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Progress report January-June 2016

StartGeoDelineation

State-of-the-art geophysical and geological methods for delineation of mineral deposits and their associated structures – Sweden and Finland

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Students: Georgiana Maries (PhD), Sara Eklöf (PhD), Andreas Bierk (MSc), Ezra Yehuwalashet (MSc) and Björn Sandback
Short-term researchers: Mahdieh Dehghannejad, Joachim Place and Magnus Andresson

Organizations: (1) Uppsala University (UU), (2) Nordic Iron Ore (NIO), (3) Yara, (4) Geological Survey of Finland (GTK) and (5) Geological Survey of Sweden (SGU)

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Summary

The StartGeoDelineation project has reached its one and half year period now. Three presentations from the project were given at the Nordic Geological Winter Meeting in Helsinki during January 2016. Another presentation, mainly from the Siilinjärvi seismic survey, was recently given at the Seismix meeting in Scotland. Additional physical property and gravity point measurements have been done to complete the database for modeling and interpretation of other data sets from the NIO site. Seismic data acquired last September are being processed and in conjunction with petrophysical data should allow an improved interpretation of the geological structures at the NIO site. A long-standing question about the presence of a fault, the brewery fault, displacing the Grängesberg deposit was partly addressed by revisiting existing seismic data and performing a novel processing method on the old noisy data from this site. Magnetic property measurements on more than 40 samples have allowed an improved way of distinguishing hematite from magnetite but also providing a way to suggest which one is dominant in different parts of the Blötberget mining area. Analysis of thin sections and geochemical data from these samples and additional ones from Siilinjärvi is currently on going. While the project is speeding up towards producing sensible outcome, one of the PhD students in the project has been on sick-leave since early this year hence slowing down the geological aspects of the project. If this continues, we will inform the sponsors and take appropriate action in consultation with the sponsors on how to move forward with this matter. A progress meeting among the project participants is planned in conjunction with a second round field campaign in Ludvika area in early October 2016.

1. General planning of the project

Project participants particularly those focusing on the Siilinjärvi site (Finland) met during a meeting in Helsinki to review activities and plan for upcoming tasks. Following the meeting a short-term researcher, Mahdieh (Azita) Dehghannejad, was hired to work on the reprocessing seismic data from the site and perform tomography and new imaging algorithm that could improve the results. Additional borehole logging data including density measurements and 3D visualization of the results were used for the interpretation of the seismic results. One of the seismic lines inside the open pit is extremely crooked with half the line making a 90° turn and having a 50 m elevation difference within just 500-600 m distance. It was decided that a proper imaging of the structures would require treating the data in 3D and hence 3D swath imaging was performed and partly improved the imaging of the structures. Overall, seismic results in the open pit show a chaotic character and less of continuity except for one line where a correlation with a known shear zone running close to the end of one of the profile can be suggested. Three boreholes drilled in the context of the project (R626, R628 and R629) have now fully been logged and geochemistry data from them are available to the project. Magnetic property measurements have been conducted and currently being analyzed within the project. A special focus is now being given to different generations of dykes in the complex requiring additional fieldworks and sampling campaigns. We hope this to happen within the summer 2016. Current plan is to finalize the seismic results from Siilinjärvi by the end of summer and write a scientific article about the findings.

In the Swedish side of the project, a focus has been given to data collection and building a petrophysical and geophysical database where soon geophysical and geological data will be integrated and interpreted based on those data either as constraints or input to modeling. During April 2016, more than 100 new gravity points were measured and provided a great database for density modeling of the mineralization. Magnetic property measurements on samples obtained from the site during the first year are being finalized in an MSc thesis to be presented after summer 2016. We aim at presenting these results in a scientific article immediately after this. Downhole logging data conducted on 5 boreholes are now finalized. Additional time had to be spent to quality control the full-waveform sonic data and even manually pick the traveltimes (both P- and S-waves) for velocity estimations and comparison with geotechnical data provided by NIO on these boreholes. Seismic data acquired last year have been prepared and should be ready to be processed by Georgiana Maries. The two PhD students, Sara Eklöf and Georgiana Maries, in the project spent sometimes at the NIO coreshed to carefully look at the samples from these boreholes and conducted density measurements on the core samples. Downhole density logging was not carried out when all other logging measurements were conducted last year. Preliminary results from these measurements will be presented during the First Conference on Geophysics for Mineral Exploration and Mining in Barcelona, September 2016 by Georgiana Maries.

A long-standing question concerning the continuation of an inferred *"Brewery fault"* across the whole mining area was put forward by NIO during the early stage of the project. In a new effort and within a larger program, a part-time researcher (Joachim Place) was hired to work on the reprocessing existing seismic data from Grängesberg where initial efforts had limited success due to the high-level of cultural noise in the area. Reprocessing work started by developing a new algorithm that tackled one of the key seismic processing steps known as refraction static corrections. After the development of the algorithm, a new effort improved the imaging and provided some hints about the presence of the "*brewery fault"* displacing an unmined part of the deposit in its footwall. More studies are required to prove this interpretation. Results of this study are now published by Place and Malehmir (2016) and attached to this report.

Overall, the project is on a good speed despite of that one PhD student is not fully functional in the project. Additional people have joined the project as MSc students or researchers (e.g., Pietari Skyttä, University of Turku) and we hope by the end of the year more output and sensible deliverables are provided to the sponsors and the whole team. The *StartGeoDelineation* will present its progress during a follow-up meeting planned by Vinnova and Tekes during October 2016.

2. Seismic imaging in Siilinjärvi-Finland and Grängesberg-Sweden

Seismic data acquired in the project in the Siilinjärvi open-pit mine and around it were challenged by the complexity of the geology and the first time use of the seismic streamer in such an environment. While quality checking of the raw data indicated good quality data, imaging results showed poor reflectivity. In a new effort involving researchers from GTK and Uppsala University, these data were also revisited during early spring 2016 and improved results were obtained. 3D first-break tomography and 2D/3D reflection imaging were carried out to properly account for the crookedness of the profiles and mixed use of streamer and wireless data recorders. Figure 1 shows a 3D view of some of these results indicating low-velocity zones along one the two profiles acquired inside the open pit.

Figure 2 shows an example of the reprocessing results, unmigrated seismic section, from profile 7+8, outside of the open-pit area, and its correlation with the density measurements conducted on core samples from R629. The density measurements as well as geological logging suggest a diabase intrusion correlating with the reflection observed on the southwestern part of the profile. Strong density drop at deeper parts may suggest fractured fenite-glimmerite contact and a reason for more transparent section until another set of reflection is observed in the central part of the profile. Northeastern part of the section has low seismic fold and hence poor quality

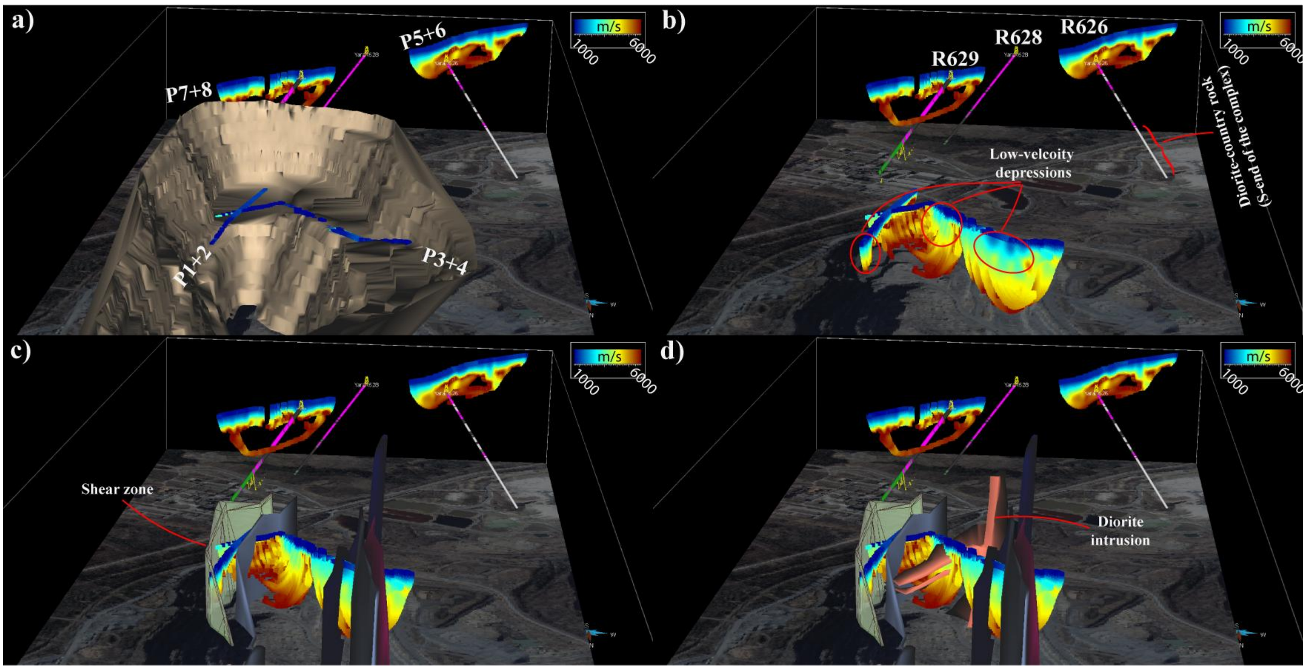

Figure 1: *3D views showing (a) location of the seismic lines with respect to the Siilinjärvi open-pit mine, (b) tomography results and boreholes (R626, R628 and R629) drilled in the project, (c) models of some of the shear zones and (d) a major dioritic intrusion intersecting P3+4 lines.*

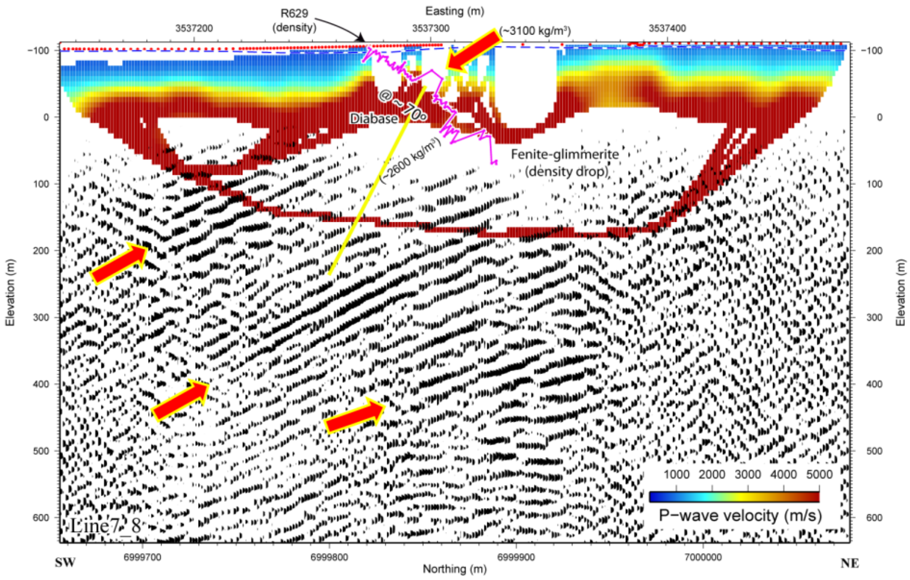

Figure 2: *Unmigrated seismic section along profile 7+8 showing a correlation between a diabase dyke (density increase) and a set of dipping reflections in the southwestern part of the profile. A number of dipping reflections are noticeable as indicated by the arrows).*

image. Similar interpretation like this one is currently on-going for the other profiles. Note that reflections would have much higher dip angle than shown here and move up-dip after migration.

Figure 3a shows seismic reprocessing results from the Grängesberg Kiruna-type iron-oxide deposit (Sweden). The section, unmigrated, shows the east-dipping footwall and hostrock structures as well as mining-induced fractures that dip towards the west. The *"Brewery fault"* seismic response was modeled in 3D using its inferred geometry as was observed in the mine and projected to the surface close the brewery in the town. The modeling results suggest that the fault response, if any, should occur in a region where there is no reflectivity observed but just above a strong reflector (marked as red). The reflector then is likely an intact part of the deposit given its strong seismic signature. This reflection is clearly observed in the processed shot gathers (e.g., Figure 3b) suggesting that it is real and not an artefact of the processing.

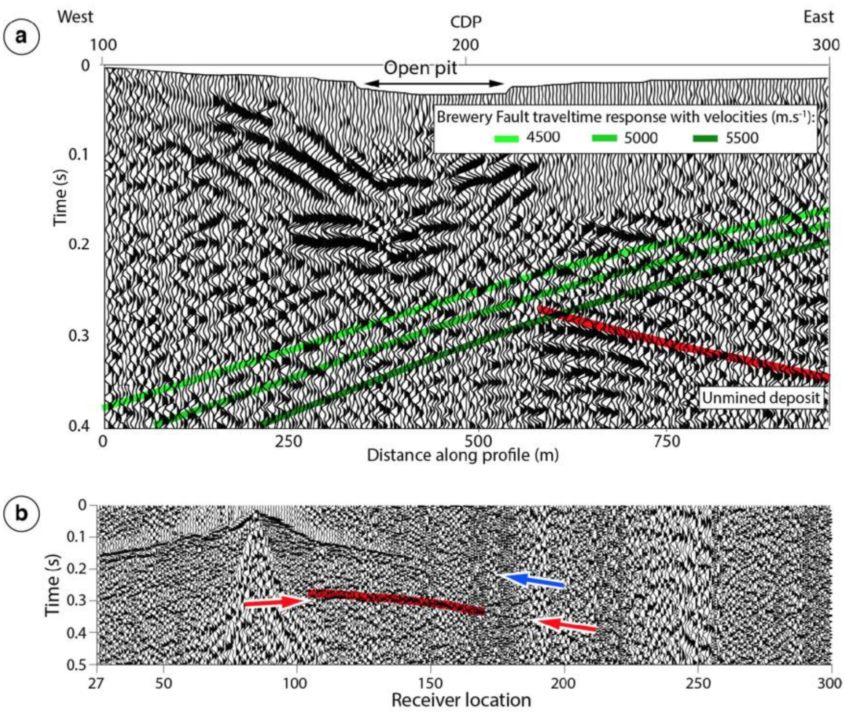

Figure 3: *Seismic modelling results for the inferred Brewery fault and the interpreted unmined part of the deposit, showing the traveltime responses superimposed onto (a) the unmigrated stacked section and (b) the source gather (deposit only). From Place and Malehmir (2016, Geophysical Journal International).*

3. Potential field and petrophysical studies

During the first field campaign in Blötberget about 50 gravity points at about every 100 m were measured. Immediately after this, it became clear that the gravity data were capable of delineating the mineralization and could possibly be used for a tonnage estimation assuming that the mineralization and excess gravity is due to magnetite-mineralization alone. With this objective, additional, about 100 new ones, gravity points were measured during April 2016. These data were then combined and leveled with a few gravity stations available from the Geological Survey of Sweden. Complete bouguer gravity was estimated after fixing geodetic data with the help of Lidar data from the study area.

Figure 4a shows the aerial photo of the study area with the location of existing boreholes, those logged in the project and gravity stations, blue triangles, measured during the first field campaign. Figure 4b shows complete bouguer gravity map of the study area and additional gravity points, blue triangles, measured in the second gravity field campaign. Two main features are noticeable in the gravity map: (1) a northeast-southwest trending gravity low slightly north of the main road connecting to the city of Ludvika (road 50) and a large gravity high northeast of the map. Around Blötberget, gravity anomaly is about 5 mGal. Using a simple dipping slab assumption and density contrast of 1750 kg/m^3 (2750 kg/m^3 for the hostrock and 4500 kg/m^3 for magnetite), it is possible to estimate an average thickness of 65 m for the magnetite mineralization. If one assumes a lateral extend of about 300 m and depth extent of 500 m, this would result in about 43 million-tone of magnetite mineralization. NIO's report on the measured resources is similar to this assuming an iron content of about 42%. 3D modeling and inversion of the gravity data should provide a better estimate for this. This combined with magnetic modeling work that is intended should help improving both inferred resources and overall structures controlling mineralization. Ezra Yehuwalashet is carrying out this work for his MSc degree project at Uppsala University.

During the fall of 2015 and early 2016, Andreas Björk (another MSc student) has focused his

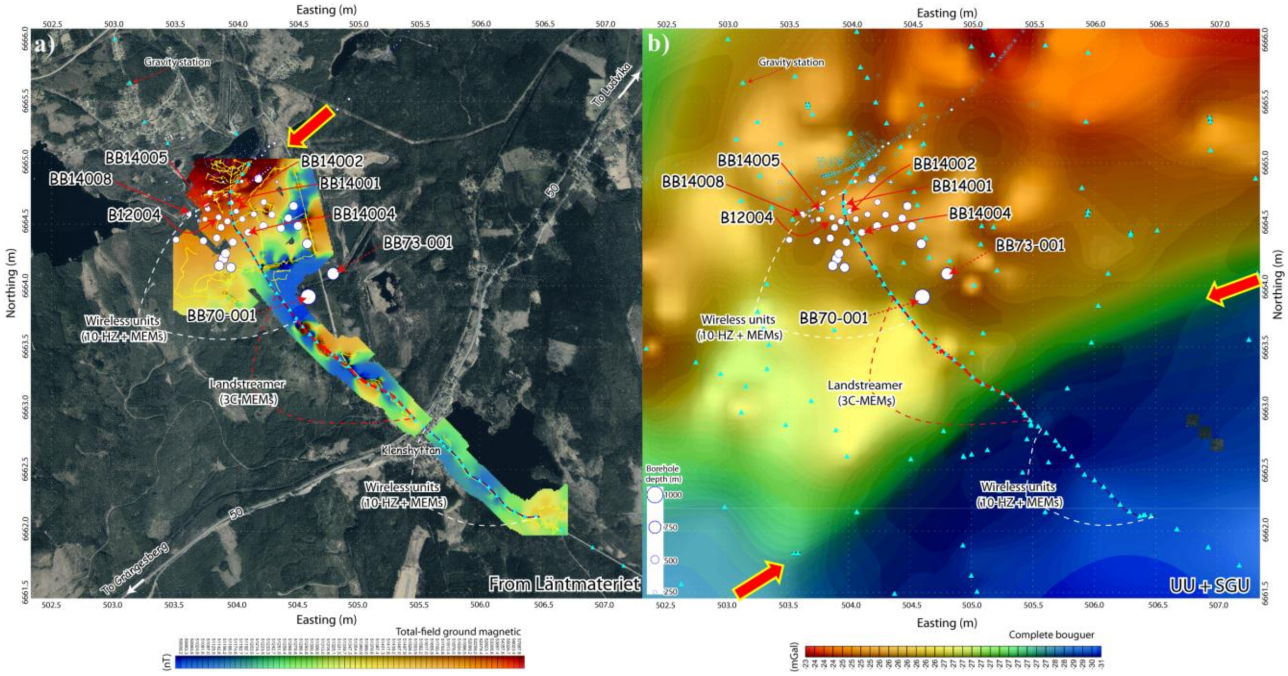

__Figure 4:__ (a) Aerial photo and the location of the existing boreholes, seismic line, gravity stations and ground magnetic data measured during the 2015 field campaign. (b) New gravity data, blue triangles, combined with those from 2015 showing a strong decrease in the gravity field just north of the road 50 and strong gravity response of the iron mineralization striking in NE-SW. The gravity data suggest a much larger gravity high towards the northeastern side of the study area, which is consistent with reports suggesting a major mineralization under the Ludvika Lake). Careful modeling and analysis of the data should shed light on this.

degree-project on determining the rock magnetic properties of magnetite-hematite iron mineralization in the Blötberget area. The sample set consists of a suite of 35 samples, which were investigated using susceptibility as a function of temperature and micro-magnetic analyses (hysteresis curves). Results indicate a close relationship between magnetic properties and volume proportion of ferromagnetic mineral content (magnetite and hematite; Figure 5). In addition, low temperature susceptibility measurements (-194 °C to room temperature) shows that hematite has a suppressed Morin transition T_M, occurring at ca -60 °C (compared to a typical T_M of ca -10 to -15 °C), which may be an indication for the presence of small amounts Ti impurity in the hematite. This however, needs more literature studies and further geochemical analysis.

Fieldwork for anisotropy of magnetic susceptibility (AMS) studies was also conducted at the Siilinjärvi mine during late August 2015. A set of about 100 samples were collected during the fieldwork, consisting of oriented drill core and block samples. From these samples about 250 cylindrical specimens (22 mm long and 25.4 mm diameter) were prepared for AMS measurements. About half of these specimens have currently

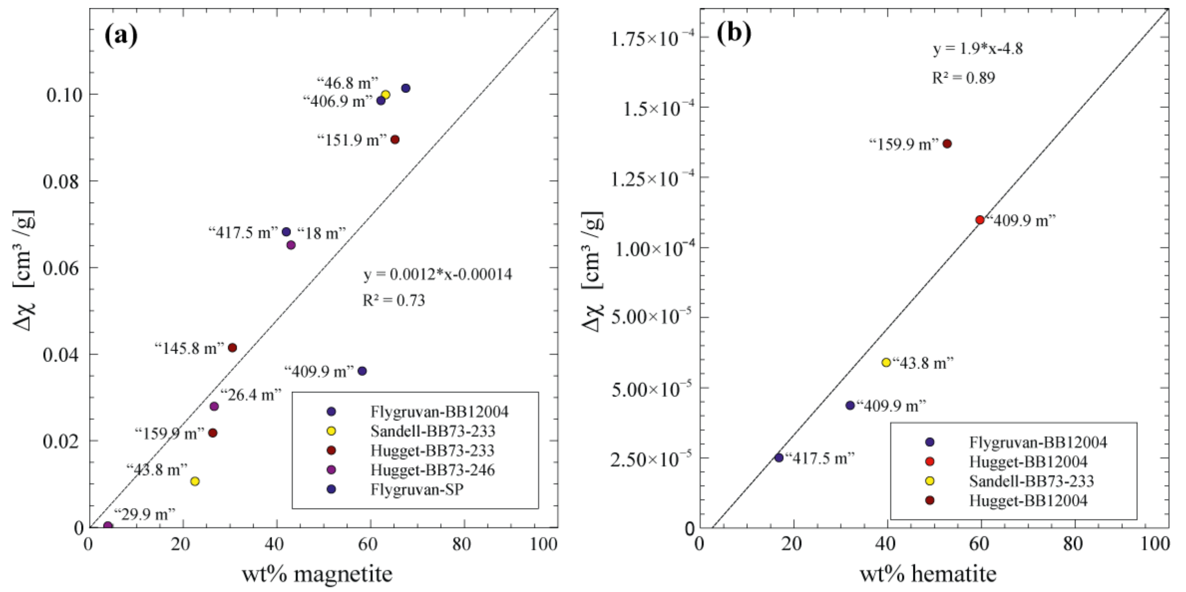

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***Figure 5:** Mass dependent susceptibility (χ) as a function of (a) wt% magnetite and (b) wt% hematite. The mass dependent susceptibility is defined by the loss of susceptibility when the sample is heated above the Curie temperature (for magnetite) and the Néel temperature (hematite), and hence is expressed as the change in susceptibility (Δχ). Data were collected from drill core samples from different localities at Blötberget (as seen in the legend), and numbers adjacent to the data points represent depth of the sample in the drill core. High degree of correlation is identified between Δχ and wt% for both magnetite and hematite, with statistically significant correlation coefficients in both cases.*

been measured, and the second half are planned to be measured during June and July 2016. In addition, we plan on conducting a series of rock magnetic analyses, including temperature dependent susceptibility and micro-magnetic (hysteresis) measurements. The preliminary results for AMS measurements are shown in Figure 6. AMS results indicate a general N-S structural trend, consistent with the orientation of regional transpressive(?)/transtensional(?) deformation zones. From Figure 6, a clear distinction can be made between samples that have degree

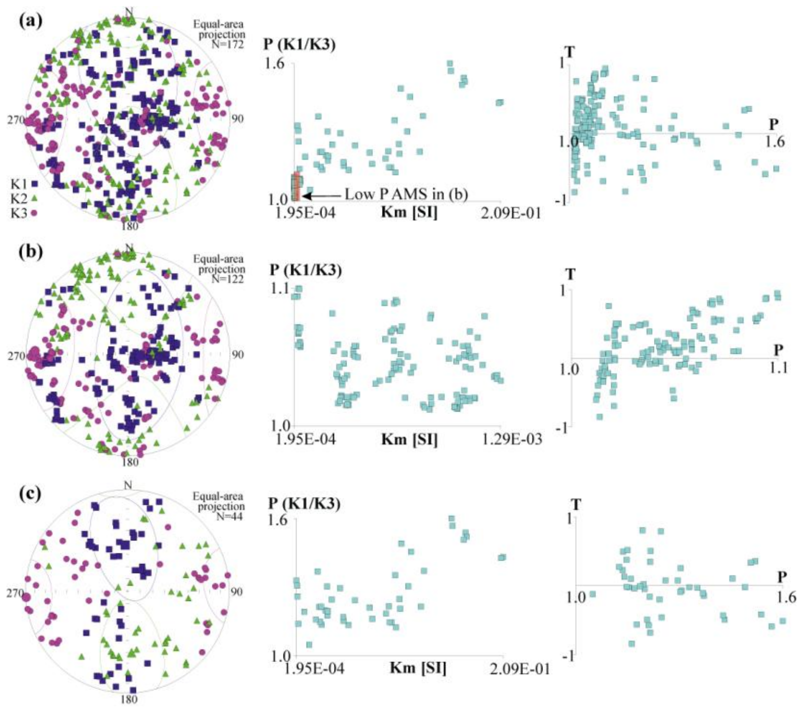

***Figure 6:** Preliminary results of AMS measurements from the Siilinjärvi phosphate mine. (a) Complete set of AMS measurements to date (172 sub-samples), where the left-most diagram displays the data in an equal area projection with geographic coordinates. Principal axes of susceptibility (K1 ≥ K2 ≥ K3) indicate a pattern of general north-south oriented magnetic foliation plane (plane containing the K1 and K2 axes). The central plot shows the degree of anisotropy (P = K1/K3) as a function of bulk susceptibility (Km). The arrow pointing to the red marked area is shown magnified in (b). In the right-most diagram, the shape factor T, varying from a rotational oblate ellipsoid (1) to a rotational prolate ellipsoid (-1), is shown as a function of P. (b) A sub-set of AMS presented in (a) for sub-samples with low degree of anisotropy (P ≤ 1.1).*

anisotropy (P) higher and lower than 1.1 (Figure 6b and 6c).

During 2015 and through different field campaigns, a total of six boreholes (see Figure 4) were logged with four different probes measuring several physical properties such as magnetic susceptibility, natural gamma, formation resistivity, fluid temperature and conductivity. Full-waveform triple sonic logging was only performed in four them. Laboratory measurements including density, magnetic susceptibility and magnetite content were performed on drill core samples from mainly 320 to 570 m depths where mineralization was primarily observed. A Matlab script was written to link all the physical properties from the 6 measured boreholes to those of core observations and laboratory measurements. Afterwards the relationships between all the observations were examined and analyzed by generating synthetic seismograms and various cross plots. To generate synthetic data, densities were assumed except for the mineralized zone where this was measured (this analysis will be updated since we have now measured densities from the core samples for the whole hole). Synthetic traces, Figure 7, generated suggest that mineralized zones should produce strong seismic signal supporting the idea of acquiring surface seismic data in the study area. Georgiana Maries is currently aiming at refining this analysis and improved the modeling work using refined velocity information from the full-waveform sonic data.

5. Geological and ore mineralogical studies

A short field campaign was conducted in the Blötberget area during 2015 with the aim to collect geologic structural data. Preliminary results show that the most prominent foliation, related to D2 and peak-metamorphic conditions, strike in a NNE to NE with a moderate southerly dip. A strong stretching lineation has occasionally formed and the orientation varies between E and S with a moderated plunge. The D2-structures appear to have experienced a 10-20° clockwise rotation compared to equivalent structures at Grängesberg, c. 10 km to the south. Both this rotation and the scatter are most likely related to the large-scale, retrograde D3-folds in the area.

The dominating rocks in the Blötberget area are felsic metavolcanic rocks, amphibolites and pink, fine-grained gneissic granites and pegmatites. The felsic metavolcanic rocks are mainly massive, but banded and laminated varieties occur sporadically.

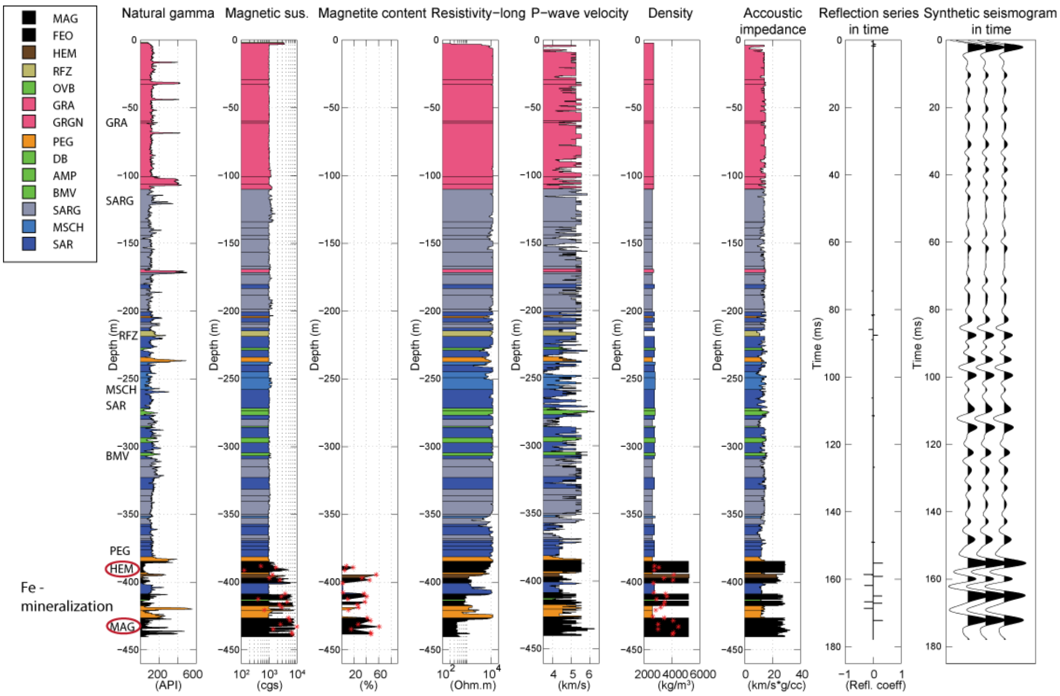

Figure 7: Physical properties from downhole logging measurements (BB14002) including the synthetic seismogram suggesting a strong seismic response to be expected from the mineralized zones but also likely from zones of strong fracturing in the hanging-wall.

In the ore zone phyllo-silicate altered rocks, traditionally referred to as sköl, are common, but rather unaltered felsic meta-volcanic rocks are also present as dykes or layers.

Undisputable S1 structures are rare, but have been recognized in both platy hematite and in chlorite-rich sköl zones as a crenulated cleavage (Figure 8). The presence of both S1 and S2 structures in the platy hematite imply that this hematite variety were formed prior to peak metamorphism and may be a primary feature. The pegmatites are also deformed and appear commonly as boudinage, which probably is related to D2.

Figure 8: *A chlorite-rich sköl zone in contact with magnetite-dominated ore at Blötberget. The S1 fabric in the sköl zone has been crenulated during D2, a similar fabric has also developed in platy hematite.*

In different areas the D2 strain is either prolate or oblate forming L-dominated and S-dominate structural domains. This could be related to lens tectonics similarly to the structural architecture at Grängesberg, where the ore lenses, granites and sub-volcanic intrusions have acted as component bodies and strain is mainly accommodated in sköl zones and other readily deformed rocks.

During the summer and autumn 2016 Sara Eklöf is going to conduct additional field works together with Karin Högdahl and possibly a master student. The field work will focus on collecting structural data and to identify and sample key lithologies for geochronology and further characterizations. The geological and geophysical data (petrophysical and potential field data) will be used to construct a 3D/4D model of the study area.

In order to yield a better understanding of the metallogenesis of the apatite iron-oxide deposits and adjacent iron oxide mineralization in western Bergslagen LA-ICP-MS analysis will be conducted on magnetite and some hematite as a part of the master degree project by Björn Sandback. In February 2016, 24 iron oxides samples from different paragenetic and textural settings were collected in drill cores from Blötberget and Väsman. Additional samples included in this study are from outcrops and from the apatite iron-oxide deposits at Grängesberg and Koplsahyttan. 49 polished sections have been prepared and studied by optical

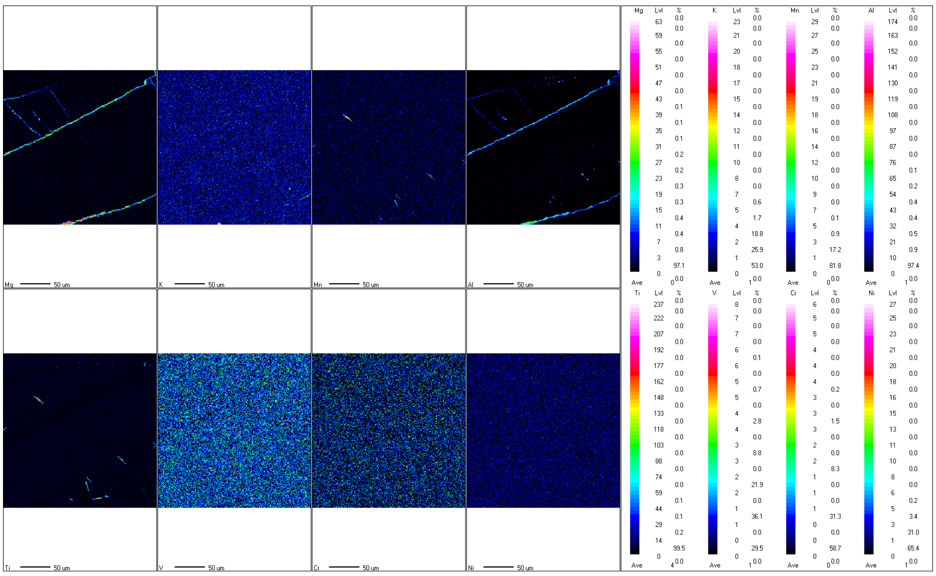

Figure 9: *Elemental XRD-maps of magnetite from Blötberget showing elevated contents of K, Mn, V and Cr and the presence of ilmenite lamellas.*

microscopy. Of these, a few magnetite samples have been analyzed by WDS (Figure 9), in order to be used as a supplementary internal standard for the LA-ICP-MS analyses. The aim is also to analyze REE-bearing phases.

In August 2015, reconnaissance fieldwork was also conducted in Siilinjärvi. The aim was to get an overview of the structures and how these are related to the mafic dykes. Cross-cutting relationships and the presence or absence of deformed contacts indicate that there are at least two and possibly three generations of dykes. The youngest generations constitutes occasionally composite dykes and are referred to as diorites. These dykes have relatively sharp contacts to the carbonatite complex and are less deformed that the older generation/s, but emplaced before the end of the ductile deformation illustrated by formation of meso-scale box-folds. The older dykes have variably shear contacts, mainly showing east-side up kinematics. Thin sections have been prepared from 45 samples, including the three dyke types and four sheared glimmerite contacts, and major and trace element analyses have been conducted on 14 of the dyke samples. The thin sections of the glimmerite were prepared at the Thin Section Lab, Nancy, but were too thin for petrography and have to be re-done. Guided by the geochemical and petrographical results samples, from both the dykes and the sheared glimmerite, will be selected for geochronology.

Field work will be conducted by Karin Högdahl, Pietari Skyttä and possibly Fredrik Karell during the field season 2016. The main focus for this field campaign is to collect structural data and samples for geochronology. These and AMS data in addition to geochemistry and petrography, will be used to construct a 3D/4D model of the study area.

6. Presentations and publications

The project will have a presence at the follow-up meeting organized by Vinnova and Tekes during October 2016 in Stockholm, will have its progress meeting during fall 2016 and will have presentation at the NSG-EAGE conference in Barcelona. We are expecting a couple of scientific manuscripts from the project by the end of this year, one from the Yara site (seismic work) and likely two from the NIO site (magnetic property and down-hole logging experiments). PhD students in the project are currently working on their manuscript one from Grängesberg (Sara Eklöf) and another one from Blötberget (Georgiana Maries) mining areas.

7. Work plans for fall 2016

Gravity and magnetic data from the NIO site in Blötberget will be slightly expanded during a second field campaign planned for fall 2016. It is possible that one more borehole in the site will be logged using downhole geophysical probes at the same time. A new seismic profile will be acquired using denser receiver spacing and additional shots and receivers (wireless recorders) perpendicular to the main line. We also anticipate additional airborne geophysical data to be provided by SGU from the site since they are planning at acquiring these data already this summer and should be available to the project by early next year.

A complete study of the AMS results to identify the structural control of different geological units and to determine the intrusion mechanisms and emplacement of the diabase vein system will also be conducted.

Field geological mapping and sampling as well studies on new geochemistry and thin sections obtained from NIO and Yara sites will be done. We anticipate a higher speed for this part of the project during summer and fall 2016. PhD students in the project plan to visit Malå core storage facility to study some historical and deep core from the site. We hope this to happen before the end of summer 2016.

Collaboration among the partners has been excellent despite of the mining industry downturn. NIO and Yara are both committed to the project and have provided feedbacks and input to the project.

8. Appendixes

- Abstract to be presented at EAGE-NSG conference on Geophysics for Mineral Exploration and Mining (Barcelona 2016).
- **Upon request:** Article published by Place and Malehmir from Grängesberg seismic data.
- **Upon request:** Poster presented at Seismix in Scotland by S. Heinonen and others.

Draft compiled by Alireza Malehmir
June 14-2016.

Downhole physical properties measurements supporting iron-oxide deep exploration and mining in Blötberget, Sweden

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Several physical properties from borehole geophysics together with laboratory measurements were analysed in order to characterize the mineralized zone in Blötberget, situated in one of the most important mining districts in Sweden. Downhole geophysics provides control over the seismic response we expect to get from a seismic survey in the area, with a strong response from the mineralised zone in rock properties and in reflectivity in the form of synthetic seismic traces. While properties like magnetite content or density are clearly indicative of the ore body, magnetic susceptibility indicates that more lithologies overlap to a certain extent requiring an investigation into other properties as well. Even though magnetite dominates the ore, hematite shows that similar densities will have different response in terms of magnetite content. Full waveform sonic log gives further information on where a strong seismic response would be expected in follow up studies, as well as indicate weak zones in the hanging wall. Information about the rock quality can be obtained this way and correlated with the information about the ore geometry and associated structures. The seismic velocities as well as densely sampled density measurements of the available drill cores will provide further insight into the ore body properties.

Introduction

Bergslagen is one of the most important mineral districts located in south-central Sweden. The area of interest, Blötberget (Figure 1), has historically been economically important for rich and high-quality iron-oxide deposits and is part of the Grängesberg mining area, the largest iron ore accumulation in Bergslagen (Allen et al., 1996). Magnetite and hematite mineralization is often dominant, however, occasionally accompanied by sulphide mineralization of economic sizes. Within a newly formed consortium and after successful experiments presented by Malehmir et al. (2011) and Place et al. (2015), a systematic exploration program started that may be important for both future exploration and mining in the study area. The surveys included reflection seismic, potential field measurements and downhole physical properties measurements with the goal of delineating and better characterizing iron-oxide mineralization at depth. The present study focuses on analysing physical properties data obtained from 6 deep (> 400 m) boreholes together with laboratory measurements of various physical and chemical properties. The logging measurements were primarily aimed at helping the interpretations of geological structures associated with the mineralization and its hanging-wall as well as providing good control on seismic and potential field interpretations in the study area. We show that iron-oxide mineralization should provide strong seismic signal; washed-up amplitude regions in full-waveform sonic data correlate well with fracture systems in the hanging-wall, some of which may have noticeable seismic response in surface seismic data.

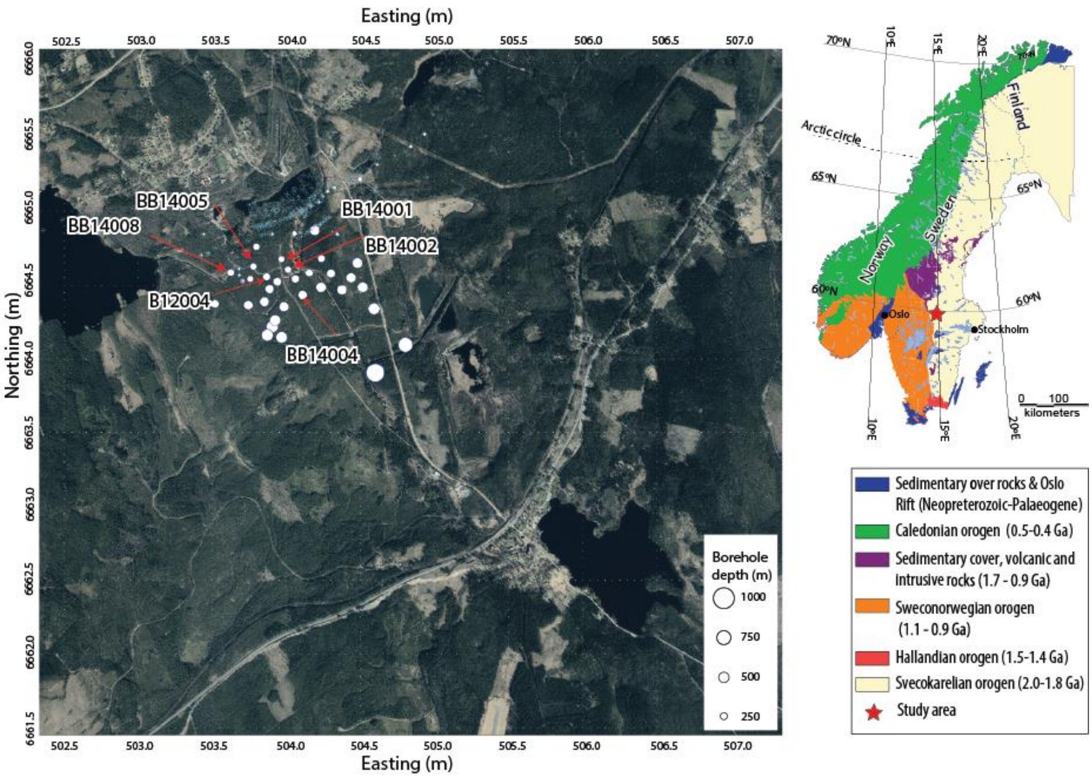

Figure 1 *Aerial photo showing the location of the study area, existing boreholes (marked based on their depth extent) and those that have been logged in this study. The mineralization dips towards the southeast in a moderate angle and is known to extend down to at least 700 m depth.*

Geological setting

Bergslagen region, characterized mainly by volcano-sedimentary rocks, belongs to the Palaeproterozoic (Svecofennian) in the Fennoscandian Shield (Stephens et al., 2009). The host rocks are mainly dacitic to andesitic, feldspar porphyritic metavolcanic rocks (Stephens et al., 2009) with granite-aplite-pegmatite intruded during subsequent metamorphism. The mineralization in Blötberget contains more than 50% iron and is hosted by magnetite mainly and hematite at distinct locations.

Methods

During 2015 and through different field campaigns, a total of six boreholes (Figure 1) were logged with four different probes measuring several physical properties such as magnetic susceptibility, natural gamma, formation resistivity, fluid temperature and conductivity. Full-waveform triple sonic logging was only performed in four them. Laboratory measurements including density, magnetic susceptibility and magnetite content were performed on drill core samples from mainly 320 to 570 m depths where mineralization was primarily observed. A Matlab script was written to link all the physical properties from the 6 measured boreholes to those of core observations and laboratory measurements. Afterwards the relationships between all the observations were examined and analysed by generating synthetic seismograms and various cross plots.

Results

Figure 2 shows the complete downhole measurements for borehole BB14002, down to about 450 m depth. Sonic logging was carried out as well, as indicated by the P-wave velocity; due to display issues the full-waveform is not shown here. According to the identified lithologies, a density log was assumed for the entire length of the hole according to which a synthetic seismogram was generated. Density measurements of all the drill core samples are planned in the near future, thus an updated synthetic seismogram will be generated for all the four holes where sonic logging was performed. Nevertheless, these results were used as a basis for planning and acquiring a 3-km long reflection seismic profile in the down-dip of the known mineralization and will be presented when ready.

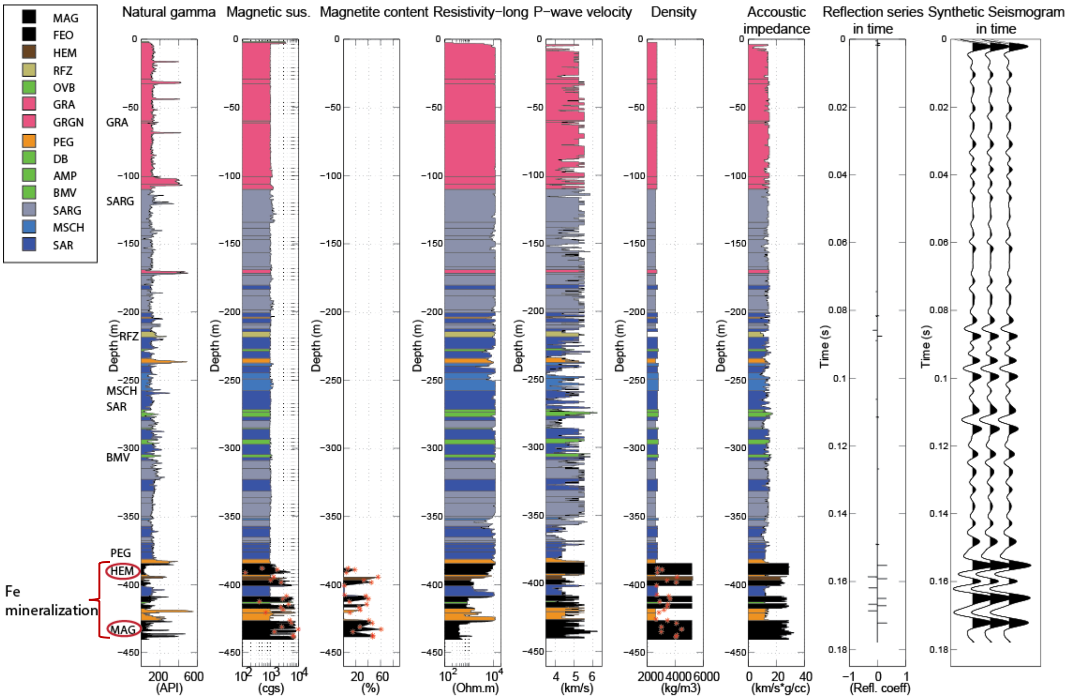

Figure 2 *Physical properties from downhole logging measurements (BB14002) including the synthetic seismogram showing strong seismic response is expected from the mineralized zones but also likely from zones of strong fracturing in the hanging-wall.*

The full-waveform sonic logging in addition to P- and S-wave velocities can provide information about rock quality and sometimes structures hosting the mineralization. We carefully studied amplitude variations in the full-waveform data in conjunction with available RQD and core photos from the samples (Figure 3). This study showed a clear correlation between amplitude washed-up regions of the waveform and places where rocks are strongly fractured. This means it may be possible to automatically extract indirect rock quality information from the full-waveform data by calculating average amplitude of the early arrivals. This will be considered in follow up studies.

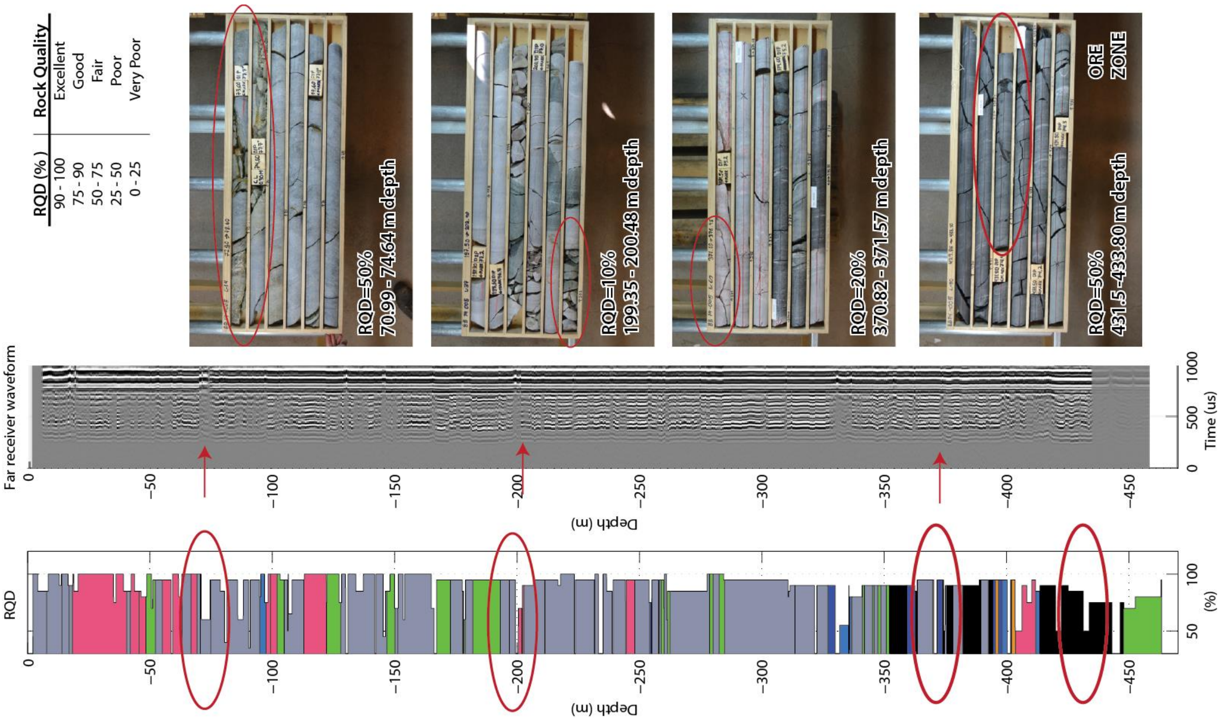

Figure 3 *Correlation between the measured RQDs of the drill core and the sonic log showing zones of washed-up amplitude, exemplified with photos of the drill core (BB14005).*

Figure 4 shows a series of cross plots of the physical properties associated with the mineralization, which may provide some important information about the relationships between the mineralization types (i.e., hematite versus magnetite) and the properties of the host rocks. An overview of the physical properties of several samples from the mineralized zones shows enriched iron mineralization in most of the lithologies, with their magnetic susceptibility overlapping to a great extent. The susceptibility rapidly increases up to 20% magnetite-content after which the increase rate is slower in the logarithmic scale. Rich magnetite zones show susceptibilities on the order of 1000 cgs unit and only at a few places hematite mineralization was apparently intersected. Even though less abundant within the mineralized zone, the hematite samples show lower magnetic susceptibility compared to the magnetite (Figure 4a and 4b), as expected due to hematite's paramagnetic character. Resistivity values from 1000 to 10000 Ohm.m (Figure 4c) cover a wide range of lithologies as well, but the most mineralized rocks (magnetite content over 80%) are not the most conductive, suggesting further investigation of properties like porosity or grain size distribution. A good correlation between susceptibility and density is also observed (Figure 4b) that can be used as a basis for tonnage estimation using both gravity and magnetic modelling methods. In most places where magnetite mineralization is observed gamma radiation is minimal (Figure 4d). Pegmatite intrusions show high natural gamma, potassic rich feldspar likely, sometimes enriched in magnetite and sometimes barren.

Conclusions

Several physical properties from borehole logging measurements were used to study the potential seismic response of the mineralized iron-oxide zones as well structures in the host rock. Given the high density and seismic velocity of the mineralized zones, a strong seismic response can be anticipated from surface seismic data if the survey is properly designed and acquired. The mineralization is anticipated to moderately dip, thus recording the seismic signal is highly feasible. Density and susceptibility relationships may support joint inversion of gravity and magnetic data for magnetite tonnage estimations, which will be considered in the near-future studies. Amplitude washed-up regions in the full-waveform sonic data showed a great correlation with low-quality rocks illustrating sonic logging's potential for mine planning and rock-quality estimations.

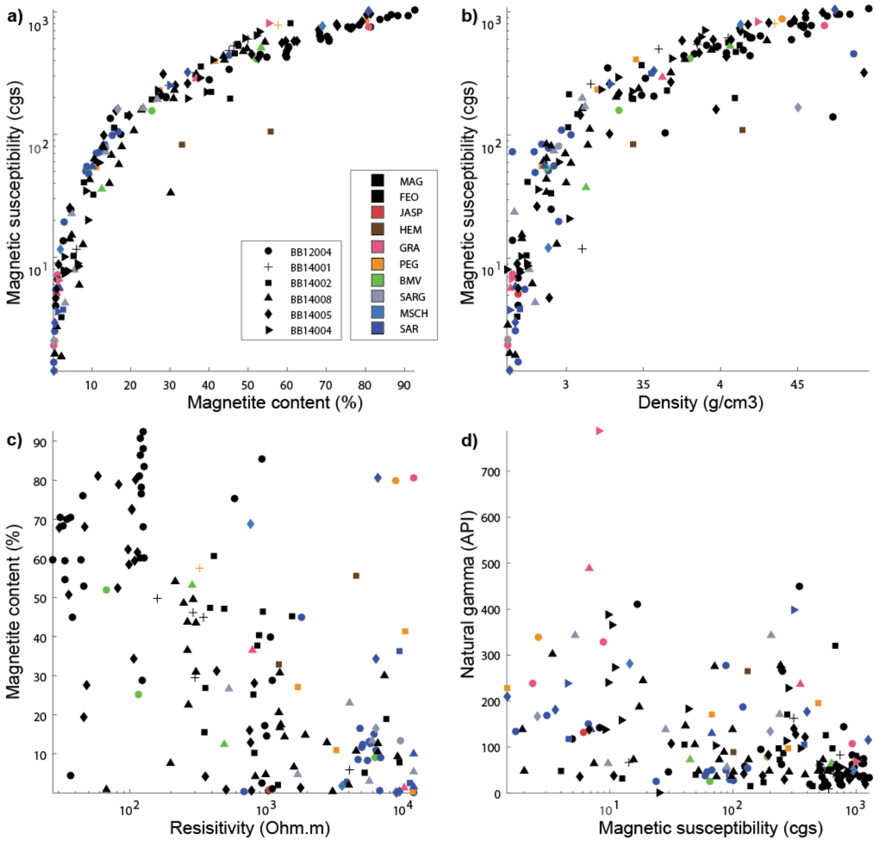

Figure 4 *Cross plots of* ***(a)*** *magnetic susceptibility versus magnetite content,* ***(b)*** *magnetic susceptibility versus density,* ***(c)*** *magnetite content versus formation resistivity and* ***(d)*** *natural gamma versus magnetic susceptibility. These plots suggest that the mineralization occurs primarily due to magnetite but it is overlapping a wide range of rocks.*

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