# MAGNETIC CONTRIBUTIONS OF MINERALS AT THE SURFACE AND AT DEPTH IN THE CRUST: COMPARING ANOMALY MAPS FROM AEROMAGNETIC AND SATELLITE DATA FROM SCANDINAVIA

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## ABSTRACT

The mineralogy and magnetic properties of crystalline rocks in southern Scandinavia can be correlated to high-resolution aeromagnetic maps. In particular, Proterozoic granulite-facies metamorphic and igneous rock bodies, with certain oxide minerals have high remanent intensity, and commonly have high coercivity and thermal stability, with corresponding Koenigsberger ratios from 5 to > 20. We have explored the contributions to anomalies the different minerals at the surface and try to predict their behavior deeper in the crust. The new high-resolution global-crustal-field anomaly maps, produced from magnetic data of the CHAMP satellite mission, now allow for more detailed quantitative geological studies of the Earth's deeper crust. To model these anomaly maps, a vertically integrated susceptibility grid is computed using geologic maps, laboratory susceptibility values of the exposed rock types and crustal thicknesses from a global seismic model. In addition, a remanent magnetization model grid is generated using the intensity and magnetization vector information for the same region. This technique is applied to compute a crustal magnetization model for the Swedish Proterozoic granulite terrain where we have ample magnetic property data and very good control on geology. Magnetic anomaly maps for total intensity are computed at an altitude of 50 km by two different methods, downward-continuation of CHAMP MF4 magnetic data and upward-continuation of aeromagnetic data over the same region. This offers the opportunity to explore the magnetic signature of these crustal rocks directly from the surface to very high altitudes.

## 1. INTRODUCTION

Deep crustal rocks, if magnetic, are usually assumed to contain MD magnetite and the resulting magnetic response of the body to be an induced magnetization. It is important that remanence, in addition to induced magnetization, be considered in areas where high-coercivity phases, such as members of the hematite-ilmenite solid solution hemo-ilmenite (hematite with ilmenite lamellae) and ilmeno- hematite (ilmenite with hematite lamellae) are present. These phases are capable of acquiring a large and stable natural remanent magnetizations (NRM).

## 2. GEOLOGY

The Swedish Granulite Region (SGR) is part of the Sveconorwegian belt of the Baltic shield, and consists of high-grade metamorphic rocks [*1*]. It lies west of the Protogine zone, which is the thrust front of the Sveconorwegian orogen against older stable Baltica, and it lies east of the Mylonite Zone that brings the amphibolite-facies rocks against the pyroxene granulites. Thermobarometry and geobarometry indicate peak metamorphic temperatures of 770°C, and pressures from 7.5 to 10.5 kbars [*1, 2*]. The granulite-facies metamorphism is considered to have taken place at approximately 975 Ma [*3*]. The SGR granulite crust is approximately 40 Km thick at the eastern side [4].

## 3. OXIDE MINERALOGY IN SGR

In the mafic granulite rocks ilmeno-hematite (an exsolved Ti-hematite) is the dominant oxide. Optical observations indicate the ilmeno-hematite grains are well crystallized and range from ~400 µm to 20 µm with exsolution lamellae dividing the grains up, such that the effective grain size is single domain size. Much less abundant are discrete grains of ilmenite with hematite exsolution lamellae (< 0.5%). Homogeneous magnetite grains 1- 2% are also present. Magnetite is common in both the amphibolite and granulite facies rocks in the region. Discrete multidomain (MD)- size magnetite grains are typically 200 to 50 µm in diameter. Discrete magnetite grains are relatively free of microstructures, but contain rare oxidation-exsolution lamellae of ilmenite and minor spinel needles. Figure 1 shows an electron backscatter image. Highest atomic number magnetite is white, lower atomic number hematite is light gray, still lower atomic number ilmenite is dark gray, and surrounding silicates and cracks are black**.**

An aeromagnetic survey recently conducted by the Swedish Geological Survey shows numerous positive and negative anomalies over the SGR. The high abunda-

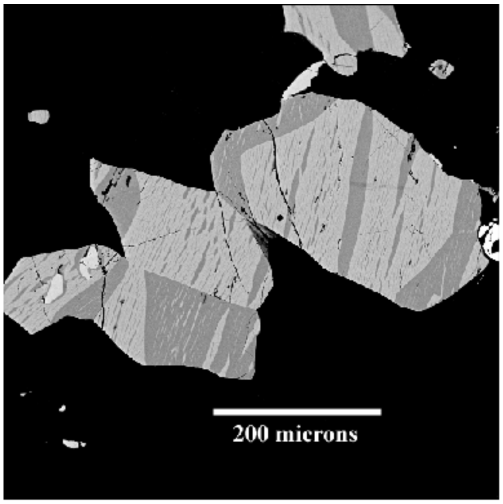
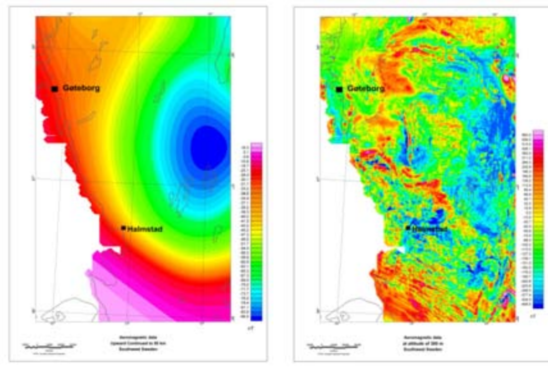



*Figure 1: electron backscatter image of ilmeno-hematite with multiple generations of ilmenite and hematite lamellae. From the TEM studies we know that the exsolution lamellae continue down to a few nanometers in size [5].*

nce of magnetite in the region shows as magnetic highs with positive magnetic anomalies. Numerous magnetic low regions are areas where there is abundant titanohematite and MD magnetite. Over 300 samples were measured for natural remanent magnetization and susceptibility. The mafic granulite samples had significant NRM values (1-20 A/m). Susceptibility values are also high, 2-3 $*10^{-2}$ SI. Though considerable MD magnetite is present the remanent vector is much larger and nearly antiparallel to the present day field. Rocks of similar age in the Rogaland province of Norway have similar rock magnetic properties though there the dominant oxide is a hemo-ilmenite [5-9]. A similar study made in the Adirondacks Mountains, NY over a microcline gneiss show ilmeno-hematite as the dominant oxide [10]. This rock unit also showed remanent dominated magnetic anomalies with Q values up to 100. In the SGR the crust is composed of uplifted granulite rocks, which likely have similar properties to the samples collected at the surface. We are using this area to compare upward continued aeromagnetic data with downward continued satellite data to explore the possibilities of the SWARM data, and to develop more robust methods for that data.

## 4. UPWARD CONTINUATION OF AEROMAGNETIC DATA

Here we present the upward continued low altitude fixed winged aeromagnetic data, flown at 30 m elevation. The data was upward continued to 50 km (Fig. 2a) in order to make a comparison with the satellite data. The upward continuation was performed using Geosoft software (standard FFT techniques). Although the grid was expanded before upward continuation, severe edge effects exist (perhaps relating to both inherited methodological problems and data edges). This will be improved in future by incorporating more data. Comparing the low-level aeromagnetic data (Fig. 2b) with the upward continued data (Fig. 2a) shows that a prominent magnetic low exist in both data sets, testifying to the regional significance of this low. We think that the low can be explained by measured remanence values of outcropping rocks.



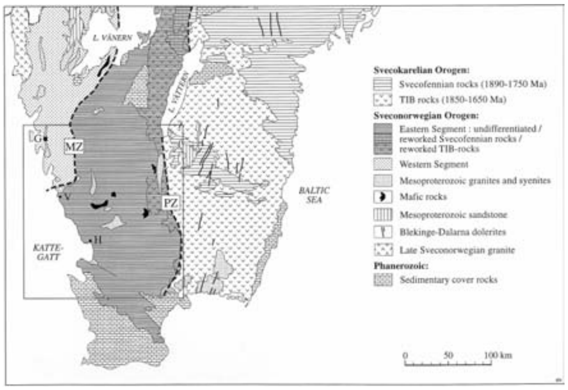

(a) (b)

*Figure 2: High-resolution aeromagnetic map of southern Sweden (b) and 50 km upward continued map (a) to help evaluate the nature of the negative anomaly over much of the SGR region in southern Sweden.*

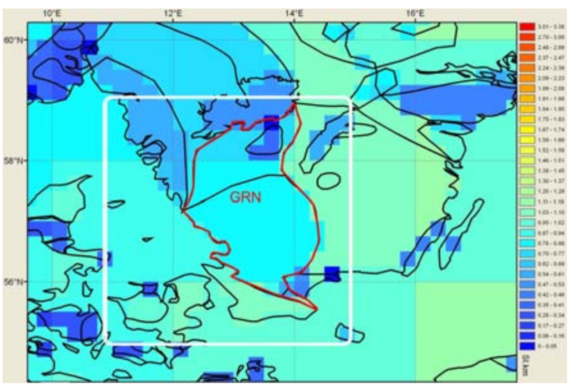
## 5. MODELLING

A GIS based forward modelling technique developed by Hemant and Maus [11] is used to model the magnetic anomalies derived using satellite data. Considering geological and tectonic information for different geological provinces and laboratory susceptibility values an average susceptibility value is computed. Finally, taking its product with the known seismic crustal thickness, a vertically integrated susceptibility (VIS) is derived. A similar study is undertaken here for Sveconorwegian region of the East European platform shown in Figure 3(a). All known rock types from this region is compiled and using their maximum volume susceptibility value an average maximum susceptibility is computed and assigned to different terrains. A factor of 0.55 is used to normalise this maximum average susceptibility value [12]. In addition, the lower crustal susceptibility value is enhanced by a factor of 1.2 for the Archean and 1.6 for the post-Archean provinces. The VIS model for Sveconorwegian region is shown in Figure (3b). The regions marked as GRN in Figure (3b) are granulites extending from Lake Vänern in the north to the Phanerozoic sedimentary cover in the south (Fig. 3a). To the east of this block lies the late

Sveconorwegian granites. The TTZ (Tornquist-Teisseyre Zone) is believed to extend below the Baltic Sea on the west [13]. Mylonite Zone (MZ) and the Protogine Zone (PZ) mark the eastern and western boundaries of this granulite zone (Fig. 3a).




(a)



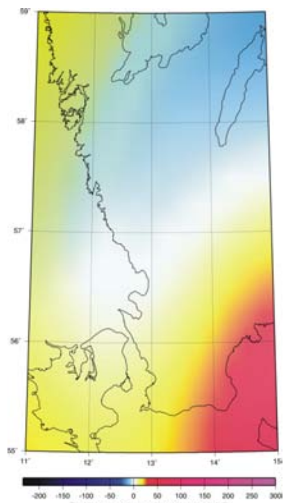

(b)

*Figure 3: (a) Geological map of the Sveconorwegian SGR region, East European platform. The inset shows the major tectonic provinces of this region. (b) Vertically integrated susceptibility value computed based on the geological information of the tectonic provinces shown in (a). The observed and the predicted magnetic field anomaly maps shown below (area marked in white).*

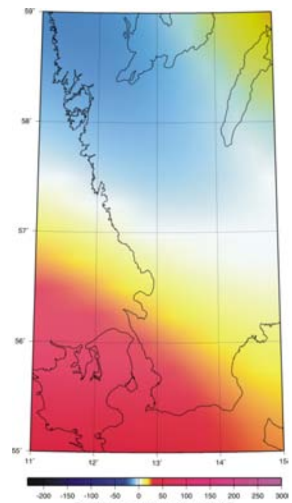
## 6. RESULTS AND INTERPRETATION

The observed scalar magnetic anomaly shown in Figure (4a) is produced by downward continuing MF4 model to an altitude of 50 km altitude [14]. The scalar magnetic anomaly map predicted at 50 km altitude using the VIS model (Fig. 3b) is shown in Figure (4b). Induced magnetisation is considered as the source of the anomaly. A comparison of Figure (4b) with the observed anomalies (Fig. 4a) reveals that the observed low anomaly over granulites (marked with GRN in Figure 3b) is reproduced well. The high magnetic anomaly in the southeast and the low observed in the southwest of the granulite region (Fig. 4a) is however, not reproduced (Fig. 4b). This suggests that there is a need to investigate the effect of VIS contrast due to the geology beneath the Baltic Sea in the east and the possible extension of TTZ zone in the west below the Baltic Sea.

In the north, the observed NE-SW trending weak magnetic anomaly feature partly disagree with the predicted anomaly patterns which however, appear to trend NW-SE. The discrepancies between the two maps highlight the limitation of surface geology to explain the observed anomalies in this region. This suggests that we need to modify VIS by incorporating local geological and geophysical information, especially the magnetisation content and composition of the lower crust in this region.




(a)




(b)

*Figure 4. (a) Observed MF4 scalar magnetic anomaly calculated at 50 km altitude. (b) Predicted scalar magnetic anomaly calculated at 50 km altitude using VIS model shown in Figure 3b.*

## 7. SUMMARY

This exercise was carried out to explore the contribution of magnetic properties of upper crustal rocks to the aeromagnetic and satellite data. The region is characterised by uplifted granulite-grade rocks and a large collection of petrophysical measurements and detailed information on the petrology, mineralogy and geology is available. The measured low susceptibility and high NRM values over all explain the nature of the negative aeromagnetic anomaly. The comparison of the upward continued aeromagnetic data with the downward continued satellite derived magnetic anomaly over southern Sweden shows a moderate to good agreement but partly disagrees with the predicted magnetic anomaly map derived based on known surface geological information. Future work is needed to evaluate the contribution of upper and lower crustal granulites in southern Sweden to satellite measurements. The present resolution of the satellite derived anomaly maps, having reliable wavelengths greater than 400 km, to some extent prevents us to make a more detailed comparison with the low-altitude aeromagnetic anomaly maps. With high resolution crustal magnetic anomaly maps to be expected from the upcoming Swarm mission certainly would not only help in alleviating some of these problems but would allow for a better understanding of the geology, rheology and composition of the crust at mid- to short wavelengths.

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## 8. REFERENCES

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