3D magnetic susceptibility model of a deep iron-oxide apatite-bearing orebody incorporating borehole data in Blötberget, Sweden

M. Bastani[1,2], M. Sadeghi[1], A. Malehmir[2], S. Luth[1], P. Marsden [3]
1. Geological Survey of Sweden, Uppsala, Sweden, mehrdad.bastani@sgu.se; martiya.sadeghi@sgu.se; stefan.luth@sgu.se
2. Department of Earth Sciences, Uppsala University, Sweden, alireza.malehmir@geo.uu.se
3. Nordic Iron Ore, Sweden, paul.marsden@nordicironore.se

BIOGRAPHY

Mehrdad Bastani has a PhD in geophysics. He works at SGU with processing and modelling of large geophysical datasets. He is also an adjunct professor at the department of Earth Sciences, Uppsala University.
Martiya Sadeghi has a PhD in Economic geology. He has experience over 20 years in field mapping, spatial data analysis, geochemical exploration and ore deposit modeling. He is AE to the Journal of Geochemical Exploration and GEEA.
Alireza Malehmir is a professor of applied geophysics at Uppsala University. He has over 15 years of experience in 2D/3D seismic imaging in hard rock environment. He is the coordinator of the H2020 Smart Exploration project and vice-chair of the Near Surface Geoscience Division of EAGE.
Stefan Luth has a PhD in structural geology and works with field mapping as well as 3D modelling of ore deposits in a regional context.
Paul Marsden is graduate geologist and chartered engineer in mineral processing. He is an experienced senior executive with a wide range of technical and commercial skills, comprehensive understanding of exploration, mine development and the iron ore markets.

SUMMARY

We have processed and modelled in 3D available airborne magnetic data flown over the Blötberget iron-oxide deposit in central Sweden. 3D magnetic susceptibility models were then compared to the existing borehole information, downhole logging data and ground geological observations. Use of such information in the 3D inversion of the magnetic field data in the form of a reference model has considerably improved the 3D model in resolving the deeper parts of the iron-oxide orebody as well as the geometry of nearby geological structures. Unconstrained inversion results, however, do not resolve the true dip and depth extension of the iron-oxide orebody.

INTRODUCTION

2D and 3D models either from forward modeling or inversion of geophysical data such as gravity, magnetic, reflection seismic and EM have provided detailed images

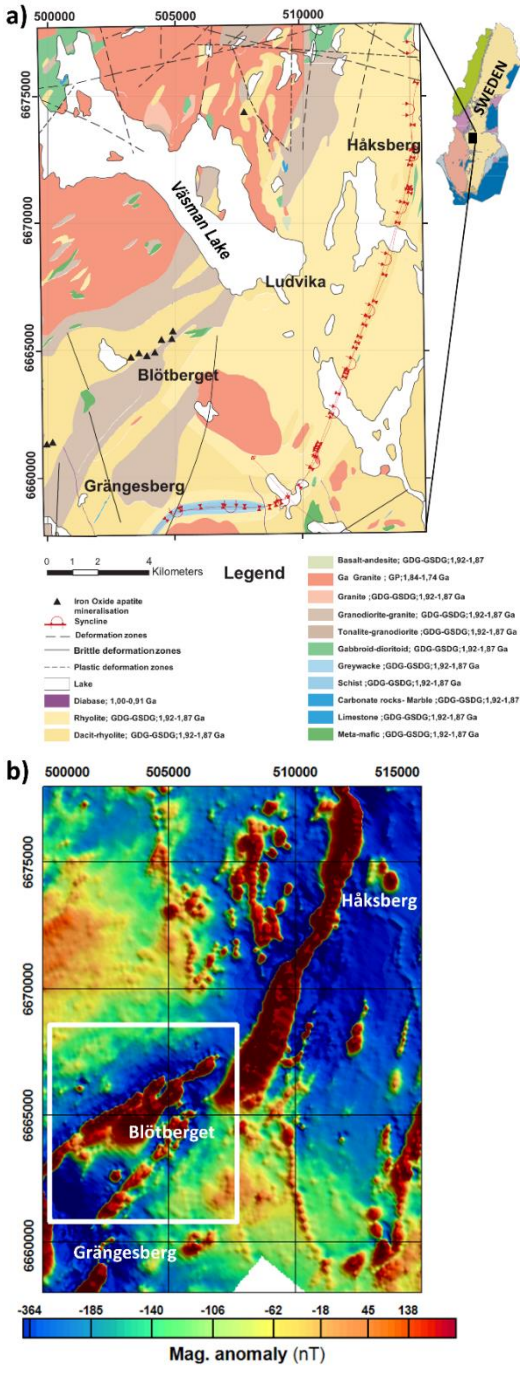

Figure 1. a) Simplified geological map of the study area showing the locations of major iron-oxide deposits in the Ludvika mining area from Grängesberg to Håksberg. b) Residual magnetic field anomaly map from the airborne data acquired by SGU. Maps courtesy of SGU.

of crustal structures from a few meters down to as deep as tens of kilometers (England and Ebbing, 2012; Arora et al., 2012; Hedin et al., 2014; Cherevatova et al., 2015; Kamm et al., 2015). In the inverse modeling, measured data is used to determine the geometry and physical properties of the geological structures. The models are the result of an iterative process that is mainly governed by data quality and the regularizations used. Leliéver et al. (2009) discuss the importance of including geological knowledge in the inversion of geophysical data as constraints or a-priori information. The a-priori knowledge is usually gained by the laboratory measurements of the physical properties of rock samples, or downhole logging of for example magnetic susceptibility, or in some cases the known values extracted from areas with similar geological settings.

In the frame of an EU-funded project, Smart Exploration, existing geophysical and geological data at selected sites are reprocessed and modelled. The data sets are mainly acquired in brown-fields, i.e., close to active or abandoned mines. The main idea is to apply the state-of-the-art and more sensitive tools to the existing data to explore for new resources and where necessary acquire new data with instruments developed within the project.

In this study we present the results from 3D modeling of an airborne magnetic field dataset collected by the Geological Survey of Sweden (SGU) in parts of the historical Bergslagen ore district of Sweden in 2016-2017 in the frame of Bergslagen project. We show an example from the Böltberget iron-oxide apatite-bearing mine, where a comparison is made between the 3D susceptibility models from constrained and unconstrained inversions. The constraints used are from the existing boreholes drilled through the orebody.

GEOLOGICAL SETTINGS

The study area is situated in the ore district of Bergslagen in south-central Sweden extending from Grängesberg in the south to Håksberg in the north (Figure 1a). Geologically, Bergslagen belongs to the Svecokarelian orogen in the Fennoscandian Shield. Metamorphosed volcano-sedimentary rocks of Palaeproterozoic age (1.85-1.80 Ga) dominate the host rocks (Figure 1a). Metavolcanic rocks including feldspar porphyritic rocks show close spatial association with iron-oxide mineralisation in the area. Most of the rocks show metamorphic grades ranging from medium to upper amphibolite facies. Post-mineralisation intrusion of granite-aplite-pegmatite and metamorphism severely resulted in the deformation of these rocks (Allen et al., 1996; Ripa and Kübler, 2003). The iron-oxide mineralisation types in the area are of banded iron formation (BIF), skarn-type and apatite-rich (likely magmatic) deposits. The latter deposits account for more than 40% of the iron ore produced in Bergslagen (Magnusson, 1970; Stephens et al., 2000). Our study area, Blötberget is known for its high-quality iron-oxide sometimes apatite-bearing deposits. Malehmir et al. (2017a) show the results of their study using several geophysical datasets including high resolution reflection seismics, yielding the depth extent of the mineralization to 800–850 m depth in a moderately dipping, approximately 45-50 degrees, towards the SE. A follow-up study of the same high resolution reflection seismics by Markovic et al. (2019) suggests that the mineralization may extend down to 1200 m depth. UAV-based magnetic field data collected by Malehmir et al. (2017b) have also been used to show how distinctly two sets of mineralized horizons (magnetite-rich and hematite-rich) are notable.

AIRBORNE DATA

SGU acquired airborne magnetic field data using a fixed wing system with a 10 m sampling along flight lines of 200 m spacing, and at a nominal height of 60 m above the ground surface. The measured data are processed and micro-levelled using standard tools. The residual magnetic field anomaly, shown in Figure 1b, is then calculated using the 1965.0 DGRF model. Considerably high magnetic anomalies (as high as 5000 nT) correlate well with the known iron-oxide deposits, for example at Blötberget and Håksberg. The extremely magnetic high west of the city of Ludvika that is partly located under the lake Väsman is of great interest for the Nordic Iron Ore (NIO) mining company. The area marked with a white square (Blötberget) is chosen for 3D modelling of the airborne data as it can offer a wealth of borehole and petrophysical property data. It includes a strong magnetic high caused by the well-known iron-oxide orebody (>50% magnetite content). Choice of smaller area facilitates the use of smaller cell sizes in 3D and consequently modelling of the ore geometry with a higher resolution. This in turn provides a firm ground for comparison between the ore-model derived from the existing, considerably dense arrangement of boreholes in the mine area and the 3D susceptibility model.

3D INVERSION

The residual magnetic field data were modelled in 3D using the VOXI Earth modelling program developed by Geosoft®. The model cells have horizontal dimensions of 50 m by 50 m with a logarithmically increasing thickness towards depth. Parameters such as lower and higher bounds, directional smoothing, starting and reference models can be adjusted. We show two models from the 3D inversions, one with no constraints and the other one with a reference model built from the depth information extracted from the lithological logs mapped in the borehole provided by NIO. The petrophysical data are measured by downhole logging and reported by Maries et al. (2017). For the horizons with iron-oxide mineralisations we have assumed an average magnetic susceptibility value of 0.5 (SI units) extracted from the downhole logging data.

RESULTS

The 3D susceptibility models from the unconstrained and constrained inversions are shown in Figure 2a and 2b,

respectively. The models are from the surface down to a depth of about 3000 m. The models fit the measured data equally well with the high susceptibility features coinciding with magnetic highs caused by the mineralization.

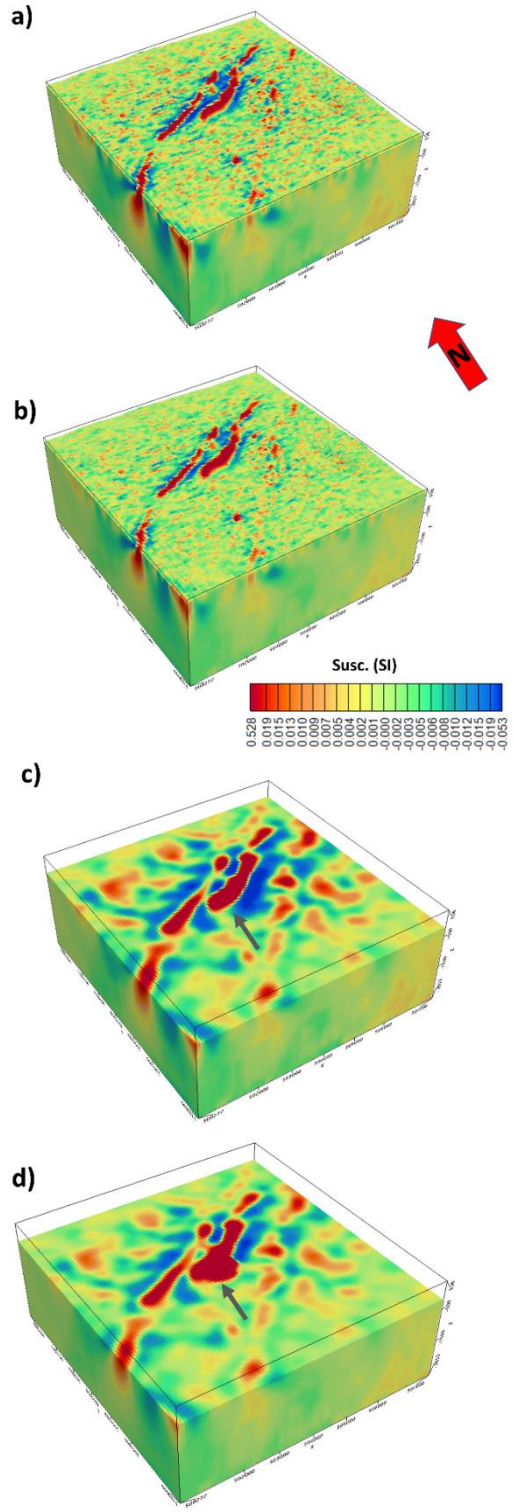

Figure 2. Susceptibility model from 3D inversion of residual field data in the area marked by the white frame in Figure 1b. a) Model with no constraints. b) Model with constraints using borehole information. c) Same model as in (a) but clipped to elevation -250 m. d) Same model in (b) but clipped to elevation -250 m a.s.l. The black arrows in (c) and (d) point to the area where the two models show significant differences (dip component of the mineralization).

In order to demonstrate the differences between the two models, mainly because of the applied constraints using the a-priori susceptibility model, we clipped the upper parts down to -250 m elevation (a.s.l.) and present them in Figures 2c and 2d. The black arrows in both figures point to the area where the models differ most which is mainly because of the use of borehole information (reference model). In the model shown in Figure 2d a SE-dipping high susceptibility zone is resolved, which is related to the existing orebodies confirmed by drilling data.

Figure 3 shows the orebody model obtained from the borehole data together with the iso-susceptibility surface for values larger than or equal to 0.05 SI. The green and red bodies represent two distinct mineralized zones, one hematite and another magnetite bearing, respectively. The iso-susceptibility surface shown as a grey mesh, is taken from the constrained 3D magnetic model. The iso-surface better matches the orebody model in terms of geometry and provides confidence on the existences of mineralization at least down to 800-900 m depth at which only historical data were used to build the orebody model. The susceptibility model suggests that the orebodies may continue to deeper depths of about 1000 m (see also Markovic et al., 2019). The iso-surface also resolves a large ore volume in the NW part of the orebodies modelled by NIO. In that area no deep boreholes exist to constrain or confirm the modelling.

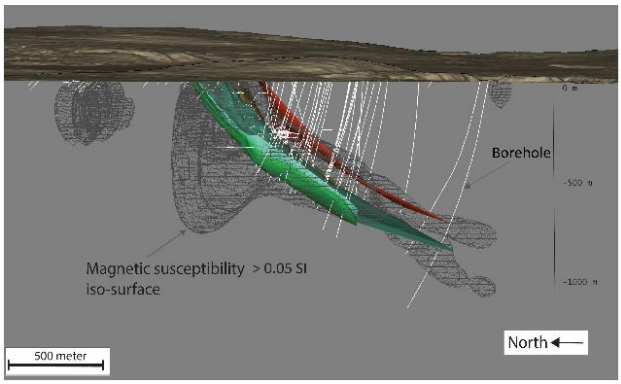

Figure 3. Comparison between the iso-susceptibility surface (values larger than or equal to 0.05 SI) and orebody models using just the borehole data. The white lines show the existing boreholes used to constrain the model. The red and green surfaces represent the magnetite and hematite rich ores, respectively.

CONCLUSIONS

Unconstrained 3D inversions of airborne magnetic data using various regularization parameters were tested to

model an iron-oxide orebody. The resulting models do not match the geometry of orebody at the parts known from the borehole data. They do not either resolve the deeper parts of the orebody properly.

The susceptibility model from the 3D inversion of the same dataset incorporating the borehole information in the form of reference model show a significant improvement in imaging the orebody and correlates very well with the orebody model constructed independently based on just the borehole data. Moreover, compared to the unconstrained models, the use of constraints at the borehole locations has limited the depth extent of high susceptibility zones in the vicinity of the boreholes. This means that some of the artefacts imposed by smoothing regularization are eliminated in the final models.

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