complete profile(s) or a part of several profiles, which were extended perpendicular to major lithological units (Fig. 2b1). Seven profiles were selected for the regional-scale modelling of the potential field data, three of which are in a SW–NE direction and four others with W-E direction. All modelled profiles were created long enough so that they cover the key lithological structures with length ranging between 17.5 and 35 km.

The main purpose of the modelling along these profiles was to study the following:

(i) Geometry of the Dundret gabbro, which was previously explained as a bowl-like structure with margins dipping 60° to almost horizontal at the centre of the intrusion (Martinsson, 1994; Sarlus *et al*., 2019); (ii) lateral and vertical extension of the Malmberget magnetite-rich mineralizations and its host rocks and its complex internal stratigraphy, (iii) relationship between the Dundret and Vassaravaara gabbro at depth, (iv) nature of the Nautanen deformation zone (NDZ), dominant lithologies within NDZ and their continuation at depth, (v) dominant mafic intrusions to the SE of the study area.

All geophysical data used in this study have been processed prior to the interpretations or otherwise received in a format ready for interpretation. The Slingram data were gridded and integrated into the database and then used qualitatively for interpretation as real and imaginary components. A brief description of the modelling of the potential field data is explained below.

4.1 Modelling of the potential field data

The International Geomagnetic Reference Field (IGRF) correction was applied on the magnetic data with a total field intensity of 52,824, 76.7° inclination and declination of 8.5°. However, the regional field trend which has been defined and separated for magnetic and gravity data using the second polynomial degree (Tavakoli *et al*., 2012a, 2012b, 2016a) for the magnetic data is somewhat lower than the IGRF value, that is, 51875 nT.

The 2.5D modelling of the magnetic and gravity data was performed using Model Vision 14 (Tavakoli *et al*., 2012b). A 2.5D model is a two-dimensional model, with the exception that the bodies are limited in direction perpendicular to the direction of 2D profiles. The 2.5D models provide a more realistic representation of the geology compared with the conventional 2D models, especially where a 2D assumption is not

valid, but less compared with the 3D geological models since some of the structural features such as faults and folds will be only represented completely in 3D models. The strike lengths of the bodies were primarily determined based on information from geological data.

A forward model of the subsurface geology is first created using the known physical properties of the rocks based on the average values from SGU database (Table 1); in this case, density and magnetic susceptibility data. The model response is then calculated and compared with the measured data, making the start model. The inverse modelling was then performed using *a priori* information, including surface geological data, petrophysical data and borehole information. During the inversion, we allowed free parameters to modify within a known data limit defined based on the petrophysical information. The free parameters include petrophysical data where lower and upper bounds were defined based on the information from SGU's petrophysical data set; however, minor adjustment was allowed to deviate from the defined bounds when the target misfit was not achieved. In addition, lateral and vertical extensions as well as strike and dips of the modelled bodies were set as free parameters to evaluate if improved models were achieved.

5   RESULT AND INTERPRETATION

5.1   Profile A – A'

Lina-type granite is responsible for the anomaly low on both magnetic and Bouguer anomaly curves along profile $A – A'$ (Fig. 3). The upper parts of these granites indicate a higher density compared with its lower parts. A notable decrease in the magnetic anomaly to the east of the Vassaravaara intrusion is associated with a small increase in the Bouguer anomaly which encompasses dykes with intermediate densities ($x = 4.6–6$ km; Fig. 3a and b). The magnetic low anomaly can be related to the felsic volcanic or sedimentary rocks, where in either case their density and magnetic susceptibility are considerably lower than their surroundings ($x = 5–7$; Fig. 3c). However, why these rocks indicate a higher Bouguer anomaly response than expected is unclear. One explanation could be the presence of a mafic intrusion at depth which, although affects the gravity data, imposes a lower effect on the magnetic anomaly owing to their location at great depths. Another scenario can be presence of an intrusion within the felsic volcanic rocks with similar magnetic susceptibility, but higher density compared with the felsic volcanic rocks. The last 4-km end of profile $A – A'$ towards the east is located within the Nautanen

deformation zone (NDZ), which is associated with frequent occurrences of strongly altered rocks, and hence rocks with different degrees of magnetization, which is reflected on the magnetic anomaly curve (Fig. 3a).
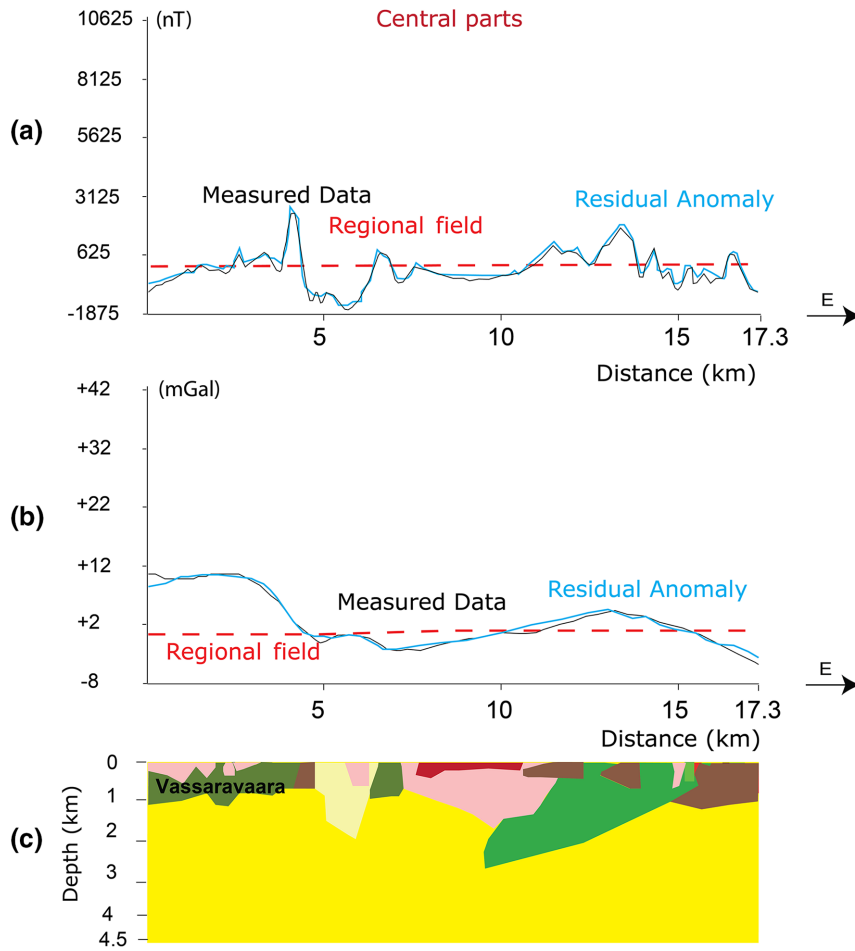
5.2   Profile B – B'

A significant magnetic anomaly can be observed at $x = 10$ km within the Malmberget felsic volcanic rocks and can be explained by known magnetite mineralizations as well as deeper occurrences of magnetite-rich rocks and its host rock which has not been modelled previously and continues at depth down to 1.2 km ($x = 6–12$ km; Fig. 4b and c). The previously modelled magnetite ore bodies shown as small, black units were inferred from earlier drilling activities and integrated into the models to account for their influence on the magnetic anomaly. (Fig. 4a). The Bouguer anomaly indicates two hill-like anomalies which are separated by an anomaly low, interpreted to be caused by low density of the granites ($D = 2600$ kg m^{-3} at $x = 12–17.5$ km; Fig. 4c). The first peak in the Bouguer anomaly is possibly produced as a response to the occurrences of the magnetite ore within the felsic volcanic rocks, and the second one interpreted to be caused by the mafic rocks within the NDZ indicating a higher density compared with the felsic volcanic rocks. A considerable magnetic high anomaly can be observed within the NDZ at $x = 20–23$ km which can be explained by magnetite alteration within the intermediate magmatic rocks in this part of the NDZ (Fig. 4a and 4c).

5.3   Profile C – C'

Magnetic data indicate several high and low anomalies within the 15 km beginning of the profile $C – C'$ which are the result of the frequent interchanges between the gabbroic rocks and the low-magnetic granite/diorite dykes ($x = 2–13$ km; Fig. 5c). At $x = 20$ km, the residual magnetic anomaly reaches to 15625 nT and is modelled as massive magnetite mineralizations and its host rock ($x = 17.5–22$ km; Fig. 5a and c) which continues from surface down to ~3 km at depth and encompasses the Johannes, Skåne, Josefina and Upland hematite–magnetite ore bodies. Dundret gabbro in profile $C – C'$ extends down to ~3.7 km in depth and produces an outstanding rise in the Bouguer anomaly (Fig. 5b). The presence of the magnetite–hematite ore and their andesitic host rocks of the Malmberget deposit did not produce as large Bouguer anomaly as for the Dundret, expectedly. This is because (i) the average density of the ore body and its host rocks is lower than that of the

Potential Field Modelling of profile A - A'

Figure 3 Magnetic and Bouguer anomalies and the resulting model depth section for the profile *A – A'*. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.
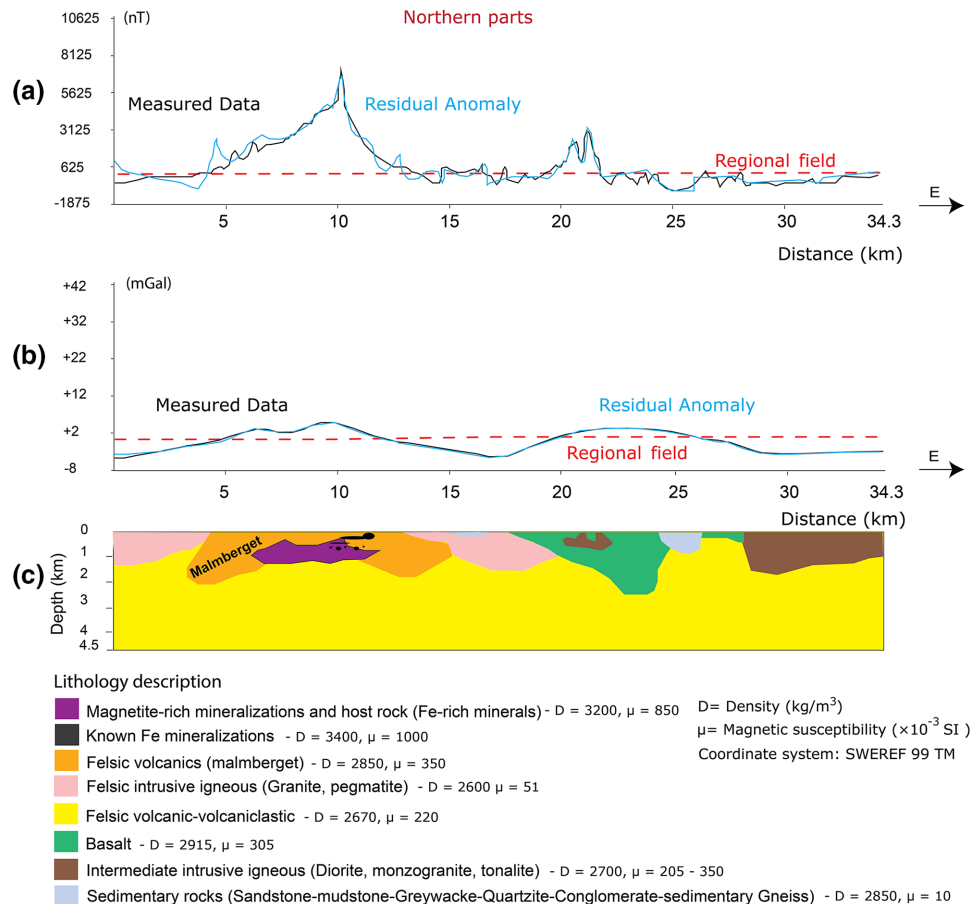
Potential Field Modelling of profile B - B'

Figure 4 Magnetic and Bouguer anomalies and the resulting model depth section for the profile $B - B'$. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

gabbro and (ii) Dundret gabbro continues to a greater depth than the Malmberget unit does (Fig. 5c).

5.4 Profile D – D'

The beginning of profile $D - D'$ to the SW is associated with irregular fluctuations of the low amplitude magnetic anomalies (Fig. 6a). The maximum thickness of the mafic unit, which causes the gravity high, is located at $\sim x = 11$ km and its continuation along the profile towards the NE crops out at the surface (Fig. 2b1). Further towards the NE, these mafic rocks get thicker and appear closer to the surface which can indicate the SW continuation of the Vassaravaara intrusion at depth (Fig. 6b and 6c). From middle towards the end of the profile $D – D'$, granites occur frequently near the surface and small fluc-

tuations in the magnetic anomaly are interpreted to be caused by random occurrences of the mafic and granite dykes.

5.5 Profile E – E'

In the magnetic anomaly, two peaks along the northern and southern edges of the Dundret gabbro are distinctive. Both magnetic and Bouguer anomaly peaks can be explained by higher density and magnetic susceptibility of the Dundret gabbro compared with the background geology. A comparison between the proposed model for profiles $C – C'$ and $E – E'$ indicates that the Dundret gabbro gets thinner towards the west (Figs 5c and 7c). The amplitude of the magnetic anomaly for the Malmberget felsic volcanic rocks is considerably higher on profile $C – C'$ compared with that
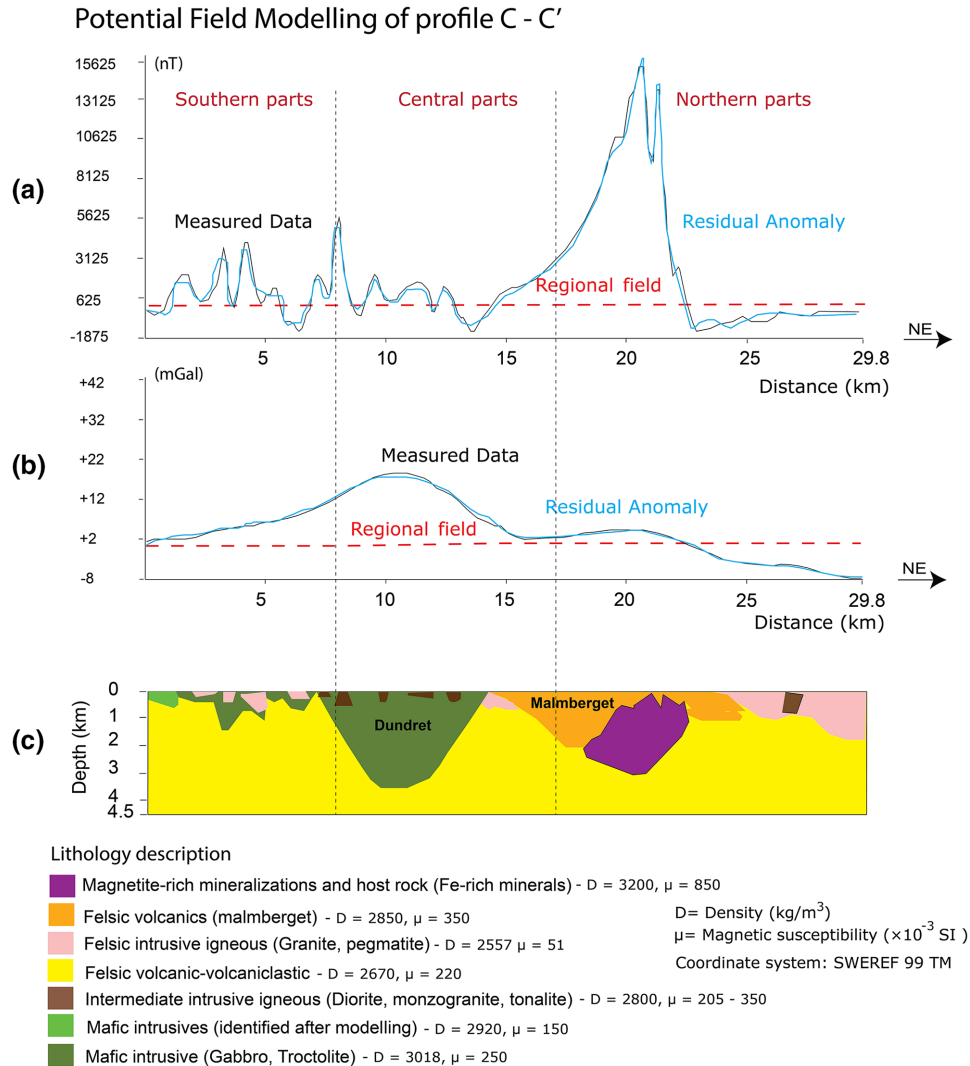
Potential Field Modelling of profile C - C'

Figure 5 Magnetic and Bouguer anomalies and the resulting model depth section for the profile *C – C'*. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

on profile *E – E'*, which is presumably due to the absence of the abundant hematite–magnetite mineralizations within the western parts of the Malmberget block and possibly shallower depth extent of the volcanic rocks to the west compared with the central parts of the Malmberget. Similar to profile *C – C'*, profile *E – E'* also ends within the low magnetic and low Bouguer anomaly to the NE, which fits well with the presence of the massive and homogeneous granites which are located sub-horizontally at shallow depth.

5.6 Profile F – F'

The maximum depth for the Dundret unit along profile *F – F'* is consistent with that in profiles *C – C'* and *G – G'*, that is, 4 km (*x* = 3–11.5 km; Fig. 8c). The Dundret and Vassaravaara gabbro together constitute a continuous and smooth anomaly which decays towards the NE, indicating that the two adjacent gabbroic units are surrounded by other mafic intrusions with similar density. The geometry of the Vassaravaara gabbro is consistent on profiles *D – D'* and *F – F'* showing a maximum depth extent of 2 km. At the beginning of the profile
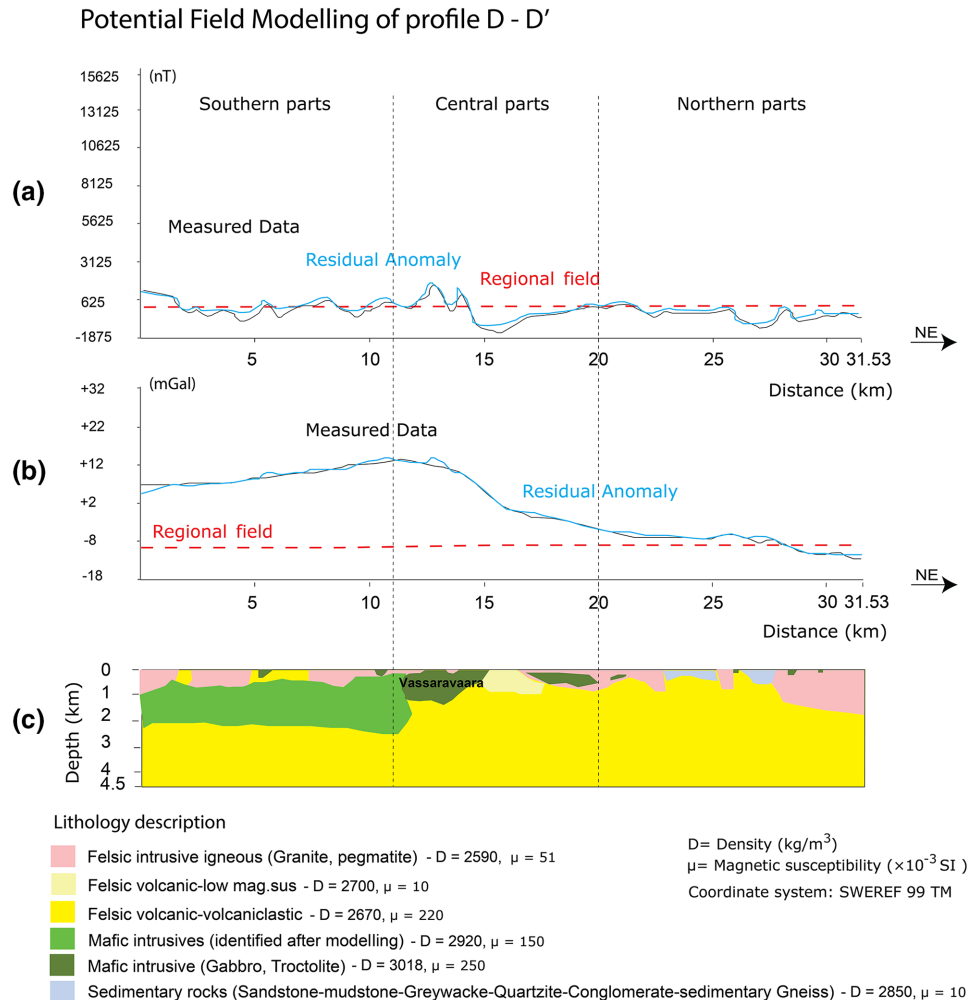
Potential Field Modelling of profile D - D'

Figure 6 Magnetic and Bouguer anomalies and the resulting model depth section for the profile $D – D'$. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

$F – F'$ the magnitude of the magnetic anomaly increases dramatically which is explained by a ∼1 km wide magnetite-rich layer extended down to 1 km depth (Fig. 8a). The two horizontal layers shown with blue colour at 1 km depth indicate higher magnetic response than the background gabbro and could be related to the magnetite-rich cumulate band within the Dundret unit (Fig. 8c). Frequent presence of large bodies of mafic intrusions is responsible for gravity and to lower extent magnetic highs observed at the end of profile $F – F'$ which agrees well with drill-hole data ($x = 12, 17, 20$–24 km; Figs 8c and 12).

5.7 Profile G – G'

The distinguishable modelled magnetite-rich mineralizations located at $x = 5$ are extended vertically at depth between 0.2 and 1.4 km and probably indicate disseminated magnetite-rich mineralizations (Fig. 9a and c). Additional highly magnetic bodies can be observed at $x = 4, 8$ and 10.5 km (Fig. 9c). The modelled Dundret gabbro based on the residual Bouguer anomaly starts at $x = 2$ km (Fig. 9b and c), whereas the surface geology indicates the start of Dundret from $x = 3.3$ km (Figs 2b1 and 9c) which can indicate that the gabbro covers a larger area below the surface, compared with what is
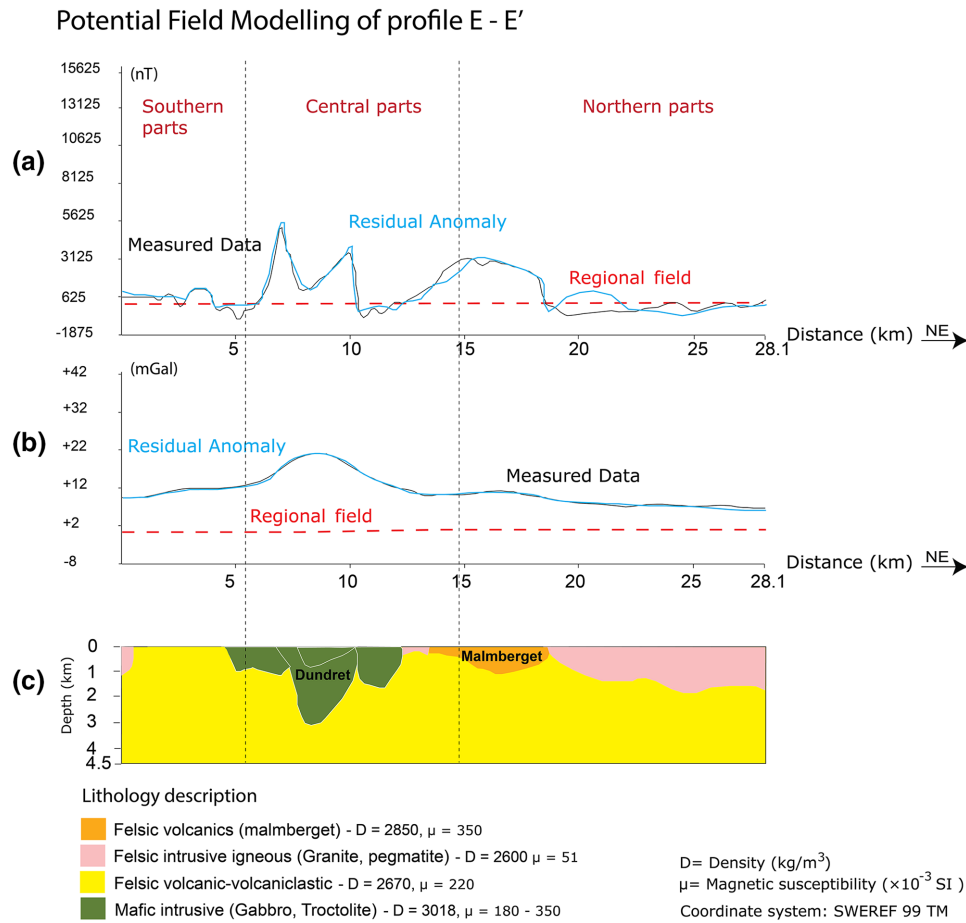
Figure 7 Magnetic and Bouguer anomalies and the resulting model depth section for the profile $E – E$'. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

indicated on the surface geology map. The magnetite-rich mineralizations indicated in purple do not affect the overall shape of the magnetic anomaly observed on top of Dundret due to (i) the average low degree of magnetization together with low magnetic surroundings or (ii) their location at great depth (iii) disseminated pattern for the mineralizations or combination of the three.

6 DISCUSSION; REGIONAL PERSPECTIVE

6.1 Northern parts

Both profiles $B – B$' and $C – C$' in the northern parts are associated with magnetite-rich mineralizations. In both profiles the magnetic high anomaly is produced from a structure composed of two distinguishable parts: (i) a dominating felsic volcanic rock and (ii) a high magnetic structure—interpreted as

magnetite-rich mineralizations—and its host rock all together extended down to ~2.2 km (profile $B – B$') and 3 km (profile $C – C$') at depth. The high magnetic structure probably designates an andesite/felsic volcanic unit which hosts disseminated magnetite and hematite with varying degrees of magnetization. The ore in Malmberget contains magnetite and hematite and is hosted by strongly metamorphosed and deformed rocks of felsic to mafic composition. The individual known ore bodies could not be modelled with the current resolution of the aeromagnetic and gravity data.

Slingram data indicate three conductors near the NE end of profile $D – D$' which might depict sulphide mineralizations (C_1, C_2 and C_3 in Fig. 11). All three anomalies are associated with a high real part and a low imaginary components, which is often an indication of the conductive metallic minerals or strong alterations. The host rocks to mineralizations within the Nautanen deformation zone (NDZ) were
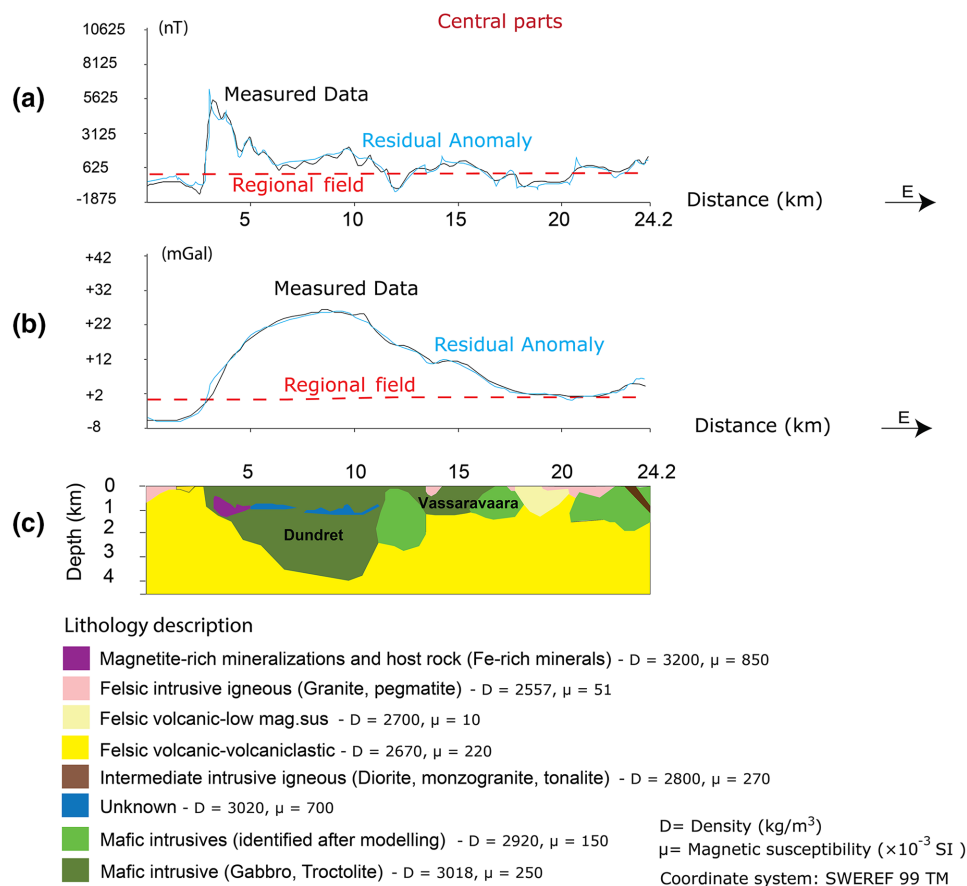
Figure 8 Magnetic and Bouguer anomalies and the resulting model depth section for the profile *F − F'*. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

described as strongly altered and deformed (Lynch *et al.*, 2015). The mineralization style within the NDZ varies from disseminated to vein-type with a mineral assemblage composed of chalcopyrite, pyrite and magnetite accompanied by gold (Lynch *et al.*, 2015; Årebäck and Dean, 2018). Consequently, the NE end of the profile *D − D'* is likely to be associated with disseminated sulphides and iron oxides and/or their host rocks which in the Nautanen zone consist of volcanogenic sedimentary rocks with intermediate composition. The magnetic anomaly between $x = 18$ and 23 km in profile *C − C'* (Fig. 5c) is probably produced from a massive magnetite ore body which can be observed to a less extent even further to the west along profile *E − E'* (Fig. 7c).

6.2 Central parts

6.2.1 Dundret gabbro

The upper part of the Dundret gabbro is associated with frequent occurrences of magnetic highs and is interpreted to be caused by high magnetic susceptibilities of the magnetite-rich structures. A comparison between the SW–NE trending profiles *C − C'* and *E − E'* indicates that the Dundret gabbro with a dome-shaped structure narrows down further to the west. In addition, the left and right edges of Dundret on profile *E − E'* (Fig. 7), which are associated with magnetic highs, are evidently distinguishable from the central part which indicate a low magnetic susceptibility but similar density to the
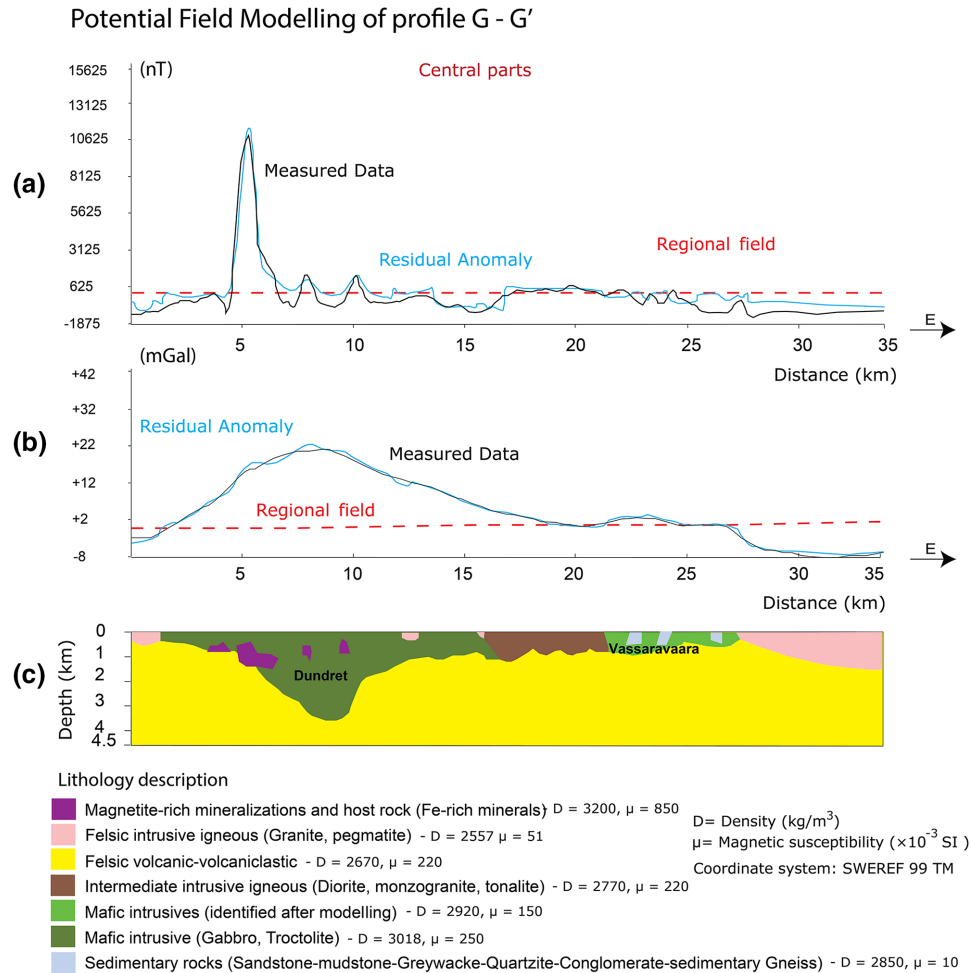
Figure 9 Magnetic and Bouguer anomalies and the resulting model depth section for the profile *G − G'*. (a) Magnetic anomaly, (b) Bouguer anomaly and (c) model depth section. The used magnetic susceptibility and density data for this profile and for each rock type are specified in front of each rock type.

major parts of the Dundret gabbro. According to Martinsson and Wanhainen (2000) and Sarlus *et al.* (2019), the deeper and outer margins of the Dundret intrusion differ in terms of lithology from its upper and central parts. The Dundret intrusion is sub-rounded massif with bowl-like structure that dips ~60° at the margins to almost horizontal at the centre (Martinsson and Wanhainen, 2000; Sarlus *et al.*, 2019), which fits nicely with the proposed models for the profiles *C − C'* and *F − F'* (Figs 5c and 8c). The model along profiles *E − E'* and *G − G'* shows that the bowl-like structure of the Dundret and its shape differs in different parts, suggesting an inhomogeneous model for the Dundret gabbro.

A high number of mafic intrusions were identified from the result of the potential field modelling, particularly within the central and eastern parts of the profile *F − F'*. Occurrences of the large mafic bodies in the Gällivare area at depth have been earlier suggested by Bergman *et al.* (2001), which in this study can be observed near the Dundret in all of the modelled profiles. The gabbroic rocks in the eastern parts of Norrbotten have been explained as (i) layered gabbro with variations in magnetite contents or (ii) intrusive sheets of magnetic gabbro surrounded by pegmatites and granites (Bergman *et al.*, 2001). The weathered gabbro dykes containing iron, aluminium, phosphorus, titanium and sulphur and low silica contents occur frequently within the foliated granites to the NE of Gällivare (Lindroos and Henkel, 1981), which explain the magnetic and gravity highs on profile *F − F'* (Fig. 8c).
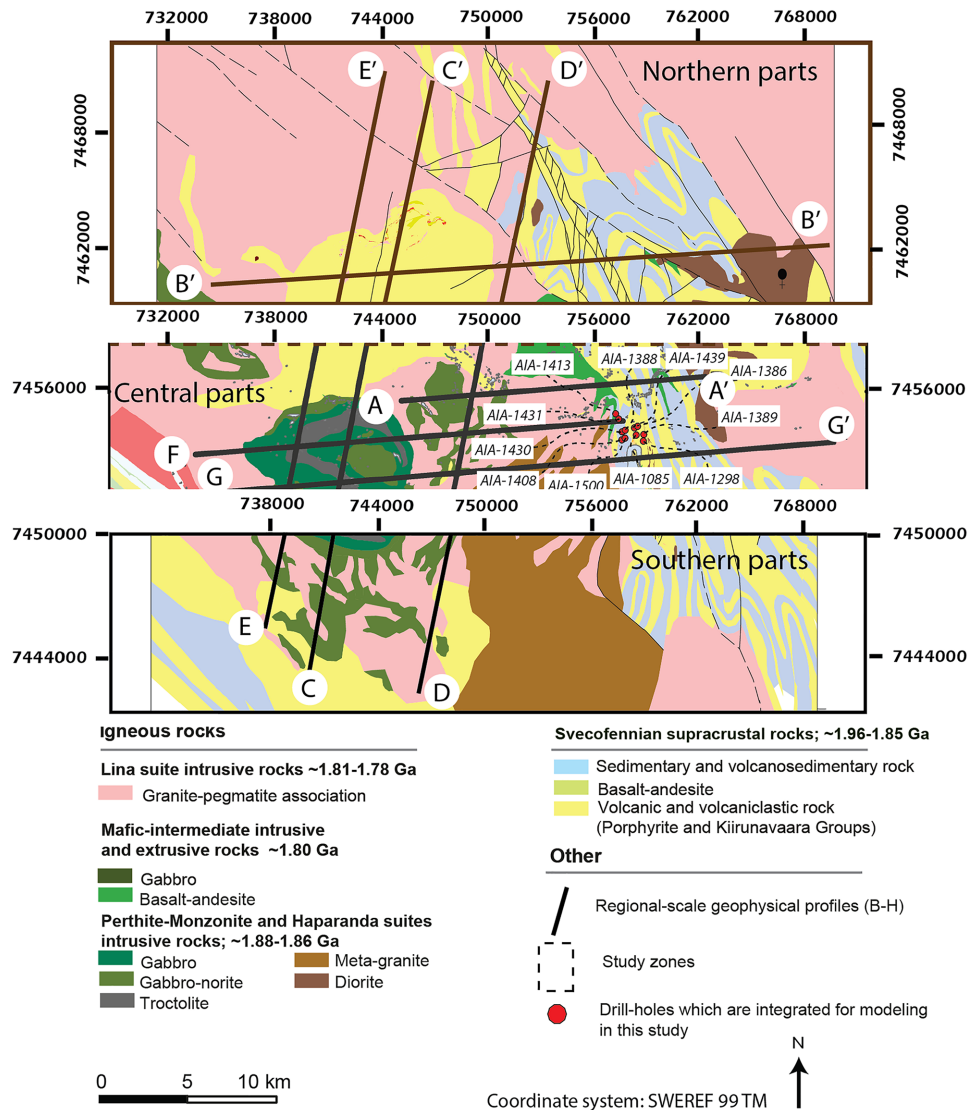
Figure 10 Study areas, that is, northern, central and southern parts and the surrounding lithology. Location of the drill-holes integrated in the modelling of this study is indicated on the map for the central parts.

6.2.2 *Vassaravaara gabbro*

The Bouguer anomaly indicates that the Vassaravaara intrusion has its greatest depth along profile *F – F'* and gets thinner towards the south and north. In profile *A – A'*, the upper 200 m of the Vassaravaara gabbro are covered by sequences of high and low magnetic units, modelled as granite, gabbro and magnetic dykes.

Radiometric age determination confirms that the Vassaravaara and Dundret gabbro are emplaced with a time gap of at least 80 Ma (Sarlus, 2016; Sarlus *et al.*, 2018); therefore, they cannot constitute one single unit. The magnetic and gravity

models for profiles *F – F'* and *G – G'* proves that the two gabbroic units are associated with great amount of mafic intrusions within the central parts of these profiles, which cause the Bouguer anomaly look like as if the two units are connected at depth (Fig. 8b and c).

6.2.3 *Drill-hole data*

Drill-holes were selected from the vicinity of the Aitik mine to constrain the modelling results. These boreholes were all ≥ 0.5 km at depth and all located within horizontal distance of ≤1 km from the profiles (Figs 10 and 12). Exceptions are
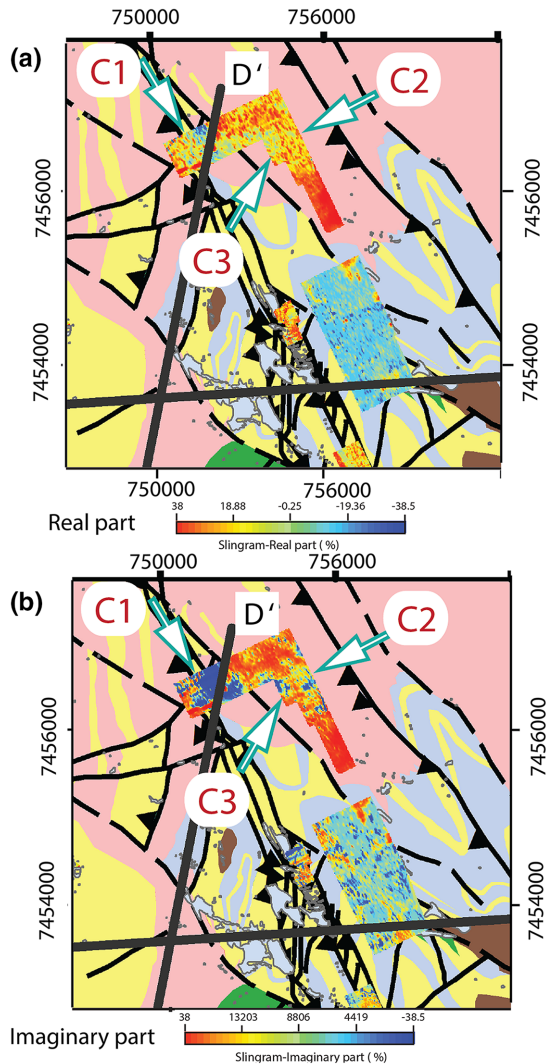
Figure 11 Real and imaginary components of the Slingram data. (a) Three conductors showing high real component are marked with the arrows; (b) three conductors showing low imaginary component are marked with the arrows.

drill-holes with no lithology description or with single lithology unit throughout the core, which were excluded from this study.

A common interchange between the sequences of the metamorphic rocks (amphibole/biotite /hornblende gneiss and muscovite schist) is often a dominant trend for studied drill-holes in the entire area. The two deepest drill-holes, that is, AIA1430 and AIA1431, indicate the presence of mafic intrusive rocks such as gabbro at depths between 300 m and 750 m, which agrees well with the model suggested based on the potential field data. Drill-hole data also show that the inter-

mediate intrusive igneous rocks (e.g. diorite) are present at ~500 m depth and are responsible for the magnetic low anomaly at the end of the profile *F – F'*. Moreover, the study of the drill-hole data shows that sedimentary rocks can be located at depths greater than 1 km; hence, they are responsible for the lows in the magnetic and Bouguer anomaly within the eastern end of profile *F – F'* (AIA1408; Fig. 12).

6.3 Southern parts

6.3.1 South-western shear zone

The SW beginning of the profiles *C – C', D – D'* and *E – E'* is associated with common interchanges between granitic and dolerite sills/dykes with small dimensions, which makes it impossible to constrain with the resolution of the gravity data in this study. Nevertheless, the mafic intrusions, for example, Harrträsket gabbro (Martinsson, 1994), are likely to be responsible for the gravity high in the east of the Dundret intrusion. Despite the Bouguer anomaly curve, which suggests a rather smooth curve within the southern parts of the profiles *C – C', D – D'* and *E – E'*, the magnetic anomaly in this part is somewhat irregular. This can be explained by the presence of small-scale dykes along profiles *C – C'* and *D – D'*, which produce irregular high anomalies on the magnetic data whereas their small dimensions make them invisible on the Bouguer anomaly curve.

6.4 The 2.5D integrated geological model

A 2.5D geological model of the Gällivare area was created in regional-scale using Model Vision Pro. Aeromagnetic, gravity and Slingram data alongside geological, petrophysical and borehole information were used to constrain the models. Figure 13 shows the 2.5D geological model of the studied profiles down to 4 km depth in the Gälivare area. The presented model resulted from the integration of the individual profile models and reveals significant information about lateral and vertical extents of the key geological structures but also presents new horizons possible to host magnetic and sulphide mineralizations and can be used as focus areas for detailed geophysical investigations in the future (see Tavakoli *et al.*, 2016b).

7 CONCLUSION

The regional-scale geometry of the Gällivare area was studied using the potential field and petrophysical data and was

(a) Potential Field Modelling of profile F - F'
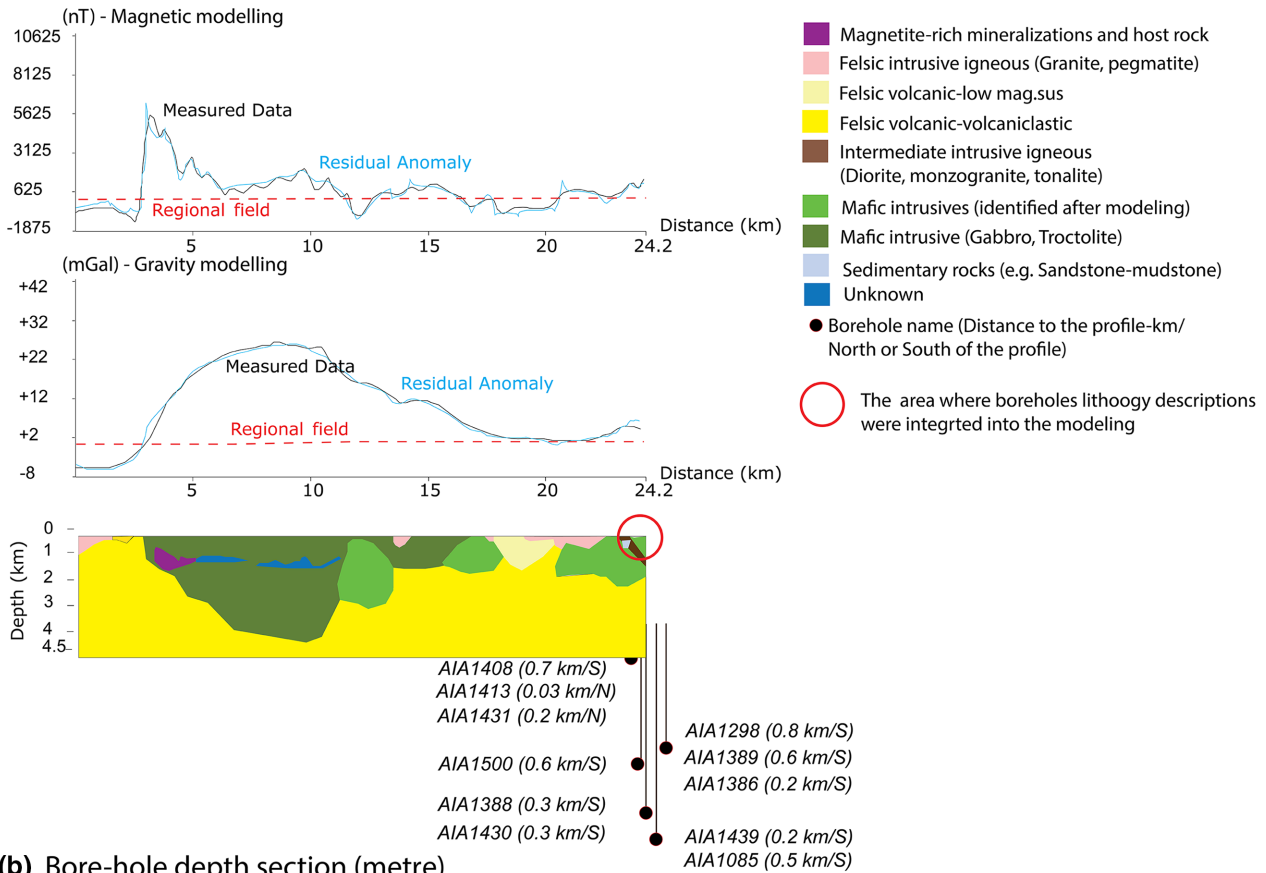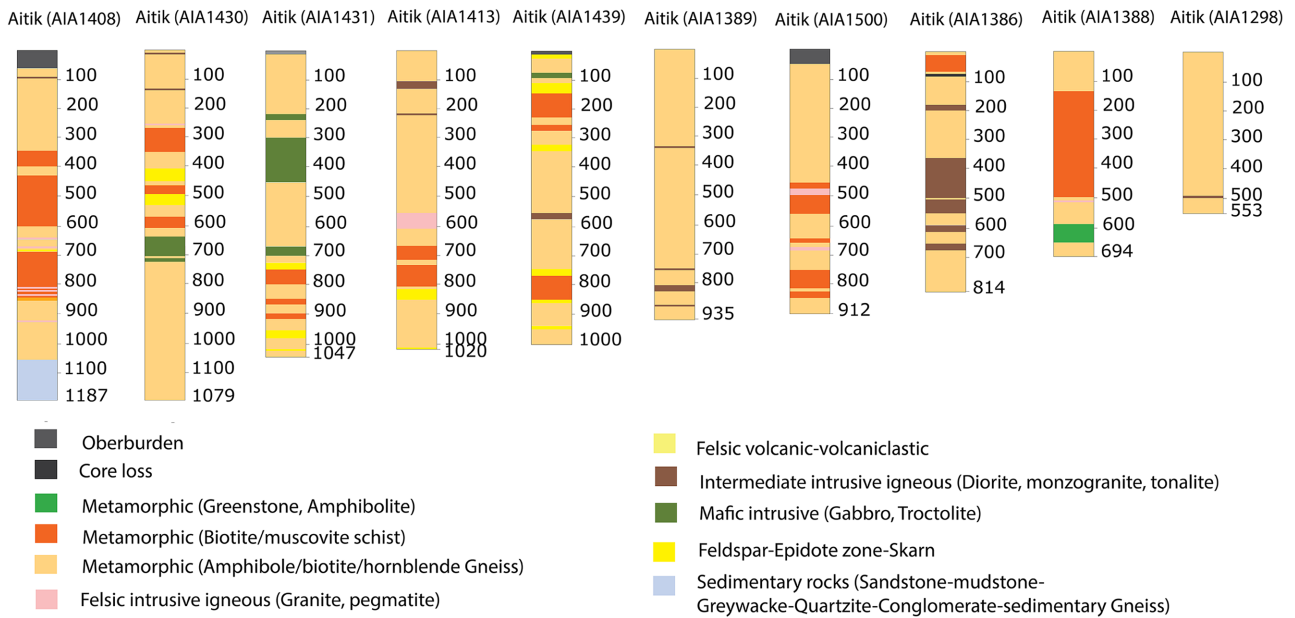

(b) Bore-hole depth section (metre)

Figure 12 Integration of the drill-hole data in modelling of the profile *F − F'*; the eastern part of profile *F − F'* marked by red circle is modified based on the information acquired from drill-hole data.
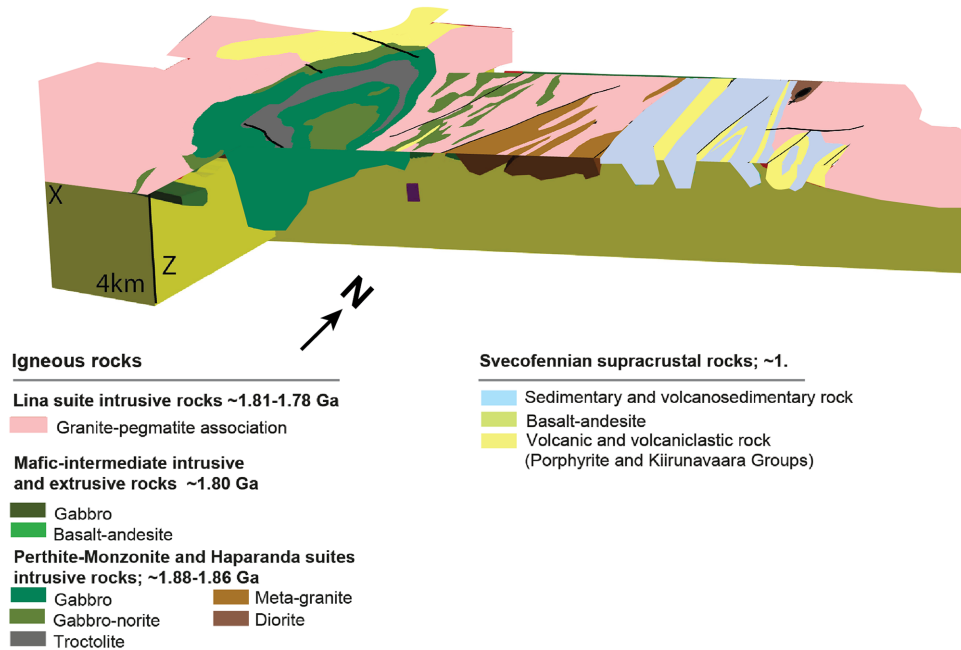
Igneous rocks

Lina suite intrusive rocks ~1.81-1.78 Ga
- Granite-pegmatite association

**Mafic-intermediate intrusive
and extrusive rocks ~1.80 Ga**
- Gabbro
- Basalt-andesite

**Perthite-Monzonite and Haparanda suites
intrusive rocks; ~1.88-1.86 Ga**
- Gabbro
- Gabbro-norite
- Troctolite
- Meta-granite
- Diorite

Svecofennian supracrustal rocks; ~1.
- Sedimentary and volcanosedimentary rock
- Basalt-andesite
- Volcanic and volcaniclastic rock
  (Porphyrite and Kiirunavaara Groups)

Figure 13 2.5D model of the studied profiles down to 4-km depth. The model shows regional-scale geology around the Gällivare and Malmberget area and is constrained by geological, potential field, Slingram, borehole and petrophysical data.

constrained with, where available, drill-hole information and Slingram data.

The study result revealed new findings, that is, the 3D geometry of main lithologies was constrained, new magnetite-rich mineralizations, which can be an indication of the magnetite ore was located, and frequent occurrences of considerable amounts of mafic intrusions, particularly in the southern parts, were confirmed. More specifically, the following conclusions can be made: (i) The Dundret gabbro extends at depth down to a maximum depth of 4 km and, as suggested earlier, depicts a funnel-shaped structure with maximum depth at its centre. Moreover, the Dundret gabbro exhibits the presence of magnetite-rich layers within the uppermost 2 km of the suggested model. (ii) The Malmberget felsic volcanic rocks host a considerable amount of magnetite-rich mineralizations and extend downwards to a maximum depth of 3 km. The known magnetite-rich mineralizations and/or newly located mineralizations and the host rocks to the Malmberget deposit were modelled and fit well with the potential field data, in particular, with magnetic anomaly. Indication of additional magnetite-rich mineralizations is suggested within the central parts of the Malmberget felsic rocks along profiles *B – B'* and *C–C'*. (iii) High real component and low imaginary response of the Slingram data suggest conductive zones along the NE end of the profile *D – D'* within the NDZ and further to the SE within the sedimentary rocks which could result from dissem-

inated sulphide minerals. (iv) Mafic intrusions were detected and modelled using the potential field data. These intrusions were associated with intermediate magnetic susceptibility but high density similar to that of the gabbro. The mafic intrusions can be found in large volumes within the southern parts of the study area, further towards the east along profile *D – D'*. (v) Drill-hole data agree well with the suggested model along the last 2 km of the profile *F – F'* to the east, suggesting the presence of mafic intrusions within ~top 1 km of the subsurface.

Findings from this study and the modelled geological structures in 2.5D which are acquired from detailed modelling of the seven studied profiles provide valuable information for the continuation of the mineral exploration activities in the Gällivare area.

DATA AVAILABILITY STATEMENT

Gravity, magnetic and Slingram data – Swedish Geological Survey (SGU), access provided via agreement between SGU and the project. Data are also available at the common folder for geophysics group at the Luleå University of Technology. Geological maps—Modified by and available at the local repository drive at Ore Geology group, Division of Geosciences and Environmental Engineering, Luleå University of Technology. Drill-hole data—Provided by SGU, confidential properties, access provided via agreement between SGU and

the project. Data are also available at the common folder for geophysics group at the Luleå University of Technology. Petrophysical data—Density, magnetic susceptibility and *Q* values were provided by—and are property of the SGU and measured density data from selected core samples are Boliden properties. Data are also available at the common folder for geophysics group at the Luleå University of Technology.

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