Case History

MT and reflection seismics in northwestern Skellefte Ore District, Sweden

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ABSTRACT

A seismic reflection and MT survey was carried out along a 27-km long transect in northwestern Skellefte District, as part of a bigger 3D modeling project. The main motivation for the data acquisition is to elucidate the geologic relationship between the known mineralizations in the Adak mining camp to the north and in the well studied Kristineberg area south of the transect. The seismic reflection data were acquired with a VIBSIST system, and show reflectivity down to 3 s. Apart from the conventional processing for crystalline environments, the seismic data was also subject to an azimuthal binning procedure and cross-dip analysis, allowing the orientation of planar reflectors in 3D. Regarding the MT data, it is primarily of good quality along the 17 installed sites. The inversion of the determinant of the im-

pedance tensor yielded a stable 2D resistivity model, dominated by resistors corresponding to the postorogenic intrusions along the transect. Adding the location of the analyzed seismic reflectors in the MT inversion rendered an integrated model that facilitated a preliminary joint interpretation of the data sets. Overall, the results are in good agreement with surface observations and reveal a crude configuration of the geologic units below the transect. The most prominent outcomes are the lateral and depth extent of the large postorogenic intrusions in the area reaching to 5- or 6-km depth, the dimensions of the nearly vertical Brännäs gabbro extending to 6-km depth, and the presence of enhanced conductivities along the transect at about 10 km depth. The latter is probably related to the deep conductor previously identified in the district.

INTRODUCTION

The Skellefte District is a very rich mining area in northern Sweden. The main deposits consist of volcanic-hosted massive sulphides (VHMS) rich in zinc, copper, lead, gold, and silver. Because the area has been mined and explored for over a century, today's challenge is to locate deeper deposits. New geophysical and geologic data have been acquired across the district to improve the understanding of the regional geologic setting and help target deeper deposits (Bauer et al., 2011; Skyttä et al., 2012).

A pilot study consisting of two 20-km long seismic reflection profiles, and an accompanying MT survey (see Figure 1) were acquired in the surroundings of the large Kristineberg mine (Malehmir

et al., 2006, 2007, 2009; Tryggvason et al., 2006; Hübner et al., 2009). Given the success of this study, the project VINNOVA 4D modeling of the Skellefte District was launched, and more localized seismic and MT data were acquired in the area (Dehghannejad et al., 2010; García Juanatey et al., 2012; Hübner et al., 2012). In the framework of this project, the Geological Survey of Sweden (SGU) funded the extension of the area of investigation to the north, towards the Adak mineralizations. Thus, a 27-km long seismic reflection and MT profile was acquired between the localities of Brännäs and Adakliden to complete the already existing studies in the Kristineberg mining area (see Figure 1 for the location of the new and previous studies). The new 27-km long MT and seismic profile comprises the core of the current study. For consistency, processing,

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analysis, and interpretation of the new data sets were carried out in a similar manner to previous studies in the area (e.g., Hübner et al., 2009; Dehghannejad et al., 2010; García Juanatey et al., 2012).

The Brännäs–Adakliden profile is located along a narrow corridor (2–4 km wide) of outcropping metamorphosed volcanic and sedimentary rocks, surrounded by large postorogenic intrusions. These intrusions cover a large portion of the area that sets apart the Kristineberg (south) and Adak (north) mines, obscuring the geologic relationship between them. For this reason, the motivations to extend the area of study towards the north are to (1) elucidate the relationships between the different geologic units, (2) determine the depth extent of the postorogenic intrusions, and (3) place the known mineralizations of the Kristineberg area and Adak mining camp in a common geologic context.

The particular aims of this paper are to present the acquired seismic reflection and MT data, their processing and outcomes (only in 2D for the MT data), together with a preliminary joint interpretation in geologic terms. A more detailed interpretation and modelling,

considering additional data (e.g., available potential field data), will be presented in a subsequent contribution.

GEOLOGIC SETTING

The Skellefte District forms a c. 120 × 30 km large area of Paleoproterozoic volcanic, sedimentary, and intrusive rocks in northern Sweden. The district hosts several important Zn–Cu VHMS deposits, orogenic gold deposits, mafic-hosted Ni, and porphyry-type Cu deposits, forming one of the most mineralized Paleoproterozoic arc systems in the world (Weihed, 2010). The stratigraphy of the rocks in the Skellefte District may be divided into a lower volcanic part, the Skellefte Group with ages in the interval 1.89–1.88 Ga (Billström and Weihed, 1996; Montelius, 2005; Skytä et al., 2011), and the upper, mainly sedimentary Vargfors Group (Weihed, 2010). An extensional continental margin arc, including a basement of continental or arc crust, not significantly older than the Skellefte Group rocks, is the most likely tectonic setting (Allen et al., 1996, 2002; Weihed, 2010).

In the southwestern part of the Skellefte District, the structural picture is dominated by the west to southwest plunging Kristineberg and Vindelgransele antiforms, which expose the Skellefte Group metavolcanic rocks in their cores (Årebäck et al., 2005). The Kristineberg dome structure also includes 1890 Ma Jörn G1 type tonalites in the core (Skyttä et al., 2011). The tonalitic rocks of the core have a subvolcanic component, the Viterliden porphyries (Årebäck et al., 2005), which intrude the surrounding volcanic rocks. The intrusive Jörn granitoids and the Skellefte Group volcanic rocks are considered to be comagmatic (Kathol and Weihed, 2005). The Vindelgransele antiform does not include any known Jörn granitoid intrusive component, but the area is not very well known, due to poor exposure, and the intrusion of the younger Släpstråk granite. The Skellefte Group in the area consists mainly of dacitic to rhyolitic coherent or clastic volcanic rocks, which due to strong and pervasive alteration patterns rarely show preserved volcanic textures. Massive sulphide deposits are found along two principal stratigraphic horizons in the Kristineberg antiform (Allen et al., 1996; Årebäck et al., 2005), the Kristineberg–Kimheden horizon to the east and the Rävliiden horizon to the west, along the contact to the younger Vargfors Group sedimentary rocks (Årebäck et al., 2005). The mineralizations in the Vindelgransele antiform are fewer and do not have the same economic potential as the ores in the Kristineberg antiform.

The Vargfors Group sedimentary rocks are conformably deposited on top of the Skellefte Group volcanic rocks and the contact zone is distinguished by the occurrence of graphitic slates and epiclastic volcanic-sedimentary rocks (Kathol and Weihed, 2005). These rocks grade stratigraphically into fine-grained argillites and greywackes, which surround the antiform structures of Kristineberg and Vindelgransele. To the north and northeast, these rocks are progressively replaced by a thick unit of basaltic to andesitic rocks, the Tjamstan formation (Bergström and Sträng, 1999). In the proximal part, in the Malå town area, the Tjamstan formation include thick units of plagioclase phyrlic lavas and syn-eruptive graded volcanoclastic units. To the south, the basalts and andesites form more distal, ash-dominated units, intercalated with the argillitic rocks. The upper parts of the Vargfors Group include a thick unit of rhythmically deposited turbiditic greywackes. Well-preserved examples are found on the Fäbodliden and Näverliden hills southwest and west of the Vindelgransele antiform. The Vargfors Group is closed by the Bjurås formation described in detail by Bergström and Sträng (1999), which consists of high-Mg lavas and sills in the uppermost

Figure 1. Geologic map of western Skellefte District showing the main lithological units, closed and current mines, and acquired seismic surveys and MT stations. Lines and sites in red are part of the pilot study (Tryggvason et al., 2006; Hübner et al., 2009), in blue and green is the follow-up within the VINNOVA project (Dehghannejad et al., 2010; García Juanatey et al., 2012; Hübner et al., 2012), and in orange is the extension funded by SGU and treated in this paper. SG: Skellefte Group, VG: Vargfors Group, TF: Tjamstan Formation. Coordinates in meters in the Swedish national grid (RT90).

part of the Vargfors Group. Northeast of Näverliden, rhyolitic intercalations within the turbiditic greywackes are exposed in a local syncline, and correspond quite well stratigraphically with the Bjurås formation. These rhyolites are interpreted as distal components of the Arvidsjaur Group volcanic rocks, which outcrop north of the Skellefte District. The age of the Arvidsjaur volcanism is around 1.88 Ga (Kathol and Weihed, 2005).

The volcanic and sedimentary rocks of the Skellefte and Vargfors Groups were subsequently deformed and metamorphosed in the greenschist and lower amphibolite facies (Skyttä et al., 2012). West and south of the Kristineberg and Vindelgransele dome structures, large amounts of gray, coarse microcline porphyritic, postorogenic granites (the Revsund granites) intruded the deformed rocks. Further to the north, the postorogenic granites are represented by the Adak granites, which include more equigranular and reddish rocks. A dating of the Släppträsk pluton, which cuts the Vindelgransele antiform structure, results in an age of 1.80 Ga (Bergström and Sträng, 1999).

SEISMIC REFLECTION DATA

Acquisition

A reflection seismic survey was carried out in the field campaign of summer 2009. The source used was the VIBSIST system, based on the swept impact seismic technique (SIST) described by Park et al. (1996) and Cosma and Enescu (2001). It consists of an hydraulic hammer mounted on a tractor and a computer control system. This type of source has been used in other studies in Sweden with good results (e.g., Juhlin et al., 2004, 2010; Juhlin and Palm, 2005; Dehghannejad et al., 2010; Lundberg and Juhlin, 2011; Malchmir et al., 2011). It is generally preferred to explosives due to its lower cost and uniform source signature (Juhlin et al., 2004). Moreover, it can be used where explosives are not allowed.

Given the nature of the source (or rather the vehicle it was mounted on) the location of the survey line depended on available roads and trails, resulting in a considerably crooked acquisition line (see Figure 2). The source spacing was 25 m with gaps where the survey line crossed dense forests or villages. Further details are listed in Table 1.

Processing

The seismic reflection survey is located over a complex hard-rock environment subject to deformation and several intrusion episodes. Steeply dipping events with varying strike directions can occur throughout the investigated area. Adding a crooked line geometry to this, for which the reflective points are scattered within a 3D volume instead of a 2D slice, it is to be expected that standard 2D processing and stacking may not render the optimal stack. However, the crookedness of the line and subsequent scattered midpoints is a blessing and a curse, because it makes it possible to estimate the real 3D orientation of the reflective structures. Therefore, apart from the standard 2D processing, cross-dip analysis and an azimuthal binning procedure were carried out in an attempt to assess the true geometry of the reflectors and to improve the coherency of the imaged reflectivity.

Standard processing

The main processing steps applied to the data are listed in Table 2. The data was decoded down to 4 s revealing shot gathers of varying data quality. A layer of low-velocity postglacial sediments, reaching

Figure 2. Close up of the map in Figure 1 showing seismic survey receiver line, shot points, distribution of midpoints, and position of CDP bins, together with MT sites. MT sites are labeled in bold font and CDP bins in italic. The MT sites were projected along the CDP line to calculate the resistivity model of Figure 11. Coordinates in meters in the Swedish national grid (RT90). Legend of lithological units as in Figure 1.

Table 1. Acquisition parameters of the seismic reflection survey (see Figure 2).

Spread type	Asymmetric split
Number of channels	240–300 (80–120)
Near offset	0 m
Geophone spacing	25 m
Geophone type	28 Hz single
Source spacing	25 m
Source type	VIBSIST
Sweeps per source point	3–4
Nominal fold	50–200
Recording instrument	SERCEL 408 UL
Sample rate	1 ms
Record length	20 s
Profile length	26.8 km
Source points	733

Table 2. Processing steps of the seismic reflection survey (see Figure 2).

Step	Parameters
1	Read decoded VIBSIST data
2	Bulk static shift to zero time
3	Correct and apply geometry
4	Trace editing
5	Pick first breaks
6	Refraction statics: Datum 450 m, Replacement velocity 6000 m/s, Overburden velocity 1800 m/s
7	Remove 40 Hz and 60 Hz noise
8	Spectral equalization: 20 30 70 90
9	Time variant filter: 0–500 ms, 25 35 80 100 600–3000, 20 30 70 90
10	Mute of first breaks and air wave
11	AGC: 200 ms window
12	Velocity analysis
13	NMO correction: 40% stretch mute
14	Stack
15	Residual statics
16	Stolt Migration with 5800 m/s

Figure 3. Top stacked section just before migration (see Figure 2). Bottom, seismic section after migration with constant velocity (5800 m/s). Reflections listed in Table 3 are highlighted with arrows.

several tens of meters in thickness, covers the bedrock along the entire profile. Due to the rapid variations in thickness of this layer, it is obvious that refraction static corrections are needed to mitigate the negative impact this may have on stacking. For this, first arrivals were picked out to a maximum offset of 700 m. In general, first arrivals are strong and clear for all channels making automatic picking possible. Nevertheless, a fairly time-consuming manual tuning was required after a careful examination to achieve a good statics solution.

After testing several different band pass filters, a time variant filter retaining low frequencies was chosen (Table 2). CDP sorting was carried out over a straight line because it led to stronger and more continuous reflections than a slalom line (e.g., Wu et al., 1995; Rodriguez-Tablante et al., 2007). Different means of binning were tried to optimize the stack, as will be discussed in more detail in the next section. The resulting fold varies along the stacking line between CDP 50 and 200 (see Figure 3). After sorting, a velocity analysis and NMO correction were performed. Dip moveout (DMO) was attempted but discarded as it decreased the quality of the stack, most likely due to the irregular offset distribution.

The resulting stack, Figure 3, shows five prominent reflections, four dipping to the northeast and one to the southwest. A migrated section with constant velocity is shown in the lower part of Figure 3.

Azimuthal binning

The orientation of the current seismic survey is not perpendicular to the strike of geologic units (see Figure 2). Moreover, there is no such thing as a single consistent structural trend in the area. Given that reflections stack coherently along the strike direction, which in this case is not always perpendicular to the stacking line, standard CDP stacking is not the best choice. Instead, if stacking is carried out along CDP bins rotated to coincide with the strike direction of the reflectors, stronger and more continuous reflections are to be expected. Thus, by examining stacked sections with systematically rotated CDP bins, it is possible to obtain not only sharper and more coherent reflections, but also an estimate of the strike of the reflectors (Tsumura et al., 2009; Kashubin and Juhlin, 2010; Lundberg and Juhlin, 2011).

Our chosen stacking line (see Figure 2) is at 30° azimuth (with 0° being true north) and thus, perpendicular CDP bins are at –60°. To search for the optimal binning azimuth, we tested angles in 10° intervals between –110° and –10° azimuth (i.e., ±50°). The most prominent reflections, highlighted in Figure 3, are visible for several of the re-binned stack sections, but are optimally enhanced by only one or two of them. Table 3 lists the most satisfactory binning azimuth angles for each reflection. These angles vary from –80° for reflection C, to –40° for reflection B, with a maximum deviation of ±20° from the original CDP bin orientation. Even though there is not one azimuth value that favors all reflections simultaneously, we found that an azimuth angle of –50° significantly improves the overall stacked section. Therefore, we employed this azimuth binning in the processing work flow to obtain the stack section of Figure 3 as noted in the previous section.

Cross-dip analysis

The cross-dip angle is the dip component of a reflector perpendicular to the stacking line. It is present when the survey line is not perpendicular to the strike of the reflectors (Larner et al., 1979; Wu et al., 1995; Nedimović and West, 2003; O’Dowd et al.,

2004). In crooked line geometries, the midpoints within a CDP bin are scattered and have a variable transverse offset (distance to the stacking line). The variations in the transverse offset together with a cross-dip component hinder the proper function of CDP stacking because traces within the same CDP bin will have different delay times and thus stack incoherently. To dodge this problem, a cross-dip correction δt_{ij} can be applied. It is given by:

$$\delta t_{ij} = \frac{2 \sin \phi_i}{V_i} Y_{ij}, \quad (1)$$

where ϕ_i is the cross-dip angle at the i th CDP, V_i is the velocity above the dipping layer, Y_{ij} is the transverse offset between the j th midpoint and the stacking line (Larner et al., 1979). The estimation of the necessary cross-dip angle ϕ_i , can be done by visually inspecting stacked sections cross-dip corrected with different ϕ_i (e.g., Wu et al., 1995; O'Dowd et al., 2004; Rodriguez-Tablante et al., 2007; Dehghannejad et al., 2010; Lundberg and Juhlin, 2011).

In our case, because the azimuth of the CDP bins is not perpendicular to the staking line (see previous section), the transverse offset, Y_{ij} , is not the shortest distance to the stacking line, but the distance along the rotated CDP bins. Considering this, we examined the effect of cross-dip corrections in 5° intervals, taking into account northwest and southeast cross-dip angles (the latter represented as negative angles). Figure 4 shows the influence of the cross-dip correction with six different values of ϕ_i on reflections B and C. The results obtained from the visual inspection using cross-dip angles from 85° to -85° are shown in Table 3. In general, the found cross-dip angles are small (0 to 10°), but have a significant effect. The cross-dip correction was not implemented in the processing work flow for the final stack as the optimal cross-dip angle varies not only with profile distance, but also with time (depth).

Reflection's dip and strike

With the outcomes from the previous analysis, i.e., optimal azimuth binning and cross-dip angle, plus the inline-dip observed in the migrated section (listed in Table 3), and assuming the reflectors to be planar surfaces, there is redundant information of their strike and true dip angle. Taking into account the inline- and cross-dip angles, it is possible to calculate the strike direction of the reflectors. Figure 5 shows the expected true dip angle as function of strike direction for the inline- and cross-dip angles obtained for each reflection. Considering that the estimates of cross-dip angles are every 5° , curves with $\pm 2.5^\circ$ cross-dip angle have been added to the plot to show the associated uncertainties in the strike direction calculation. Low-angle reflections show considerably greater errors than the steeper ones.

Table 3 lists the obtained values for true dip and strike direction with associated errors. The true dips are very close to the inline-dips as cross-dips are small. The strike directions determined from inline- and cross-dip angles coincide with the optimal azimuth for CDP bins. Only reflec-

tion B shows a big difference (-44° versus -22°). This difference is even greater than the uncertainty associated to the estimation of the cross-dip angle. This could be caused by errors in the azimuthal binning procedure given that this technique is not sensitive to low-angle reflections (Lundberg and Juhlin, 2011).

MT DATA

Acquisition and processing

During the summer of 2009, 17 broadband MT stations were installed in northwestern Skellefte District. The sites were located along the transect between the localities of Brännäs and Adakliden, following the seismic reflection survey. Figure 2 shows the position of the MT stations and the seismic reflection line. Many of the MT sites are far away from the survey line to avoid noise sources like small villages and power lines.

All MT channels (e_x , e_y , h_x , h_y , and h_z) were recorded for all stations. The employed sampling modes were: 3000 Hz for half an hour in daytime, 1000 Hz for two hours around midnight, and 20 Hz for 24 hours continuously. The instrumentation consisted of non-polarizable Pb/Pb-Cl electrodes (Uppsala University, Sweden), induction coils of the type LEMI120 (Ukraine) and Metronix MFS05 (Germany), and Earth Data PR 6-24 data loggers. All measurements were synchronized with GPS clocks.

The transfer functions of the MT impedance tensor $\mathbf{Z}$, relating horizontal electric and magnetic fields, and the tipper $\mathbf{T}$, relating vertical and horizontal magnetic fields, were estimated with the

Figure 4. Portion of the stack between CDP 30 and 250 (see Figure 2), with different cross-dip corrections. The arrows highlight the reflections when optimal cross dip is reached.

Table 3. Results from optimal azimuth binning and cross-dip component together with the inline dip component, true dip, and strike (see Figure 2). True dip and strike were calculated from inline- and cross-dip components. Negative cross-dip values indicate dip directions to the southeast. Dip directions coinciding with the stacking line would have strike directions of 60° .

Reflection	Optimal bin azimuth	Cross-dip	Inline-dip	True dip	Strike
A	-70 to -60	5 to 10	27.5	27.5	-65 ± 6
B	-40	-5	8.5	10.7	-22 ± 15
C	-80 to -70	5	12.1	12.4	-73 ± 15
D	-50	0	25	25	-50 ± 6
E	-60	5	21.8	21.8	-63 ± 8

algorithm MTU2000 (Smirnov, 2003). The obtained transfer functions have a frequency range from 0.002 s to 200 s and are primarily good data quality (see Figure 6).

The apparent resistivities and phase show a similar behavior for all sites. Apparent resistivities are very high for short periods, between 10^4 and 10^5 Ωm , decreasing smoothly to about 10 Ωm to 100 Ωm for long periods. Phases are 40° for short periods, rising to 80° from 0.01 s to 0.1 s and then decreasing to 60 – 70° at 100 s to 200 s. This behavior is very similar to those from previous studies in the district (Hübert et al., 2009; García Juanatey et al., 2012). However, previous studies showed a high site variability, particularly in areas closer to the Kristineberg mine, which is not present in this survey. This suggests a lower structural complexity or less noise in the current study area.

The real induction arrows derived from the tipper data with the Wiese convention (Wiese, 1962), show a consistent behavior throughout all sites, rotating clockwise with longer periods. They point to the northwest for short periods, to the north for periods

around 1 s, and to the northeast for the longest periods, suggesting a consistent change with depth of the geoelectrical structures throughout the area. A sample of two periods, one shorter and one longer than 1 s, are shown in Figure 7. The northeast direction of the real arrows at long periods is common to other sites in the Skellefte District as showed by Hübert et al. (2009) and García Juanatey et al. (2012).

Strike and dimensionality analysis

To inspect the dimensional complexity of the structures underlying our MT survey, we first analyzed rotational invariants of the impedance tensor. Figure 8 shows Swift's and Bahr's 3D/2D phase sensitive skews. The Swift's skew is an indicator of 2D settings vanishing for ideal 2D cases (Swift, 1967), whereas Bahr's 3D/2D skew measures the deviation from a superimposition model of local 3D anomalies over a regional 2D structure (Bahr, 1988). For our data set, Swift's skew values range from 0.01 to 2, increasing considerably with period due to 3D galvanic distortions. Sites 305, 306, 308, and 310 have very small skew values, below 0.1 for most of the periods, primarily fulfilling necessary 2D conditions.

Bahr's 3D/2D skew values are often smaller, mainly because it is not sensitive to galvanic distortions as Swift's skew is (Bahr, 1988; Ledo et al., 2002). As suggested by Bahr (1991), the threshold below which the data could be explained by the superimposition model is 0.3. Nevertheless, it has been shown to be case-dependent (Ledo et al., 2002). For our data, it is below 0.6 for nearly all sites and periods and most of the values are even below Bahr's threshold, particularly those from sites 302 to 311, excepting site 309, indicating that there is an important fraction of the data set that complies with necessary 2D conditions (i.e., low skew values). However, these conditions are not sufficient (Ledo et al., 2002; Smirnov and Pedersen, 2009) and more analyses are needed.

Zhang et al. (1987) outline a method to calculate strike directions from the impedance tensor, assuming the superimposition model and minimizing an objective function Q that takes into account galvanic distortions. The calculated output is not unique as it has a 90° ambiguity, meaning that there are two possible (perpendicular) solutions and additional independent information is necessary to rule one out. When applying this method to the data set for every site and period independently, assuming 5% errors, we obtain the strike angles shown in a rose diagram in Figure 9. Two favored directions can be recognized and are indicated with arrows on the rose plot. A prominent one is at 75° (or the perpendicular -15°) and a smaller one at 35° (or -55°).

The tipper vector also provides information about the geoelectrical strike directions and can be used in conjunction with the previous analysis to determine a strike direction. In an ideal 2D case, the induction arrows will be perpendicular to the strike. For our data set, as discussed in the previous section, the direction of the real induction arrows vary homogeneously with period. Figure 9 shows a rose plot with the orientation of these arrows for all sites and periods. Again there are two predominant directions, -30° and 35° for short and long periods respectively, indicating possible strike directions of 60° and -55° . These agree nicely with the previously derived strikes of 75° and -55° with 15° and 0° difference respectively, ruling out their perpendicular directions.

Figure 10 shows the misfit values $\sqrt{Q}$ obtained by fixing 75° and -55° as strike directions for all sites and periods. Because Q is

Figure 5. True dip versus strike direction for given inline- and cross-dip angles (Table 3). Cross-dip curves for $\pm 2.5^\circ$ are also plotted to show the effect of errors in the cross-dip component. The shadowed areas indicate the variability in strike direction. Uncertainties are much higher for strike directions rather than true dips, and for shallow reflections instead of steeper ones.

normalized by the data errors, a value of one is to be expected when the data fulfills 2D conditions within the given errors and calculated strike direction. Both directions present similar misfit values with most of the data points below four, but very few values below two. Thus, the data set does not comply with required 2D conditions within the given error floor, even though important trends in strike directions were identified in the impedance tensor and tipper.

2D inversion

Given that the station coverage of the MT survey is far from ideal for a 3D inversion, we decided to carry out a 2D inversion of the determinant of the impedance tensor even though, as discussed in previous section, not all data satisfy the necessary 2D conditions. The determinant is rotational invariant and its inversion has proven to be less influenced by 3D shallow local inhomogeneities than that of the single modes (Pedersen and Engels, 2005). In particular, this

technique has been used previously in the district yielding stable and significant results (see Hübner et al., 2009; García Juanatey et al., 2012). Moreover, a recent study in the district comparing the results from 2D determinant and 3D full impedance tensor inversions, concludes that 2D procedures cannot yet be fully replaced by 3D inversion (Hübner et al., 2012).

Considering that the stacking line of the seismic survey has 30° azimuth, and that it is almost perpendicular to -55° , one of the calculated strike directions in the previous section, we decided to project the MT sites along the same line, thus facilitating joint interpretation. The used algorithm was REBOCC (Siripunvaraporn and Egbert, 2000) with the modifications from Pedersen and Engels (2005). Error floors were set to 5% on apparent resistivities and 2.8° on phases. The starting model was a homogeneous half-space of $1000 \Omega\text{m}$ with cell sizes of fixed horizontal length, ~ 200 m, and increasing vertical length (a geometric progression with ratio 1.12) beginning with 50 m. The obtained model has an rms of 1.98.

Figure 6. Apparent resistivity and phase, for selected MT sites of the off-diagonal elements of the impedance tensor, its determinant, and the 2D forward response of the model in Figure 11. The electric fields are oriented to the north and east in Zxy and Zyx, respectively. Data points at 0.016 s and 0.022 s, were omitted from the 2D inversion.

Coarser and thinner discretizations were tested and presented very similar results.

To take advantage of the colocated seismic reflection survey, the most prominent reflections were introduced in the inversion algorithm as cuts in the regularization scheme, setting adjacent model parameters to be independent from each other. This allows the inversion procedure to place abrupt resistivity variations across the introduced reflections. The model obtained in this fashion has the same rms as the previous model and shows a weak resistivity boundary along reflection A, and less significant changes across other reflections (see Figure 11). The data fit is shown in Figure 6 for some sites.

Figure 7. Real induction arrows of the tipper vector, with the Wiese convention, for two representative periods. The length of a vector with 0.5 magnitude is shown in the legend as reference (black arrow). All other symbols are as in Figure 2.

Figure 10. The $\sqrt{Q}$ values for fixed MT strike directions (Figure 9). Neither strike direction fulfills required 2D conditions within a 5% error floor.

The resistivity distribution in the model shows, as expected, very resistive features close to the surface (most likely due to the Revsund and Adak granites) and a strong conductor at depth, as it has been observed in other MT studies in the Skellefte District (Rasmussen et al., 1987; Hübert et al., 2009; García Juanatey et al., 2012).

INTERPRETATION

Combining the results derived in the previous sections with those from earlier studies and geologic maps from SGU, it is possible to give a geologic sense to the observed reflections and geoelectrical

Figure 8. Swift's and Bahr's 3D/2D skew values for all MT sites (Figure 2). Red lines indicate threshold values below which 2D assumptions are supported. Sites below these thresholds are represented by black dots and listed at the top of each graph.

Figure 9. Cumulative rose diagrams for the calculated MT strike directions from the impedance tensor and orientation of the real induction arrows (Figure 7). Both diagrams show two preferred directions, although the second direction in impedance strikes is much smaller than the first.

structures. The following discussion is itemized by geologic unit. Figure 12 shows the migrated seismic stack overlain on the MT model.

The Brännäs gabbro

To the south end of the profile and east of the Brännäs village, there is a rock unit with important magnetic and gravimetric signatures. From the geologic mapping of the area, the rock unit has been recognized as a thick gabbroic sill with vertical igneous layering. Its age is unknown, but given its vertical orientation, it has to be older than the undeformed Revsund and Adak type intrusions. It is possibly related to the quartz monzodioritic intrusions in the Vindelgransele area with an age around 1880 Ma (Kathol and Weihed, 2005).

The southernmost resistor in our MT model, RI, constrained by sites 301 and 302, corresponds well with the Brännäs gabbro. The base of the resistor is at about 5 or 6 km depth, agreeing nicely with the obtained depth for the base of the gabbro after potential field modeling along Profile 5 in the Kristineberg area (Malehmir et al., 2006).

The current seismic section shows three of the five analyzed prominent reflections to the south (A, B, and C). Reflections B and C have gentle dips and their dip directions are east–northeast or northeast for reflection B, and north or north–northeast for reflection C (reflection A is discussed in the following subsection). In this area, the seismic survey line bends and crosses geologic contacts obliquely causing the traces of the CMP gathers to be spread out in different geologic units and stack together. Thus, it is not possible to determine with certainty if reflections B and C are to be associated with the gabbro, the granite, or a common unit below both. Given its depth, reflection C could be related to the base of the Brännäs gabbro, whereas reflection B does not seem to be related solely to the gabbro as it extends beyond resistor RI.

Postorogenic intrusions: Revsund and Adak granites

The resistors RII, RIII, and RIV show a nice correlation with the granites when comparing the MT resistivity model with the surface geology. The resistor RII is bounded at depth by reflection A, suggesting that the base of the western Revsund granite dips 28° to the northeast (with a dip direction not exactly parallel to the stacking line), reaching 5 or 6 km depth. It extends to the northeast at least 3 km below mafic volcanic rocks (TI), and it is possible that it connects with RIII, coming to the surface again to the east of the volcanics. However, the granites west of the profile are of Revsund type, and thought to be slightly different from the Adak type granites to the east. It is worth noting that this result could be biased by the a priori information added to the inversion of the MT data.

Resistor RIII is crossed by the southwest dipping reflection D, but in this case, unlike with reflection A, the MT inversion does not introduce a significant resistivity contrast in the model. Thus, reflection D could be associated with:

- The base of the granite in contact with another unit of similar high resistivity, like basic intrusions found within the granite east of the profile and often found below the granites in drill cores to the northeast, or;
- A normal low-angle fault, caused by late tectonic movements.

Resistor RIV, to the north, may be associated to the Adak granite. It is shallower than the others reaching a maximum depth of 3 km. The northeast dipping reflection E seems to correspond to the base

of this feature if a cutoff value of $10^4 \Omega\text{m}$ is considered. Nevertheless, the resistivity contrast across this reflection is not significant, indicating that the base of the resistor and reflection E do not necessarily correspond. Reflection E could have been generated within the rock unit below the intrusion.

Tjamstan formation

In the MT model, the mafic volcanics of the Tjamstan formation have a resistivity signature between $10^{2.5}$ and $10^{3.5} \Omega\text{m}$, as can be deduced from the resistivity values that fill the shallow pockets between the resistors (interpreted as granitic intrusions in the previous section) where these rocks are to be expected. From the MT model it is not completely clear if the shallow packages of volcanic rocks TI and TII have a maximum depth of 2.5 km and 1.5 km or continue to greater depths.

Figure 11. Two-dimensional inversion model of the MT data (Figure 2). Projected site positions are marked as black triangles on top, together with the geology above the profile (color code is as in Fig-

Figure 12. Superposition of migrated stack section (Figure 3 bottom) and MT resistivity model (Figure 11).

The region with intermediate conductivity between the intrusions and the deep conductor, may also be associated to this formation. These rocks in between the intrusions are thought to be a rather thick unit, and potential field modeling along Profile 1 in the Kristineberg area estimated it to reach down to 9-km depth (Malehmir et al., 2006). Given the smooth decrease of resistivities toward the deep conductor, it is not possible to determine if the mafic volcanic is the only rock unit between the intrusions and the deep conductor, or if a more conductive unit (e.g., metasediments from the Vargfors Group or volcanics from the Skellefte Group) is to be found below the mafic volcanics and on top of the deep conductor.

Deep conductor

The deep conductive feature with resistivities below $10 \Omega\text{m}$, that appears below 12-km depth, has been already reported in previous studies in the area. It was first described in the regional MT study along the FENNOLOLA profile (Rasmussen et al., 1987), as a crustal conductive anomaly below the Skellefte District, dipping to the northeast and spanning 5–32-km depth over a span of 100 km. This anomaly was later confirmed by local MT studies in the Kristineberg area (Hübert et al., 2009; Hübert et al., 2012; García Juanatey et al., 2012). It is worth noting that Hübert et al. (2009) found the top of the deep conductor at 11 km depth in the northern side of Profile 5 in the Kristineberg area (Malehmir et al., 2006), coinciding almost seamlessly with our MT model (see Figure 13).

In the pilot study, the southern part of this anomaly met a set of north-dipping reflectors on Profile 5, also visible on Profile 1, previously associated with the metasedimentary rocks of the Bothnian Basin (Malehmir et al., 2006; Tryggvason et al., 2006). The Bothnian Basin outcrops to the south of the Skellefte District and is composed of metamorphosed greywackes and pelites of 1.95 Ga just south of the district in the Barsele and Knaften areas (Wasström, 1993, 1996; Eliasson and Sträng, 1998). Thus, the high conductiv-

ity of this feature substantiates the hypothesis that could be caused by rocks with interconnected graphite.

The presence of this deep conductor in our MT model, suggests that the Bothnian Basin extends further north from the Kristineberg area. The reason why there is no change in reflectivity characteristics accompanying the deep conductor in our survey, could be due to a lack of penetration depth in the seismic survey. Profiles 1 and 5 from the pilot study had a larger penetration depth because they were acquired with explosives.

DISCUSSION

The reflection seismics and MT data along the Brännäs–Adakliden transect shed new light in the enigmatic area between the Kristineberg and Adak mineralizations. They present geologic units below the granites and their relationships have been constrained, but are still not completely resolved, especially where the seismic and MT methods show some ambiguity (e.g., reflection D and resistor RIII). Further studies with the data set and the inclusion of other geophysical data, like gravity and magnetics, will add more constraints to the modelling and help our current understanding of the area.

In the case of RI, further studies that include off-profile data can be carried out to determine if it is solely caused by the Brännäs gabbro, or if the Revsund granites to the west and east (Släpsträsk) also contribute. The resistivity model from the MT survey along Profile 5 (Hübert et al., 2009), placed a resistor (labeled RIV in that paper) to the east of RI, it has a slightly lower resistivity than RI ($10^{3.25}$ – $10^4 \Omega\text{m}$, see Figure 13), a shallower depth of 3 km, and it was interpreted to be related to the Släpsträsk granite. To sort out the relationships between these intrusions, the subject needs to be addressed in 3D. A local 3D MT inversion including sites 301, 302, and M20 will be undertaken in a coming study.

Forward modeling tests of the resistivity model, and the inclusion of potential field data, could help unriddle the depth to the base of the intrusions to the northeast (RIII and RIV in the MT model) and also help constrain the hypothesis presented for reflection D in the previous section.

Additionally, sensitivity tests of the resistivity model could indicate if there is a significant resistivity difference between RIII and RIV, that might be used to discriminate between Adak and Revsund type granites. In the present model, RII and RIII have very similar resistivities and may possibly be connected below the outcropping Tjamstan formation. If true, this would indicate that part of the post-orogenic intrusions to the east might be an extension of the Revsund granites to the west, which is contrary to the present view where the postorogenic intrusions to the east are thought to be solely of Adak type.

CONCLUSIONS

From the seismic survey, five prominent reflections were identified. Making use of the crookedness of the line and pseudo-3D processing techniques, i.e., optimal azimuth binning and cross-dip analysis, an estimate of the 3D geometry of the reflectors was obtained. This estimate showed to be more accurate for steeper reflections.

From the MT data, a stable 2D inversion model was obtained, even though a consistent geoelectrical strike for the whole data set could not be found. The addition of seismic reflections in the MT inversion, helped to understand the origin of some of the reflections, and significantly improved the geologic interpretation.

Figure 13. Three-dimensional view of the meeting point between the MT models along the Brännäs–Adak transect (Figure 2) and Profile 5 (M20 segment) in the Kristineberg area. MT stations are marked on the geologic map at the surface. Note that both profiles agree very well on the location of the deep conductor, but differ on the resistivity of the shallow resistors.

Integrating the results of both geophysical techniques and comparing the interpreted model with previous studies, the depth and local extension of the main geologic units in northwestern Skellefte District were inferred. The western Revsund granite continues to the east below the mafic volcanic rocks, and reaches 5-km depth in the center of the transect. The eastern granites are probably shallower (3 km), and might be thickened by deeper intrusions. The deep conductor, previously found in the Kristineberg area, continues to the northeast.

Even though seismics and MT helped to constrain the geology of the area at depth, the geologic picture is still not completely resolved and new questions have been posed. More modeling and the inclusion of more geophysical data (e.g., potential fields) is required to fully understand the geologic setting of this corner of the Skellefte District.

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