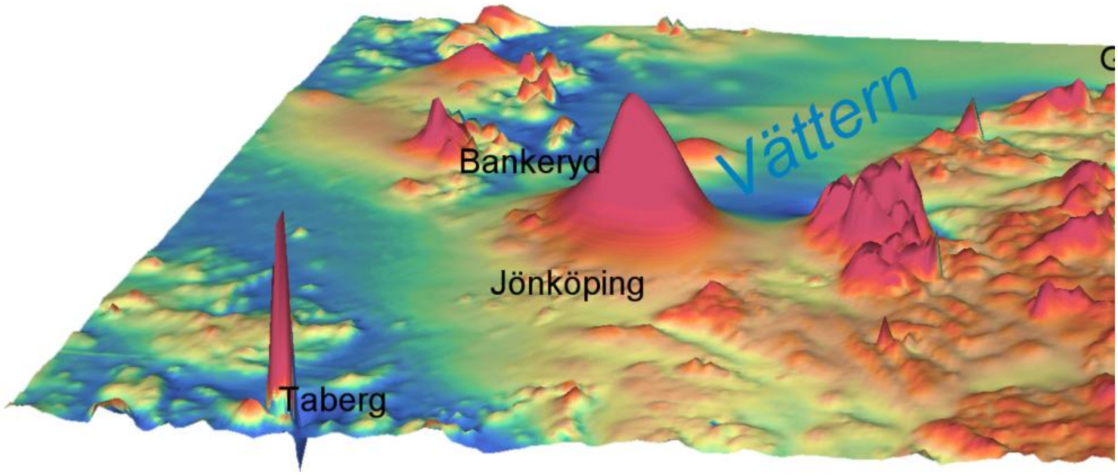
The large magnetic anomaly in Lake Vättern, Sweden

February 2012

Leif Kero, Sven Aaro, Dick Claeson, Johan Jönberger,
Mats Wedmark & Sören Byström

SGU-rapport 2012:4



SGU
Sveriges geologiska undersökning
Geological Survey of Sweden

Abstract

The bell-shaped magnetic anomaly in the southern part of Lake Vättern was discovered after airborne geophysical surveys in 1980. The smoothness of the magnetic anomaly indicates a deep-seated source. A small gravity survey along a short east-west profile over the magnetic centre was carried out on ice during the winter 2010. The magnetic anomaly is situated in a large almost north-south oriented graben structure.

For the forward modelling we have used measurements on rock samples from SGU's mapping projects in the area around Lake Vättern. It should be emphasized that only a few samples from some old mines and certain gabbroic intrusions have sufficient magnetization and density to explain the observed anomalies. In particular, a strong remanent magnetization in an almost vertical direction is required in order to explain the magnetic anomaly.

Filtering of the gravity data has been necessary in order to assess the density variation in the crystalline bedrock down to several kilometers depth, and of the thinner overlying clays and gravel as well as down faulted Neoproterozoic sedimentary rocks.

Forward modelling using the petrophysical properties of ore samples from the area have given a plausible model in the form of an elliptical 2.7 by 3.2 km wide disc, with a thickness of 0.5 km and a high induced magnetization (susceptibility around 0.4 to 0.6 SI units). A strong remanent magnetization of at least 40 to 60 A/m is necessary. The remanent magnetization must be steeply dipping to the north. The required density is about 3700-3880 kg/m^3. These petrophysical values are found in some of the magnetically oriented samples from the northern pit of Taberg. In the samples with a strong remanent magnetization the inclination of the field is often however not very large.

In some cases the high-magnetic gabbros of Inglamåla and Rymmen, of which Inglamåla has been mined in historical time, have sufficiently high magnetization and density for a good fit to the observed geophysical anomalies. These samples however represent only 15-20% of a crystallized basic magma chamber and therefore the measured gravity surplus is much too low. Futhermore the size of the modelled basic magma chambers indicate that there is more likely to be magmatic layering in them, and that the magnetite is therefore not homogenously distributed throughout such bodies. A differentiation of magnetic properties is common in gabbros. Thus a differentiated gabbroic intrusion is possible.

Introduction

During routine airborne geophysical measurements carried out by the Geological Survey of Sweden (SGU) in 1980 attention was drawn to a pronounced magnetic anomaly in the area of southern Lake Vättern. The smooth character of the anomaly indicates that it is caused by a relatively deep-seated strongly magnetized body under the lake. The investigated area is situated in the northwestern part of province Småland.

There has been some speculation as to whether the origin of the anomaly is related to the large tectonic zone, the so called Protogine zone, and other magnetic structures in the area. A military origin has also been discussed – and excluded after contacts with the Swedish army. Could it be alkaline rocks like in the Norra Kärr (Eckermann, 1968), or an ore deposit like the Taberg (Sandecki, 2000, Larsson & Söderlund, 2005), or a gabbroid intrusion similar to gabbros in the surrounding area (Claeson, 2001)?

The geological and geophysical work carried out in the area, both before and after 1980, has only focused on the upper surface, the Neoproterozoic sedimentary rocks and the older crystalline bedrock. Regional scale bedrock mapping was carried out by SGU in the counties of Kalmar, Jönköping and Kronoberg over a number of years in the late 1990s and until 2009 resulting in bedrock maps and descriptions of the bedrock in the region. In the description for the county of Jönköping (Wik et al. 2006) it is mentioned that the cause of the magnetic anomaly under Lake Vättern lies at the depth of about 1500 meters.

SGU and, in particular, the Lantmäteriet (National Land Survey) has a long term aim to carry out gravity surveys covering the larger lakes in Sweden. There is seldom ice on the southern part of the Lake Vättern and relatively thick ice is essential for accurate measurements. In the late winter of 2010 however gravity measurements were possible on Lake Vättern. Sixteen stations were measured on the lake along an east-west profile crossing the maximum of the magnetic anomaly. With these gravity measurements, it is possible to constrain some of the solutions given by the magnetic interpretations.

Magnetic, gravity and petrophysical measurements by the Geological Survey of Sweden

The magnetic and gravity fields give insights to the deeper parts of the bedrock as well as to lithological contacts, shear zones, fractures and folds. By determining the petrophysical properties of the constituent rocks the location, size, shape, and orientation of formations can, in some cases, be revealed. For Proterozoic and older rocks the best results will be given by integrating both magnetic and gravity data with information from petrophysical measurements and bedrock mapping, as well as with electromagnetics (EM) and seismic data. In Sweden, like other countries where most of the bedrock is covered with till, swamps or lakes, the geophysical information is of crucial importance for meaningful bedrock mapping and particularly for exploration.

SGU started systematic airborne magnetic measurements in the northern part of Sweden as part of a large ore-mapping campaign in 1960. Airborne radiometric measurements started in 1968 and EM measurements were introduced in 1972. Airborne surveys have been carried out at low altitude with a ground clearance of 30 m until 1994 and 60 m after that. The magnetic field is measured every c. 10 m (earlier 40 m) with 200 m separation between the flight lines.

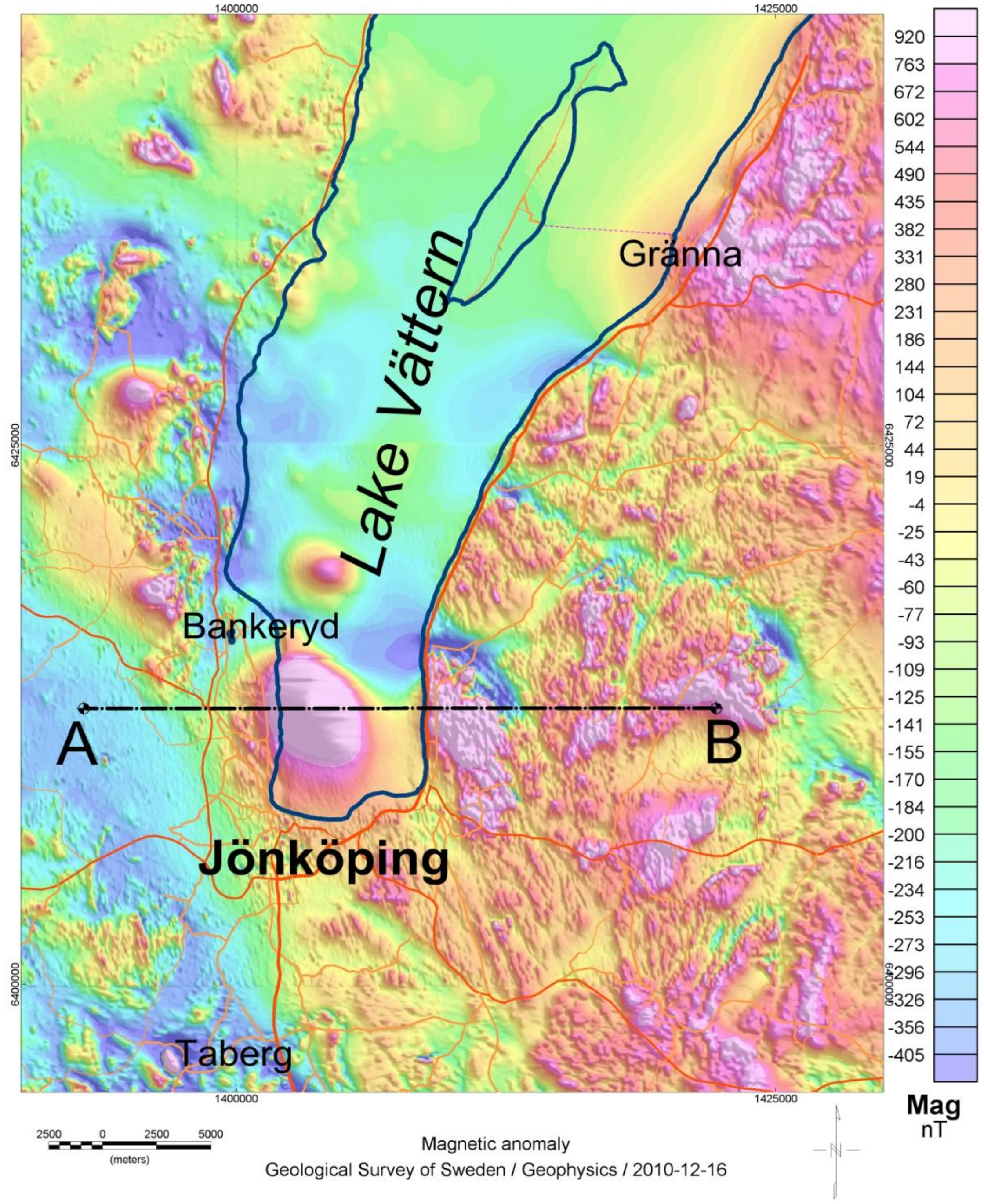
The magnetic total intensity anomaly map over the southern part of Lake Vättern area is based on measurements using a flight line separation of 200 meters and 40 meters sampling distance along the flight lines (figure 1). The magnetic field is reduced to anomaly values using the Definite International Geomagnetic Reference Field 1965.0 (DGRF 65) as a reference field. The measurements over the Lake Vättern area were carried out in 1980.

Systematic gravity measurements started in the 1950’s, in the ore-bearing regions in the northernmost part of Sweden. Petrophysical measurements began in the 1960’s. Today, systematic regional gravity measurements are normally made with a distance between the gravity stations of 1 to 2 km, but in areas with few outcrops and with an interesting magnetic signature a station distance of 0.5 to 1.5 km is used.

The gravity survey over the magnetic anomaly was done March 17, 2010, on the ice of Lake Vättern. Gravity readings as well as water depth determinations were made at sixteen stations with a rather large station separation, c. 500 m. Unfortunately no gravity data exists on the lake north and south of the magnetic anomaly. The gravity anomaly map (figure 2) shows terrain-corrected Bouguer anomalies referred to the International Gravity Standardisation Network 1971 (IGSN71) and the Gravity Formula 1980.

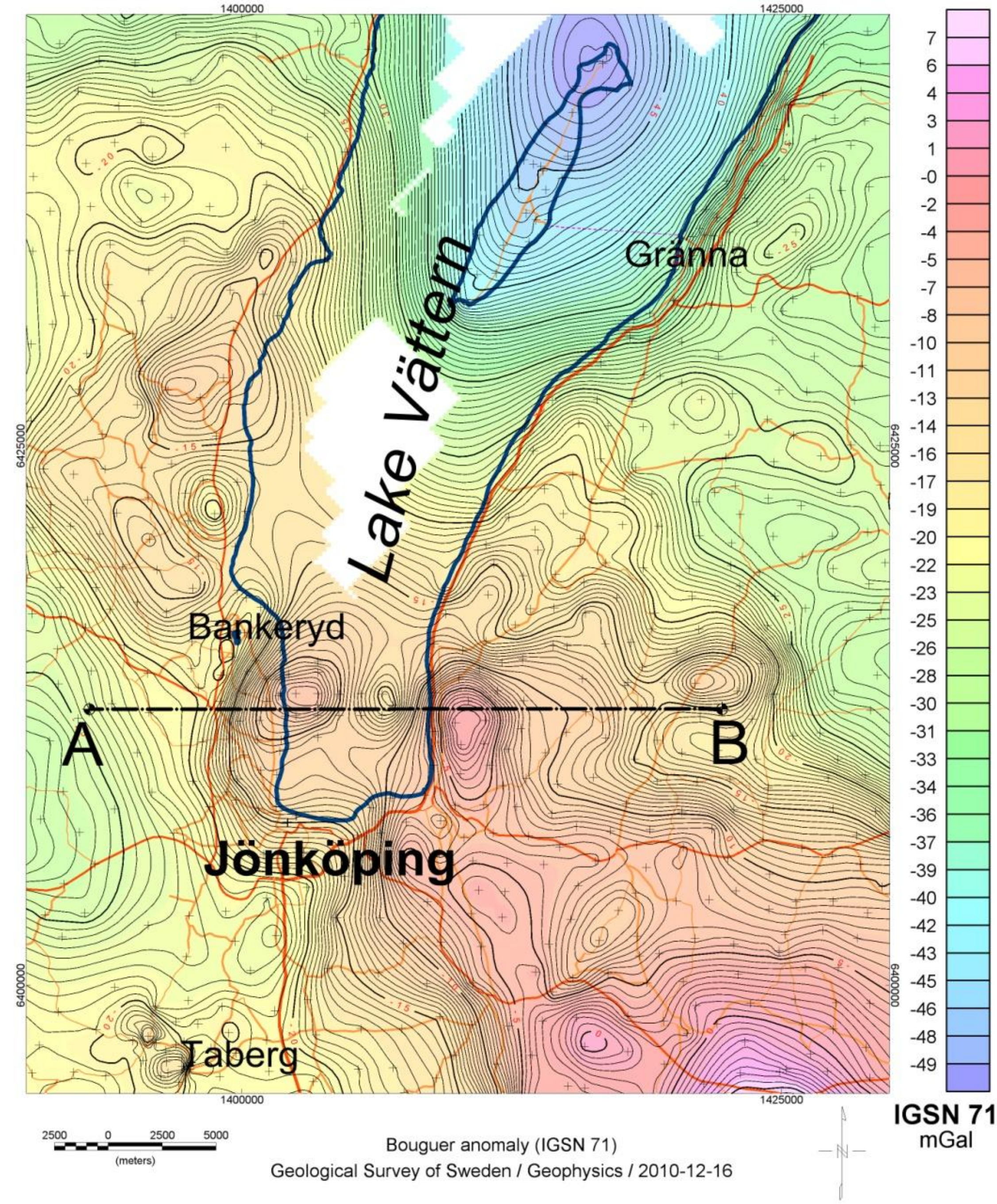
For a more detailed description of the various airborne geophysical measurements and ground gravity measurements carried out by SGU the reader is referred to Aaro and Byström (2000 and 2001).

The main geophysical databases at the Geological Survey of Sweden (SGU) contain data from airborne measurements, gravity measurements and petrophysical measurements, as well as magnetic observatory data. About 90% of the land area in Sweden is covered with airborne magnetic data and the gravity database contains around 181 000 regional gravity stations. The petrophysical databases contain density, magnetic susceptibility, and Q-value (Königsberger ratio i.e., the remanent magnetization divided by the induced magnetization) information from about 80 000 samples, in addition to some radiometric information from in-situ and laboratory measurements.



Magnetic anomaly
Geological Survey of Sweden / Geophysics / 2010-12-16

Figure 1. Magnetic anomaly map over the southern part of the Lake Vättern area. The airborne low altitude (ground clearance 30 meters) survey was carried out in 1980. The profile used for forward modelling is marked A-B.



Bouguer anomaly (IGSN 71)
Geological Survey of Sweden / Geophysics / 2010-12-16

Figure 2. Terrain corrected Bouguer gravity anomaly map over the southern part of the Lake Vättern area. Data has been corrected for water depth. The gravity stations are marked with plus-signs. The profile used for forward modelling is marked A-B.

Physical properties of ores and gabbroic rocks

The magnetic and gravity interpretation has been constrained by petrophysical information. Since no samples or drill cores exist from the rock/rocks that cause the magnetic anomaly, petrophysical information from samples of the surrounding area have been used; the abandoned iron mine in Taberg, the gabbroic rocks in Rymmen and Inglamåla, and the gabbro immediately east of the magnetic anomaly. Taberg mountain is situated 7 km south of Jönköping and the gabbroic intrusions in Rymmen and Inglamåla about 70 km south and southeast of Jönköping respectively. We also discuss the magnetic and gravity responses from using the petrophysical properties for some famous iron ores, Kiruna and El Laco, for the modelling.

The median value for a large number of measurements of the susceptibility of gabbroic rocks in the province of Småland is 0.025 SI units. This value is not sufficient to explain the magnetic anomaly when the upper surface of the magnetic body is situated below water and low-magnetic sedimentary rocks. Futher, the magnetic anomaly is so smooth that the uppermost part of the magnetic body must be at a depth of at least one kilometer.

The Taberg ore

Samples of iron ore from Taberg were studied in detail because their known petrophysical values indicate high enough concentration of magnetic minerals and Taberg is in close proximity to the magnetic anomaly.

Measurements show that the remanent magnetization (NRM) for the Taberg ore has a declination of 178 degrees and an inclination of -9 degrees (Bylund, 1992). By assuming the same remanent magnetization for the magnetic body underneath Lake Vättern it is however difficult to model the magnetic anomaly, particularly due to the direction of the remanent magnetization even though some of the oriented samples from the Taberg ore, collected by SGU, often have a flat to steep remanent direction to the north and northeast. SGU has recently however obtained some magnetically oriented samples from the northern pit of Taberg and the petrophysical properties of which can explain the magnetic and gravity measurements under Lake Vättern.

The remanent magnetization of the Taberg samples are between 8 and 150 A/m with a smaller spread of the high magnetic susceptibility, which has measured values in the range of 0.2 to 0.67 SI units. The density is high for all ore samples, around 3800-3880 kg/m^3. One sample of Taberg ore from the SGU archives was measured and showed a high susceptibility of 0.67 SI units, but with a remanent magnetization of only 8 A/m and a density of 3805 kg/m^3. Titanomagnetite is the only primary Fe-Ti oxide in the ore (Sandecki, 2000). The estimated amount of ore is c. 150 millions at 31% Fe, 6% TiO^2 and 0.3 % V^{2}O^5. It is not clear how the susceptibility is correlated to the amounts of the Fe-Ti oxides in the Taberg ore and SGU has no further information on the magnetic minerals of the Taberg deposit. Two magnetically oriented samples of Taberg ore, collected during an urban mapping project, have recently been measured and their susceptibilities are 0.46 and 0.41 SI units. The remanent magnetization is as strong as 28 and 54.8

A/m with a remanent inclination of 26.2 degrees and 67.1 degrees, respectively. The measured remanent direction is 72.6 degrees and 65.1 degrees, and the density was 3838 and 3806 kg/m^3, respectively. These values have been used in the model and the steeper inclination has provided the best fit of a large body of Taberg ore type to the measured data shown in figure 4. The remanent component is the dominant factor for the magnetic alignment, with a Q-value of 3.22.

The Rymmen and Inglamåla gabbros

Petrophysical properties for highly magnetized samples from the Rymmen and Inglamåla gabbros (situated south and southeast, respectively, of Lake Vättern) have also been used to model the geophysical anomaly in the area of Lake Vättern.

The measured values for a sample of the Rymmen gabbro, as previously modelled in Kero & Claeson 2007, are density 3167 kg/m^3, susceptibility 0.171 SI units with a strong remanent magnetization of 24.7 A/m, declination 113 degrees and inclination of 43 degrees. Other samples return values with a steep inclination of 80 degrees and a declination of 23 degrees.

The Inglamåla gabbro has previously been sampled using a technique to obtain the orientation of the remanent magnetization. One gabbro sample from Inglamåla has a density of 3722 kg/m3 and a high susceptibility of 0.6 SI units with a remanent magnetization of 30.8 A/m. Another gabbro sample from Inglamåla has a relatively low density of 3099 kg/m3 despite the relatively high susceptibility of 0.25 SI units. The remanent magnetization is however only 2 A/m. An oriented sample from this location had a remanent magnetization to the north with a declination of 352 degrees and inclination of 56 degrees, which is only magnetically adaptable to a laccolite shape.

The gabbro east of the magnetic anomaly

A magnetic sample from the gabbroic intrusion east of the Lake Vättern magnetic anomaly has a density of 3059 kg/m^3 and a susceptibility of 0.187 SI units with a remanent magnetization of 3.44 A/m. The sample is not oriented but the values above have been used for the modelling, assuming a steep remanent magnetization to the north.

Other iron ores

Samples of iron ore from Kiruna, Sweden and El Laco, Chile were measured to provide examples of extreme petrophysical data and to see how the anomaly from the magnetite ore and titanomagnetite ore, respectively, can be adapted to the measurements obtained from lake Vättern.

The susceptibility of the Kiruna ore is 3.9 SI units, which is near the maximum measurable level of susceptibility for minerals. The remanent magnetization was 142 A/m and the density was 5128 kg/m^3. The El Laco-sample had an extremely high remanent magnetization of 515 A/m and a susceptibility of 0.229 SI units and the density was 4640 kg/m^3.

Analysis of the magnetic and gravity anomalies

Background

SGU has previously committed to model the anomaly, using mainly magnetic modelling, since gravity data have been lacking (Kero and Claeson, 2007). The models from this previous report have been modified since gravity data is now available for modelling. It provides an opportunity to exclude some of the magnetic potential solutions using gravity constraints and to verify others.

Using an interpretation technique described by Caratori Tontini and Pedersen (2008), the centre of the magnetic body appears to be located at a depth of c. 1400 meter (Laust Pedersen, personal communication).

Existing geological and geophysical information has been used in the modelling. The water depth was measured accurately during the gravity survey and was entered to the profile information, flight-line 6412800 (RT90). The sedimentary layers and their thickness in the southern part of Vättern have been studied by Flodén et al. (1984). Two seismic profiles were acquired in the south of the lake, one in direction northwest to southeast to the eastern shore and continuing down to southwest to the western shore. The sedimentary layers maximum depth is c. 350 m in the seismic profiles. The calculation profile A-B (figures 1 and 2) and these seismic profiles only cross very near the eastern shore. In the area of the intersection of the profiles the depth of the sedimentary layer is approx. 70 meters in a small trough, which can be matched with the gravity minimum that exists at the location. In addition a borehole in the northern part of the town Jönköping shows a nearly 200 m thick pile of unconsolidated sediments of unknown age (Waldermarson, 1986; and references therein).

The regional gravity measurement in the form of the Bouguer anomalies must be filtered (see below) in order to be able to model the extent of the sedimentary rock layers above the maximum of the magnetic anomaly. Filtering is also necessary to try to reduce the influence of any deeper anomalies.

The interpretation of gravity and magnetic data is to some extent used to evaluate the sedimentary layers thickness. The magnetic modelling was not significantly affected by water depth or the extent and shape of the low-magnetic sedimentary layers. There was no magnetic response when the sedimentary rocks and the underlying granitic rock were entered as relatively flat layers with constant thicknesses.

The highly symmetric magnetic anomaly recorded by the airborne measurements shows that the body causing the anomaly must have a steep total magnetization in order not to create a powerful magnetic contact minimum to the north of the body, and also requires that the body lies at a depth of 1 km.

Filtering of gravity data

We have tried a number of filters for the gravity data in an attempt to highlight the small variations that exist in the Bouguer anomaly and use these residual data to predict the thickness of the shallow sedimentary layers along the profile.

Filtering of the gravity data has also focused on trying to remove the very deep-seated causes of the regional gravity high, and to focus the modelling on the uppermost few kilometers. Gravity differences, residuals between reduced ground measurement (the Bouguer anomaly) and an upward continuing grid to 12, 6, 3, 1.5 and 1 km have been produced with the software Oasis Montaj, using the module magmap. These new potential fields are subtracted from the original data, the terrain corrected Bouguer anomaly. The obtained gravity differences, residuals, seem to coincide well with the known exposed bodies of gabbro on the east side of the Lake Vättern (figure 3).

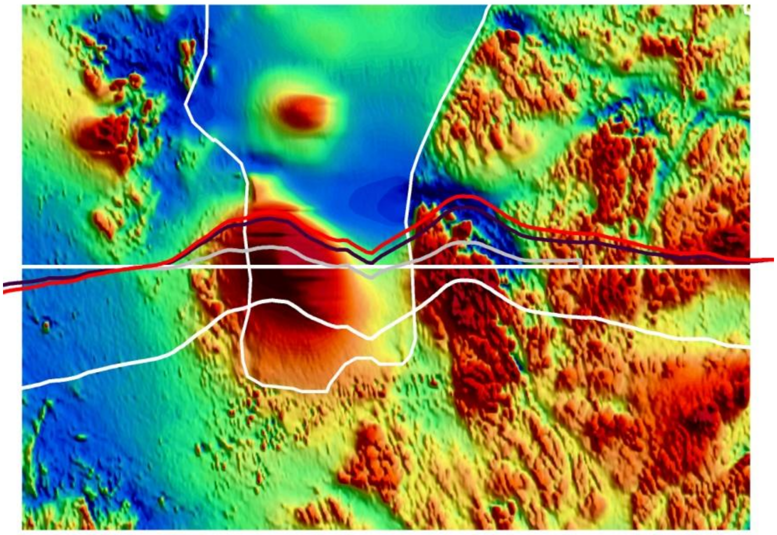


Figure 3. Magnetic field map in colour. The gravity data are sampled along the profile, shown as a straight line in white. The lowest white curve is the unfiltered Bouguer anomaly and it is plotted with the same resolution as all the residuals. The uppermost red curve is the gravity residual using the continuing up 12 km. The black curve is the gravity residual with the continuing up 6 km used in figure 6. The residual with the continuing up 1 km is the grey curve which is used in figure 4 and 5. The shoreline of Lake Vättern is shown as a white contour.

It is questionable whether the gravity residuals accurately represent the gravity measurements reported in figure 4 and 5. The distance between the measuring points on the ice is relatively far apart for the shallow modelling and therefore some subjective regional residual separations were made. The final result from the filtering superimposes different residual curves on the magnetic measurement together with the original Bouguer anomaly, which is added for comparison along the calculation line in figure 3.

Interpretation

The aeromagnetic measurements are well-documented, with a high density of lines flown over and around the anomalous area. Gravity measurements are combined in an east-west profile in order to make an integrated interpretation in order to study and try to identify the more likely of the many possible magnetic solutions.

Both the magnetic and the gravity data show that the modelled cause of the large magnetic anomaly is situated close to the maximum of all the gravity residuals (figure 3). The presentation of the models has been chosen with a gravity residual, using an upward continuing to 1 km in figures 4 and 5. This reduces the gravity anomaly in Lake Vättern to around 50% (figure 3), but represents the sediments in a better way. In figure 6, a residual with an upward continuing of 6 km is used, since this type of accounting of gravity data is a standard method. Comparison with all created residuals is done consistently. This method does not however quantify exactly the effects related to the depth of the different sources. The gravity data show that some of the gravity anomaly is situated beneath the western shore of Lake Vättern, and this surplus cannot be directly linked to the cause of the magnetic anomaly in the lake. Petrophysical values from a nearby gabbro have been used to generate this part of figures 4 to 6 and the values used are reported in detail for each model. The gravity anomalies generated by the model of the magnetic anomaly are considered to be minimum values because they do not use any low-magnetic gabbros.

Fortunately the modelling with the variations in gravity residual anomaly (figure 3) is not the determining factor for the form and depth of the magnetic model. The variations in the magnetic properties of potential rocks, mainly the size of the remanent magnetization together with the density of the selected petrophysical input data, is more important in showing explanations to the cause of the anomaly.

Forward modelling

The above mentioned petrophysical input data in the magnetic modelling have shown that horizontal layers of different thickness and depth to the upper surface can fit very well the observered magnetic anomaly. The data also gives an indication of the density associated with the extreme magnetic properties needed to explain the anomaly. The previous magnetic modelling has been assessed together with the new data from the gravity measurements. New sediment depth assumptions and new exact measurement of water depth have initiated some changes in the models.

The residual anomaly, based on the gravity measurements, has shown where these fault controlled sediments are likely to exist along the profile. Sedimentary layers have been included where the gravity measurements indicate a small deficit. The densities of the sedimentary layers, from 2350 to 2450 kg/m^3, are selected from the data that exists in the literature (Lind, 1972) and our own measurements. The sedimentary layers show a gravity deficit over the fault-controlled troughs with about 3 mGal for the deepest and c. 2 mGal for those in the eastern part of the transect.

Using the measured values from one Taberg sample with high remanent magnetization and high density, and a body shaped like an almost cylindrical disc gave a good fit (see figure 4 for values). Using a lower remanent magnetization, measured in another sample, results in a somewhat thicker (700m) body and provides a gravity surplus of about 7 mGal.

Using data from sample of Taberg ore from the SGU archives, values reported above, resulted in a 1000 m thick disc with an area of 2700 x 3200m. The density of the sample was 3805 kg/m^3 and the gravity anomaly then becomes about 10 mGal for the adapted model from magnetic data. The measured gravity anomaly is not sufficient for a slice of this thickness, so the gabbro with these petrophysical properties can only partly constitute the anomalous body.

A Taberg sample with the extreme remanent magnetization of 150 A/m, a susceptibility of 0.206 SI units and a density of 3880 kg/m^3 is matched by an approximately 250 m thick layer with a cross-section of 2700 m x 3200 m as before. In this case it created a low gravity anomaly, only 2.5 mGal, including the negative gravity input from the sediment layers. It appears that rocks with these extreme values for the remanent magnetization(between 8 and 150 A/m), with densities of 3800 and 3880 kg/m^3, for gravity reasons, could only partly be the cause of the strong magnetic anomaly. In this model the magnetic anomaly is accounted for, there can of course be additional low magnetic mafic rocks included in modelling to give the necessary gravity high for the sample with the extreme remanent magnetization. An example of this is a hypothetical amount of low-magnetic basic rock, close to the surface, that appears in the western edge of the magnetic anomaly and which does not add a magnetic signature but generates a contribution to the gravity. This makes the models fit better to the gravity anomaly. It is therefore included in the model as a small body with values from the nearby gabbro.

The layered Inglamåla gabbro has previously been magnetically modelled. Values from the high magnetic and high density samples were used. The previous magnetic modelling required a thickness of 1000 meters with the relative flat remanent inclination, and it generated a gravity anomaly of approx. 9 mGal, which is too much gravity surplus from the magnetic part of a differentiated magma. Assuming a more vertical remanent magnetization, as indicated by the aeromagnetic measurements of the magnetic total field at Inglamåla, results in a thinner slice (about 700 m thick) located slightly higher than at the assumed centre of the anomalous body at 1400 meters and gives a good fit to both the magnetic and the filtered gravity data.

Work on the Rymmen gabbro and other basic intrusions in the area (e.g., Claeson, 1999, 2001) have been the guideline for the assumptions and types of basic rocks used in the modelling (figure 5). With such a relationship between high and low magnetic types of gabbros it is not possible to adapt this model to the measured gravity.

Only relatively minor parts of the gabbro intrusions at Rymmen and Inglamåla consist of this type of high magnetic rock, which is created through a prolonged differentiation of these basic magmas. In principle this means that the modelled body, viewed as analogous to the Rymmen gabbro, can have a cross section that looks like the model (figure 5), but then 80-85% of the crystallization products from the original basic magma is missing. Such a large degree of fractionation is necessary for the formation of this type of high magnetic rock. If the magnetic part only constitutes 15-20% of the intrusion, the resulting gravity anomaly would be too large even if the residual anomaly is based on a larger filter (see for instance figures 3 and 6). Thus the model only shows the gravity effect of the differentiated magnetic body when it is adapted to the magnetic anomaly. However, using a broader filter there is space for more mass.

Using the high values reported above for the magnetization of the Rymmen and Inglamåla gabbros makes it possible to adapt an inverted bowl shape with the centre at about 1000 meters down, while also fitting the gravity anomaly when using appropriate values for the density (figure 5). In this model the magnetic alignment requires that the upper surface and the lower face of the body are given a convex shape for the magnetic data to fit. This means that the centre of the body in this case is positioned at a shallower level than 1400 meters. Our software cannot however fully calculate the response of a three-dimensional model bowl. A number of additional modelling profiles located north and south of the main modelling profile (marked A-B in Fig. 1) show that edge effects are a reasonable approximation in the present model.

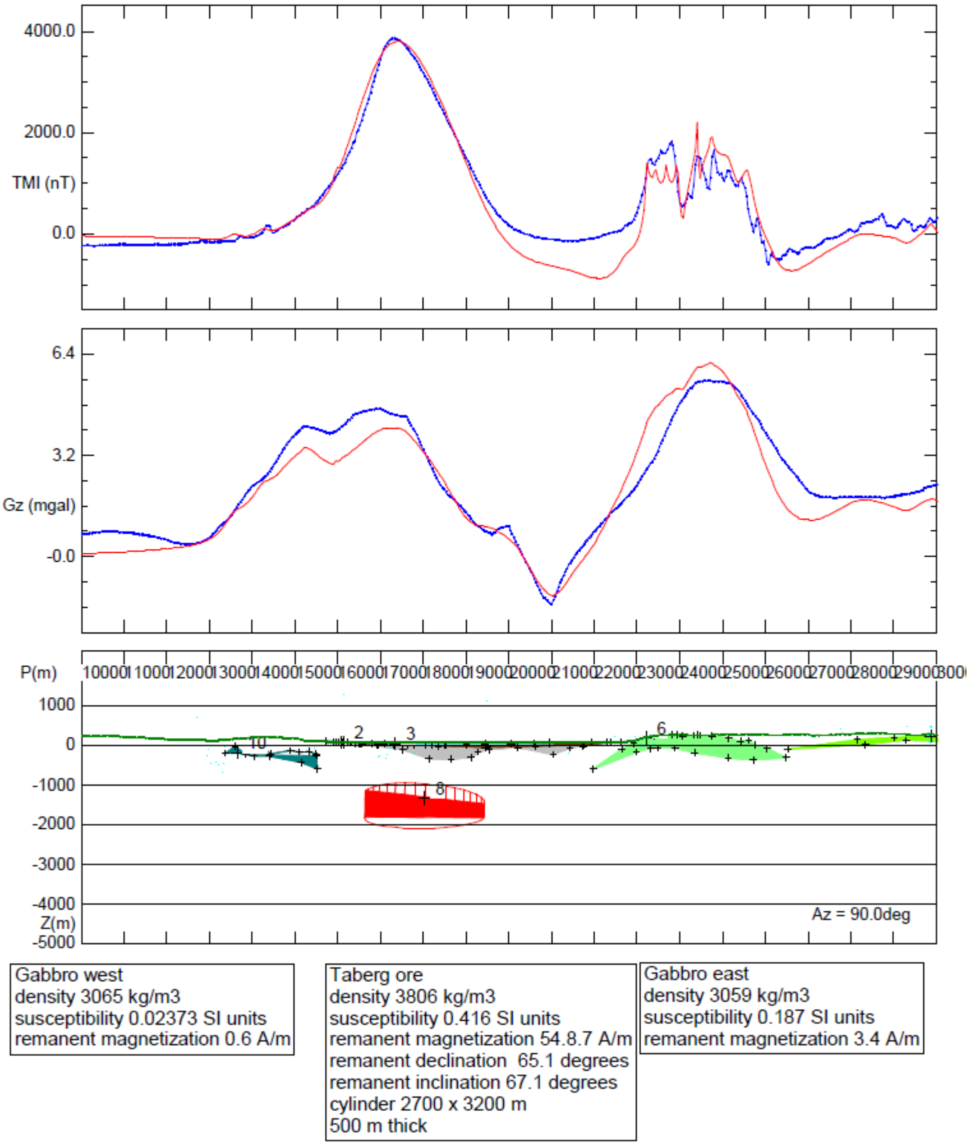
The simplifications which must be made in the modelling phase give a very rough idea of what it takes to adapt models to this geophysical data. We assume for example large homogenous mafic bodies, laccolites (figure 6), in some of the tested models. Layering is more likely in these bodies with high and low magnetized layers.

Only one petrophysical sample from the Inglamåla gabbro has a sufficiently high susceptibility and low remanent magnetization combined with a relatively low density to give a large body of laccolite shape (figure 6). The gabbro sample from Inglamåla has a density of 3099 kg/m^3 and a high susceptibility of 0.25 SI units with a relatively low remanent magnetization of 2 A/m. An oriented sample showed a remanent magnetization with a declination of 352 degrees and an inclination of 56 degrees therefore, if the softly curved shape is realistic, this type of model is possible from a geophysical viewpoint. The volume must be large to produce the magnetic anomaly and the effect is a gravity anomaly of about 9 mGal for a density of 3099 kg/m^3. The curved convex upper surface, when the anomalous body is situated at such a shallow depth in the crust, must however be extremely smooth to match the soft form of the magnetic anomaly. This sample was still classified as a cumulative crystallization product so the gravity high would be even higher and much more pronounced than the one measured. The results from the magnetic modelling does of course not change so it appears that the gravity measurements exclude a body with a laccolite shape. Furthermore the geological theories for basic magmatism suggest layering processes in such large intrusions rather than a large homogenous body.

A large volume in the model is required even when using the values from the sample of the adjacent gabbro east of the magnetic anomaly in Vättern, the green body in the model (figures 4, 5 and 6). The most body magnetic sample from that gabbro again gave a model in the form of a large laccolite shaped body with a gently curved upper surface which must be very close to but beneath the surface of the sedimentary rocks at the bottom of Vättern. The model requires a very large volume to produce the observed magnetic anomaly. The gravity anomaly is over 15 mGal thus this type of gabbro does not have the necessary magnetization to be a likely source for the magnetic anomaly.

The high remanent magnetization of the sample from El Laco results computationally in only a 140 meters thick layer with the centre of mass at 1400 m, and with a smaller cross-section than in the former model. The gravity anomaly from this body is weak, only c. 1 mGal. Such a model with a thin layer, will not give an optimal fit to the observed aeromagnetic measurements. More petrophysical data from El Laco is required to construct a reasonable model. Values for the susceptibility of 0.4 SI-units are reported and with a very large variation in the remanent magneitsation.

The high magnetic values from the Kiruna sample can be adjusted to give a 200m thick elliptic layer, 2700 m x 3200 m, which also generated a reasonable gravity anomaly of about 5 mGal. It demonstrates the strong magnetization needed to adjust a magnetic body with the centre at 1400m depth to the large magnetic anomaly in the lake. The published petrophysical data from the Kiruna iron ore are comparable with the measured data.

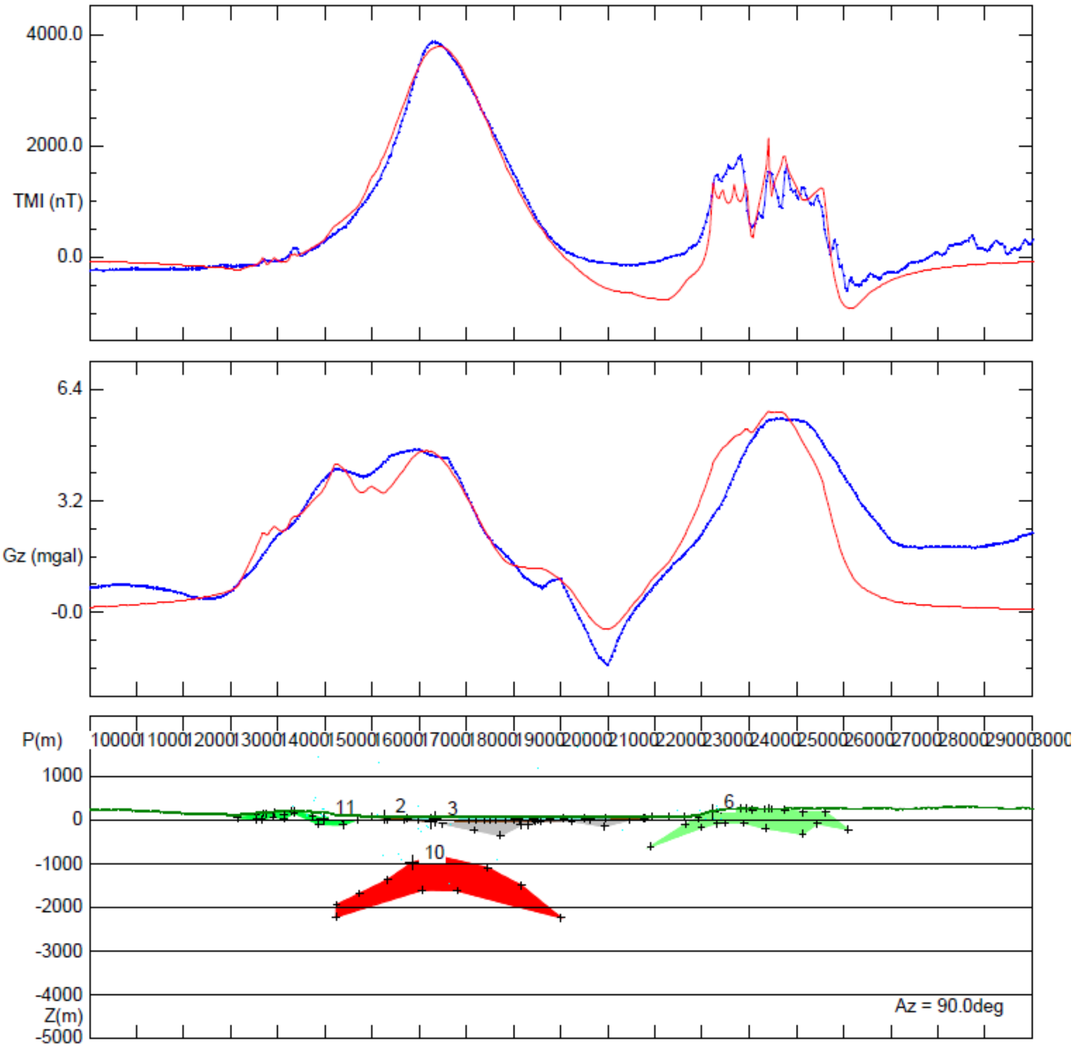


Gabbro west
density 3065 kg/m3
susceptibility 0.02373 SI units
remanent magnetization 0.6 A/m

Taberg ore
density 3806 kg/m3
susceptibility 0.416 SI units
remanent magnetization 54.8.7 A/m
remanent declination 65.1 degrees
remanent inclination 67.1 degrees
cylinder 2700 x 3200 m
500 m thick

Gabbro east
density 3059 kg/m3
susceptibility 0.187 SI units
remanent magnetization 3.4 A/m

Figure 4. A vertical section with the modelled magnetic disc of Tabergs type ore in red. Aeromagnetic data TMI (nT) are shown at the top, where the measured data is shown in blue and the models response curve is shown in red. The gravity difference Gz (mgal) for the same section is shown under the magnetic section. The curve shown in blue is measured filtered gravity data and the red curve is the response of model cells. The 3rd plot shows a vertical section of the model. The water depth in blue and the sedimentary deposits are shown in gray. The green model is the gabbro east of the magnetic anomaly. The modelled disc is about 500 meters thick and provides a gravity anomaly of about 5 mGal. This value includes some effects of the sediment layers, where the deepest fault-controlled sediments account for a deficit of c. 3 mGal. The scale of the image is equal in height and side. Reported gravity difference is that between the Bouguer anomaly and the resulting anomaly from the Bouguer anomaly continuing up 1 km. Profile along A-B in figure 1 and 2.

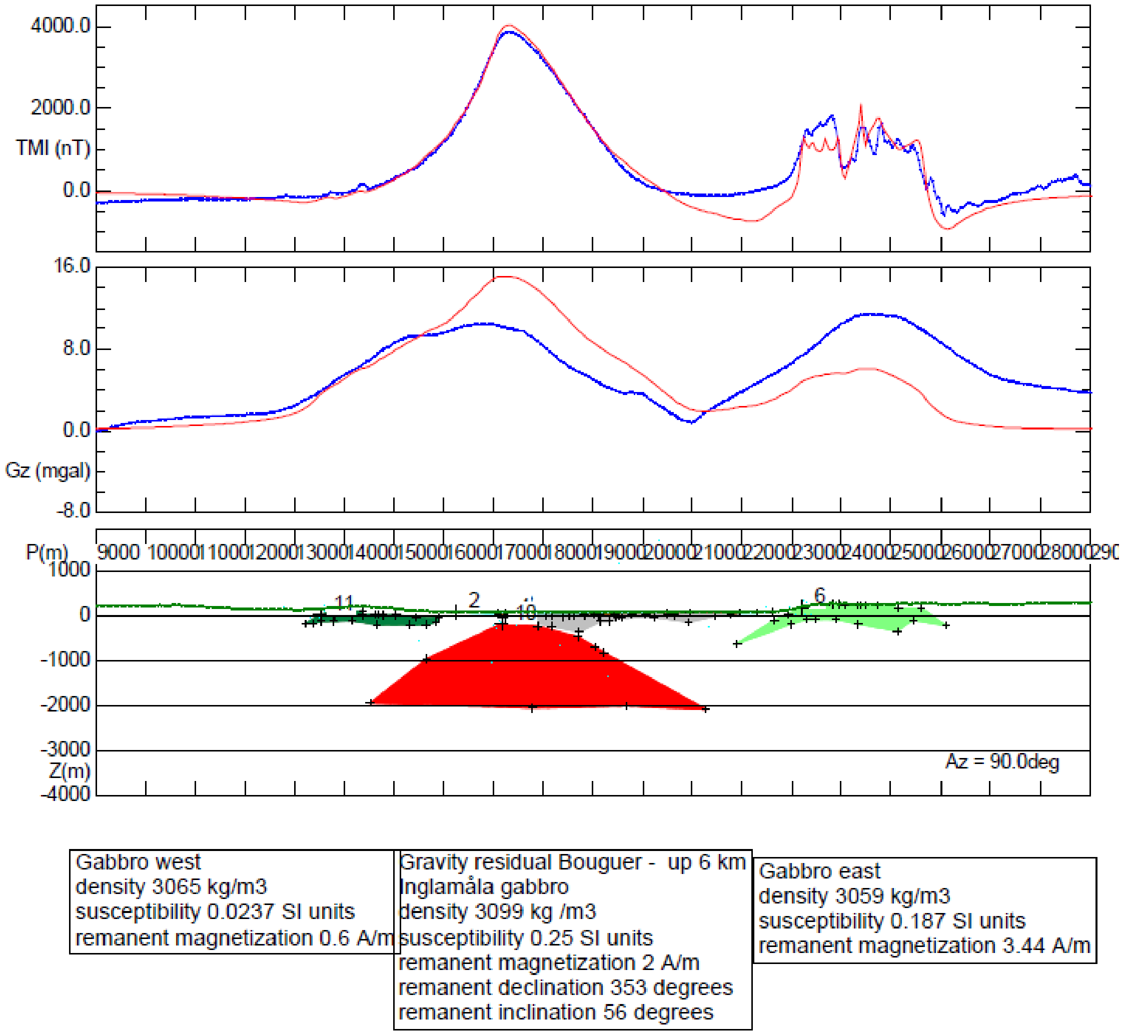


Gabbro west
density 3065 kg/m3
susceptibility 0.02373 SI units
remanent magnetization 0.6 A/m

Rymmen data
Gravity residual Bouguer up 1 km
density 3167 kg/m3
susceptibility 0.171 SI units
remanent magnetization 24.7 A/m
remanent declination 23 degrees
remanent inclination 80 degrees

Gabbro east
density 3059 kg/m3
susceptibility 0.187 SI units
remanent magnetization 3.4 A/m

Figure 5. A vertical section with the modelled magnetic convex disc of Rymmen type gabbro in red. Aeromagnetic data TMI (nT) at the top where the measured data is the curve in blue and the model response is shown in red. The section with the gravity difference Gz (mgal) is shown under the aeromagnetic data plot. Blue is measured filtered gravity data and the red curve is the response of model cells. The 3rd plot shows a vertical section of the model. The water depth in blue and the sedimentary deposits in gray. The green model is the gabbro east of the magnetic anomaly. The scale of the image is equal in height and side. The gravity residual is the difference between Bouguer anomaly and the anomaly resulting from continuing up the Bouguer anomaly 1 km. Profile along A-B in figure 1 and 2.



Gabbro west
density 3065 kg/m3
susceptibility 0.0237 SI units
remanent magnetization 0.6 A/m

Gravity residual Bouguer - up 6 km
Inglamåla gabbro
density 3099 kg /m3
susceptibility 0.25 SI units
remanent magnetization 2 A/m
remanent declination 353 degrees
remanent inclination 56 degrees

Gabbro east
density 3059 kg/m3
susceptibility 0.187 SI units
remanent magnetization 3.44 A/m

Figure 6. A vertical section with the modelled magnetic body of Inglamåla type gabbro in red. A section of the aeromagnetic data TMI (nT) is shown at the top where the measured data is shown in blue and the model response is in red colour. The gravity difference Gz (mgal) is the difference between Bouguer anomaly and the anomaly resulting from continuing up the Bouguer anomaly 6 km. This residual includes more mass than in figure 4 and 5. The blue curve is measured filtered data and the red curve is the response of model cells. The measured water depth is shown in blue colour and the modelled sedimentary deposits are shown in gray colour. The green model is the gabbro east of the magnetic anomaly. The scale of the image is equal in height and side. Profile along A-B in figure 1 and 2.

Discussion

If one disregards the calculation of the anomaly's magnetic centre at 1400 meter, one can adjust a number of models that satisfy both the magnetic and the gravity measurements. It is, for example, possible to use a 3 km deep magnetic cylindrical pipe, with the small width of 1500 m x 1900 m and an upper surface at about 1500m depth to a magnetic barrel, earlier obtained as the result of magnetic calculations with Euler Deconvolution. This modell, using the values from one of the measured samples, gives a gravity anomaly of a reasonable size and form. This highlights the complexity of modelling and the advantage of using different methods simultaneously, however, in terms of calculation this model can be adapted to both the magnetic and gravity anomalies. The two potential fields, in particular the magnetic, but also the gravity, becomes less sensitive to variations in composition at the lower levels in this modell.

Even if none of the rocks sampled in the region are similar to the one causing the geophysical anomalies in magnetic and gravity data, the modelling shows the magnetic properties and densities that the causing body must have in order to achieve the geophysical anomalies in Lake Vättern. A small remanent magnetization means that the induced magnetization must be greater than 0.4 to 0.6 SI units, which implies that elevated magnetite content, or the presence of other magnetic minerals such as titanomagnetite are required, in order to explain the magnetic anomaly. The level of the remanent magnetization seems to be the most important magnetic factor and its relation to the different magnetic mineral is not fully understood at present. The magnetic minerals in Taberg, Rymmen and Inglamåla are presented in detail in the cited papers. The two examples from Kiruna and El Laco show extreme levels of induced vs. remanent magnetization.

A complete 3D modelling is desirable for this interesting object. More gravity measurements are needed in a wider area and a comparison with the existing seismic profiles is necessary in order to beter constrain the depth of the sedimentary layers and the magnetic object.

The gravity survey shows a distinct but minor positive gravity anomaly over the source of the magnetic anomaly. One reason for this is the documented rather thick layers of low density sediments (unconsolidated and consolidated) in the Lake Vättern (Flodén et al., 1984, Waldermarson, 1986). One argument against the hypothesis that the anomalies are caused by gabbroic intrusions (like those in Rymmen and Inglamåla) is the fact that the gravity anomaly is so weak. The crystallization process of basic magmas generally only produces a relatively small part (10-20% of the volume) of the magma as rocks with high magnetic properties (e.g., Parsons, 1987, Cawthorn, 1996). Considering that the more magnetized part of the body, when assuming a gabbroic intrusion, must be rather large to explain the observed magnetic anomaly the total volume would produce a larger gravity anomaly than seen.

A reflection seismic survey would confirm whether there are kind of high density objects with a centre at about 1400 meters depth and about 500 meters thick. It would also give more accurate depth estimates for the sediment layers.

An audio magnetotelluric measurement should be able to show whether a distinct body with higher conductivity is present. With a more extended investigation it may even be possible to reveal the 3D conductive structure.

Conclusions

The magnetic anomaly in the southern part of Lake Vättern demonstrates the ability to identify and quantify items at depths of 1-2 km or more by geophysical methods. In areas with good magnetic and gravity data coverage and existing petrophysical information it is possible to get an idea of the shape and thickness of different deep seated source rocks. In this area the large water depths and the thick sedimentary layers complicate the interpretation, primarily of the gravity data. The interpretation, however, also gives an opportunity to predict the extent of the sedimentary layers in the lake. The gravity surplus from the model also includes the negative gravity anomalies that the assessed sedimentary layers provide.

Gabbros from the region, with a lower magnetization than 0.1 SI units and without a very strong remanent magnetization, cannot generate the shape and size of the observed magnetic anomaly. Thus one can exclude most of the gabbroic rocks in the area as possible explanations for the anomaly. Using magnetizations however, which are much higher than measured on gabbros in the area a differentiated gabbroic intrusion is possible.

The shape and size of the magnetic anomaly in the Lake Vättern demands very high magnetic properties to create a possible modell. The petrophysical values from the relatively magnetically homogeneous Taberg ore show corresponding magnetic values (Larsson & Söderlund, 2005). The measured densities can also be adapted to the filtered Bouguer anomaly data.

This indicates that the cause of the magnetic anomaly in the Lake Vättern is most likely a high magnetic body that generates a gravity high of 5-9 mGal. For gravity anomalies of this magnitude it is also necessary to take account of the sedimentary layers lateral extent and depth along the profile calculation. The resulting horizontal view of the body's range is roughly that of the red body of figure 7 below.

For a better control of the depth to the uppermost level of the highly magnetic body, and in order to constrain its shape such as the location of the edges and the thickness of the body in more detail, additional geophysical work is needed.

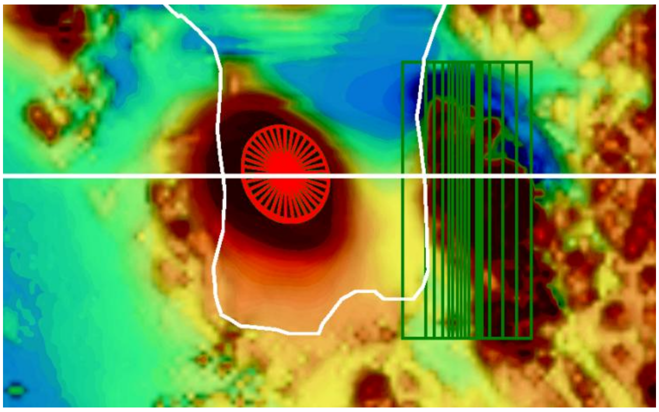


Figure 7. The horizontal view of the model presented in figure 4. The total magnetic field is displayed in color and is overlain by the two models in red and green. The model of the magnetic anomaly is the elliptical disc in the figure. The model for the gabbro east of the anomaly is represented by the green lines. The calculation line, profile A-B in figures 1 and 2, is shown in white. The breakpoints used from the measured water depth and sediment models in the vertical view are not displayed. The shoreline of Lake Vättern is shown as a white contour.

ACKNOWLEDGEMENTS

The authors wish to make special mention of State Geophysiscist Niklas Juhojuntti and State Geologist George Morris who have critically read the manuscript and made many useful suggestions for improving it.

References

Aaro, S. & Byström, S., 2000: Flyggeofysiken och de nationella miljökvalitetsmålen. *Geologiskt forum 28,* 12-16.

Aaro, S. & Byström, S., 2001: Tyngdkraften och magnetfältet – två viktiga nycklar till Jordens inre. *Geologiskt forum 32,* 21-28.

Axberg, S. & Wadstein, P., 1980: Distribution of the sedimentary bedrock in Lake Vättern, southern Sweden. *Stockholm Contribution in Geology 34*, 15-25.

Blaxland, A.B., 1977: Agpaitic magmatism at Norra Kärr? Rb-Sr isotopic evidence. *Lithos 10*, 1-8.

Bylund, G., 1992: Paleomagnetism, mafic dykes and the Protogine Zone, southern Sweden. *Tectonophysics 201,* 49-63.

Caratori Tontini, F. & Pedersen L. B., 2008: Interpreting magnetic data by integral moments. *Geophysics J. Int. 174*, 815-824.

Cawthorn, R.G. (Ed), 1996: Layered Intrusions: Developments in Petrology 15. *Elsevier Science B.V.*, 1-531.

Claeson, D.T., 1999: Geochronology of the Rymmen gabbro, southern Sweden; implications for primary versus inherited zircon in mafic rocks and rheomorphic dykes. *GFF 121,* 25-31.

Claeson, D.T., 2001: Investigation of gabbroic rocks associated with the Småland-Värmland granitoid batholith of the Transscandinavian Igneous Belt. *Göteborg University, Earth Sciences Centre, A64.*

von Eckermann, H., 1968: New contributions to the interpretation of the genesis of the Norra Kärr alkaline body in Southern Sweden. *Lithos 1*, 76-88.

Flodén, T., Wannäs, K. & Lundström, E., 1984: Refraktionsseismisk uppmätning av en geologisk sektion söder om Visingsö, Vättern. *Geol. Inst. SU, Scandiaconsult AB*

Kero, L. & Claeson, D.T., 2007: Magnetic anomaly north of Jönköping town, Sweden. *Sveriges geologiska undersökning, Dnr: 08-159/2007.*

Larsson, D. & Söderlund, U., 2005: Lu-Hf apatite geochronology of mafic cumulates: An example from a Fe-Ti mineralization at Smålands Taberg, southern Sweden. *Chemical geology 224,* 201-211.

Lind, G., 1972: The gravity and geology of the Vättern area, Southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar 94,* 245-257.

Parsons, I. (Ed), 1987: Origins of Igneous Layering. *D. Reidel Publishing Company*, 1-666.

Sandecki, J., 2000: Mineralogical and genetical aspects of the Smålands Taberg Fe-Ti-V ore, Protogine Zone of southern Sweden. *GFF 122*, 351-358.

Waldemarson, D., 1986: Weichselian lithostratigraphy, depositional processes and deglaciation pattern in the southern Vättern basin, south Sweden. *Lund University, Department of Quaternary Geology, Lundqua thesis 17*.

Wik, N.-G., Andersson, J., Bergström, U., Claeson, D., Juhojuntti, N., Kero, L., Lundqvist, L., Möller, C., Sukotjo, S., & Wikman, H., 2006: Beskrivning till regional berggrundskarta över Jönköpings län. *Sveriges geologiska undersökning K 61,* 1-60.

Wikman, H., 2000: Description to the maps of solid rocks 5E Växjö NO and NV. *Sveriges geologiska undersökning Af 201, 216*, 1-108.