An Interpretation of the 2008 SkyTEM Aeromagnetic Survey

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The intention of this report is to

1. Function as a general tutorial in the use of EMIGMA
2. Provide input as to the functionality of EMIGMA for magnetic interpretation
3. Provide structural information for the interpretation of electromagnetic surveys

Magnetics 1

Base Station Corrections: (QCTool)

Base station corrections are generally poorly understood by contractors with their understanding limited to undergraduate textbooks.

Therefore, if possible, the base station corrections should be reviewed and often re-done correctly. Developers of magnetometers often talk about the accuracy of their instruments in units of picoTesla. Bad basestation corrections can easily result in errors of 20nT or more.

There are a number of physical factors affecting the base station correction which should be considered as to their importance as the so-called diurnal variation is only one factor. The diurnal variation is a long wavelength effect caused by the daily earth's rotation in the field of the sun's radiation. But there are other factors

1) the atmospheric events which are normally considered as the source of our magnetotelluric measurements. There is a considerable spectrum of these fields which can be measured with the magnetometer depending upon the bandwidth of the particular magnetometer. These fields can have significant spatial gradients depending on their source and the size of the survey. Depending on the size of the survey, this may require multiple base stations in order to correct for various noise signals with spatial gradients.

2) Instrument drift: Both rover and base station magnetometers should be corrected for drift similar to gravity measurements. At a minimum drift between daily survey starts and ends should be corrected.

3) Noise: The noise in the base station measurements and the rover are not the same as the noise will depend on several factors including specific instrumentation and location. Thus, de-spiking and noise removal should be done on rover and base station independently before base station correction.

4) Daily Base Station corrections: Once drift and noise processing has been completed. The corrections for the base station data should be done on a daily basis. That is, each day's base data should be used to correct that day's rover data. Processing is often done incorrectly where the mean of the all the base station data is used to calculate a base station residual. The base station data is often low pass filtered before correcting the rover data as a cheap shortcut to correct noise removal

All of these corrections can be done in a proper scientific manner in QCTools prior to import to EMIGMA.

In the SkyTEM example, the base station data is obviously very poor if not completely incorrect. But, we do not have the base station data to properly correct.

Magnetics 2

IGRF Calculations: (QCTool)

These corrections if done by the contractor should be checked. NOAA provides a very good online calculator to check these values. In the SkyTEM data, for example, the IGRF intensity is on average incorrect by 77nT. Very likely, they used Geosoft which is often tardy with including using updated coefficients for the IGRF model. Also, very often the contractor does not understand that altitude above the geoid is also a factor in these calculations and does not insert these elevation values in the calculations.

Tie Line Corrections: (QCTool)

Generally, speaking I will not use the data which has been processed to do tie line leveling. These level procedures on simply low pass filters and have the effect of smoothing out the more striking anomalies and removing short wavelength anomalies. These types of anomalies may well be the types of targets we are seeking.

Heading Effects: (QCTool)

Heading effects are important aspects to consider in the magnetics corrections. These are particularly true if Geometric cesium sensors are used. This is the case in the SkyTEM data.

Comments: As the magnetic responses are very large and obviously at some depth, only the IGRF corrections were re-computer.
The heading effects while present are probably less than the errors caused by the poor base station corrections.

Magnetics 3

The magnetic data is generally a good indicator of variations in geology and thus is critical to any EM interpretation. In this particular study, the magnetic structures will likely play a significant role in the interpretation of the magnetotelluric data as the magnetotelluric varations are principally due to the effects on the electric field. The magnetic field playing the role of bulk induction and normalization of the electric field data.

But, in this situation, the magnetic field analyses proves to be an even more important tool in the interpretation and understanding of the EM data. We will see this unfold as we progress through the magnetic processing procedures.

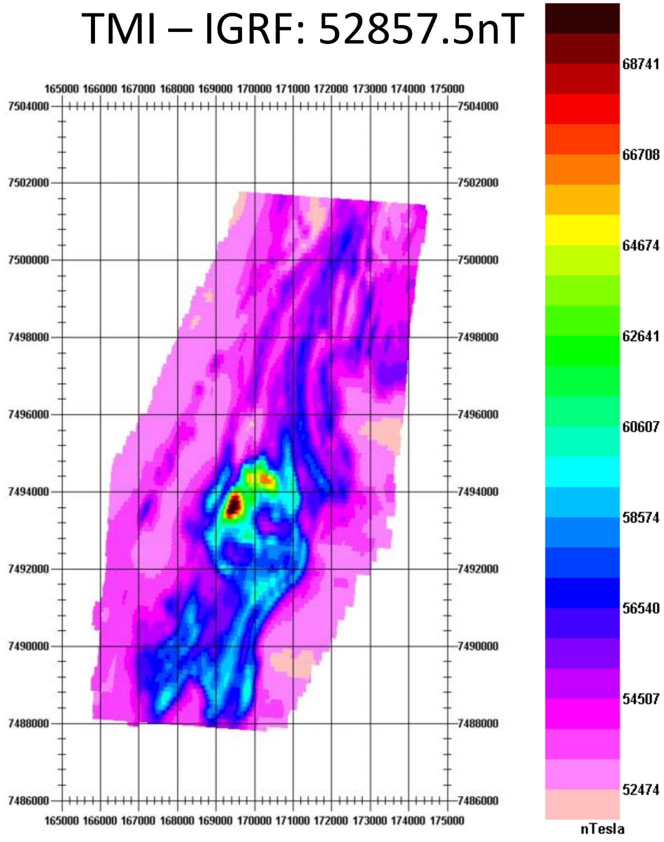
Fourier Processing (EMIGMA)

Derivative Calculations: The calculation of the derivatives allows us to address a variety of issues. The two major issues that we will examine here are the variation of strike as identified by the horizontal derivatives and the identification of the depth of anomalies via upward continuation. Reduction to the pole which would normally be performed will not be done here due to the high latitude of the survey location.

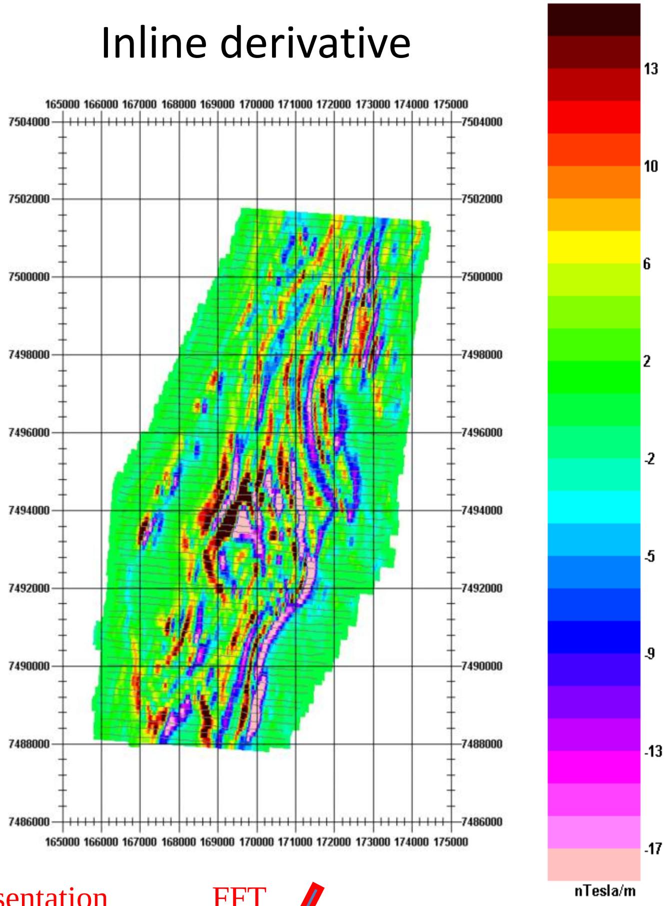
Notes on FFT processing in EMIGMA: FFT techniques require a grid which is 2^N x 2^M grid cells within the grid where N and M are integers. EMIGMA is somewhat unique in that our gridding techniques do not require the cells of the grid to be square but can be rectangular of arbitrary aspect ratio. This is critical in deriving derivatives and other processed parameters via fourier techniques. This is particularly true with man styles of modern data collection. An important example is aeromagnetic data. Aeromagnetic data is collected at very high spatial sampling along the survey line with a much lower spatial sampling across lines. In this case, we wish our FFT grid to have a much higher sampling along line than across line. FFT algorithms derived from grids with square cells suffer from too high crossline sampling and two coarse inline sampling. This often produces artifacts in the crossline derivative (Y) and lost of resolution in the inline derivative (X).

Magnetics 4

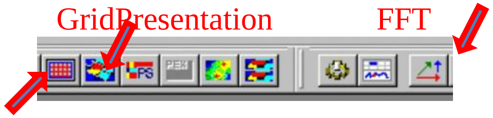
Let us examine these issues with the SkyTEM aeromagnetic data from the Ylipääsnjaska survey. In this survey, the line spacing was approximately 200m and the inline sampling was approximately 1.5m. The inline sampling is obviously excessively high as the height of the instrument above ground is on average about 40m. Thus, the survey cannot have a resolution of 1.5m. We, therefore, perform a statistical decimation which reduces the sampling to about 5m while reducing the noise statistic. In the following examples, we use a grid which is 8m x 120m in cell size. By using a high inline sampling, the inline derivative (left) shows more clearly variations in the magnetic structure



TMI – IGRF: 52857.5nT



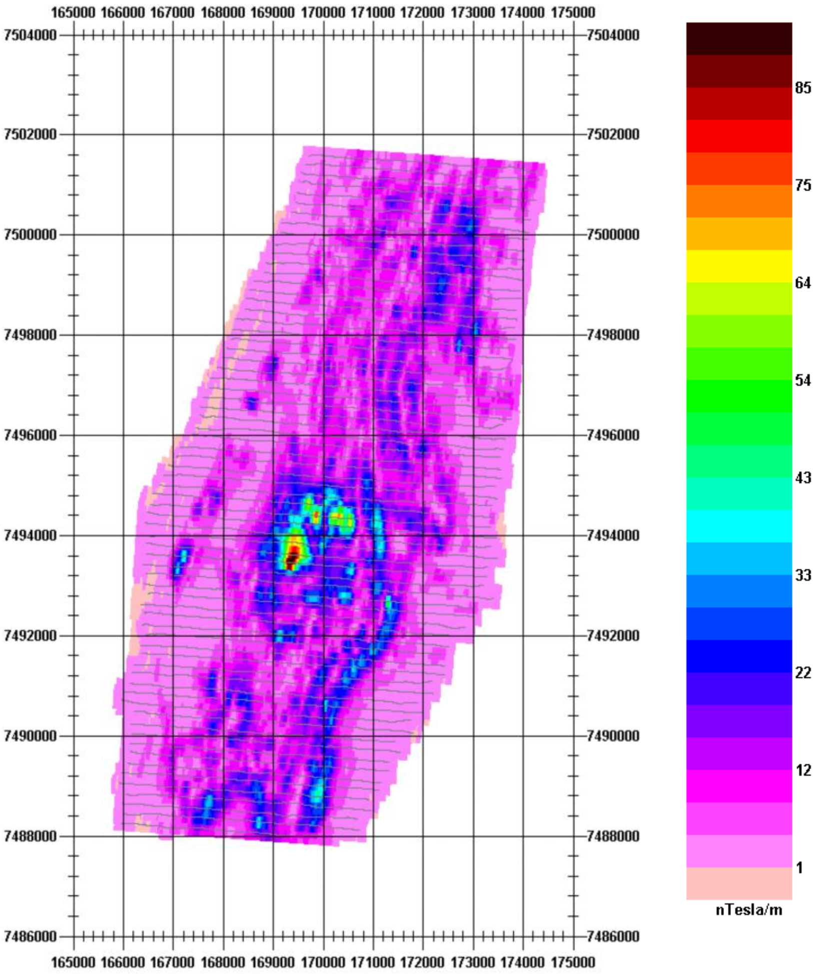
Inline derivative



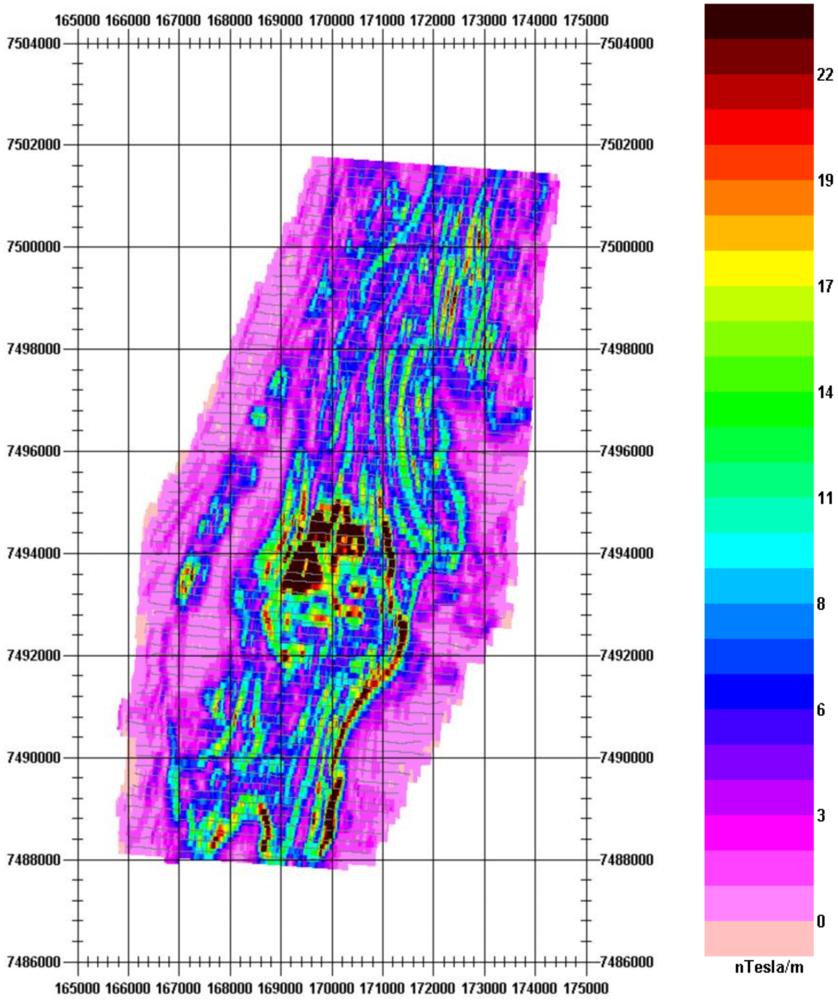
Magnetics 5

Additionally, from the derivatives, we can derive other parameters.

Analytic Signal

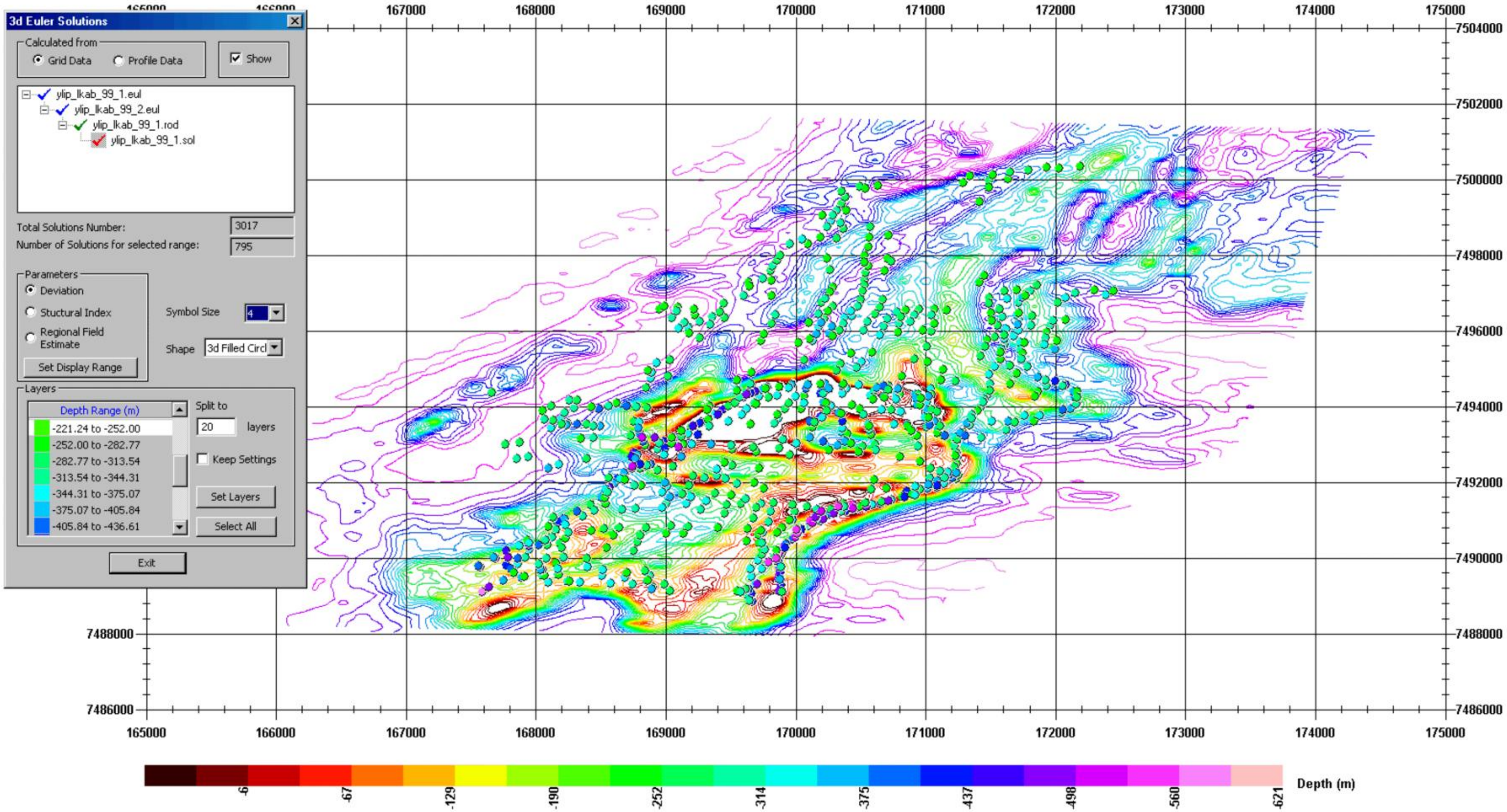


Horizontal Signal



Magnetics 6 3D Extended Euler Solutions

The derivatives allow us to perform other processing for depth estimation. Here, we show the Euler solutions for depths below 250m. There are considerable indicators of deep structure particularly below the TEM ground survey and to the south.



3d Euler Solutions

Calculated from: ● Grid Data ○ Profile Data

☑ Show

- ylip_lkab_99_1.eul
  - ylip_lkab_99_2.eul
    - ylip_lkab_99_1.rod
      - ylip_lkab_99_1.sol

Total Solutions Number: 3017

Number of Solutions for selected range: 795

Parameters:
● Deviation
○ Stuctural Index
○ Regional Field Estimate

Symbol Size: 4

Shape: 3d Filled Circl

Layers

Depth Range (m)
-221.24 to -252.00
-252.00 to -282.77
-282.77 to -313.54
-313.54 to -344.31
-344.31 to -375.07
-375.07 to -405.84
-405.84 to -436.61

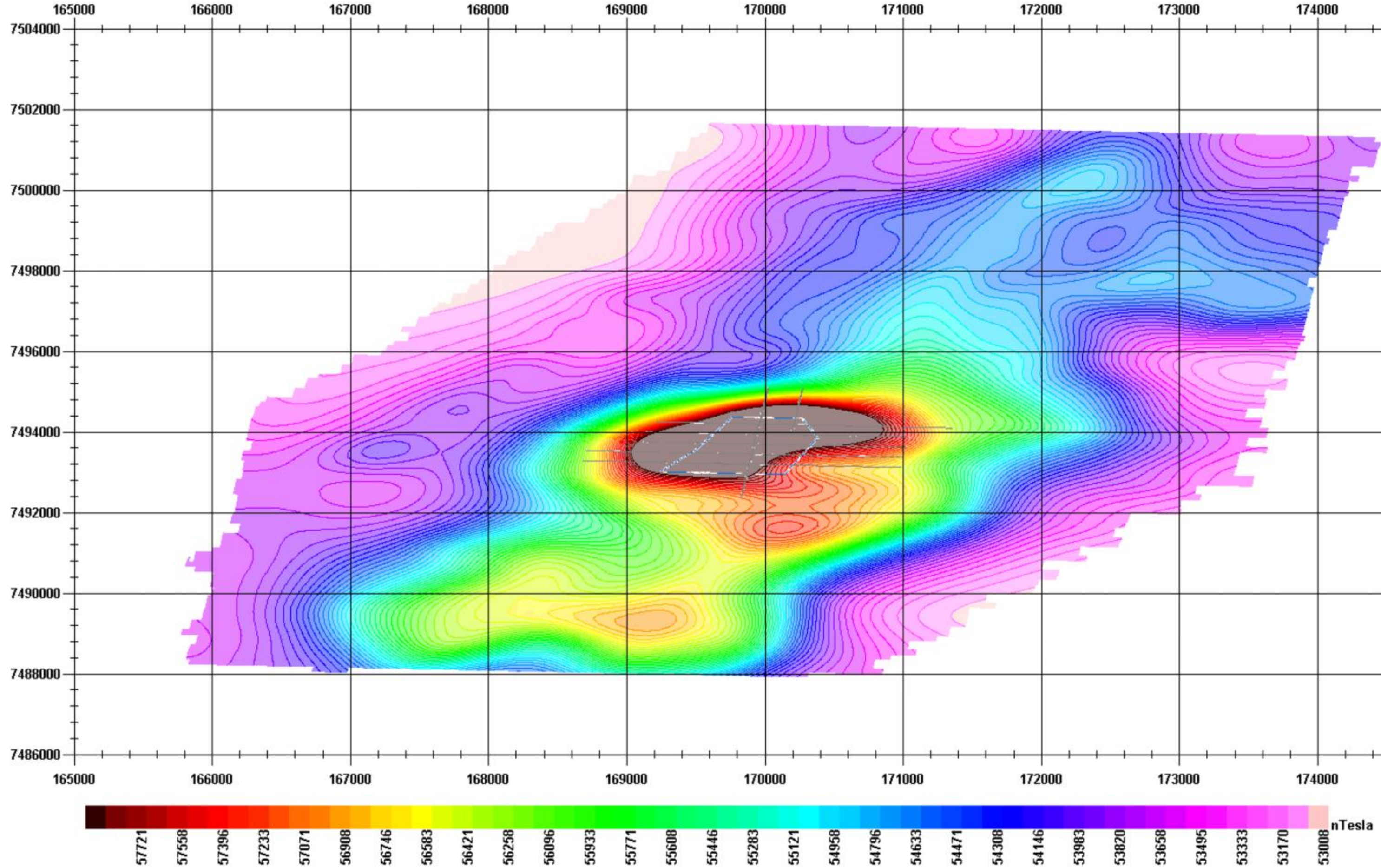
Split to 20 layers

☐ Keep Settings

Euler Solutions are accessed via the **3D** button

Magnetics 6 Upward Continuation

With the calculated derivatives, we can perform an upward continuation. Here, we show the data upward continued to a flight height of 400m. This exhibits the depth of the structure but more readily shows the nature of the deep magnetic structure beneath the ground TEM survey.



Addendum 1

EMIGMA grids

In addition to issues addressed earlier, there are other important differences to gridding in EMIGMA versus all other mapping software for geophysics. Most importantly

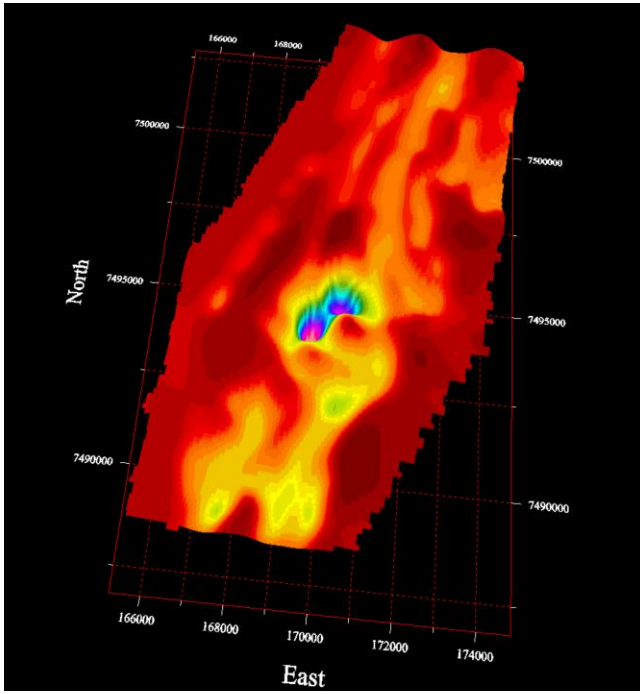
- EMIGMA grids are multi-parameter grids – generally grids consist of a data, *f*, interpolated to a regular grid {dx,dy}, where normally dx = dy. EMIGMA grids can consist of multi-parameters, f_i, $i = 1,M$. For example, in TEM data, the grid would generally consist of the data from all time windows and all components.

-Other information may be attached to the grids. As an example, Euler solutions may be attached to a grid of derivatives

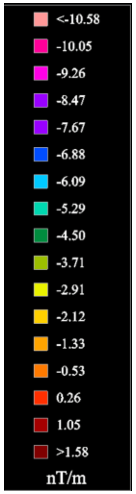
- Grids are specifically assigned (attached) to a dataset within the database. All grids associated with a dataset may be viewed through the Grid(s) button. Within the Grid Information interface, the grids, their characteristics, their parameters and their statistics may be viewed. Operations on grids are performed here

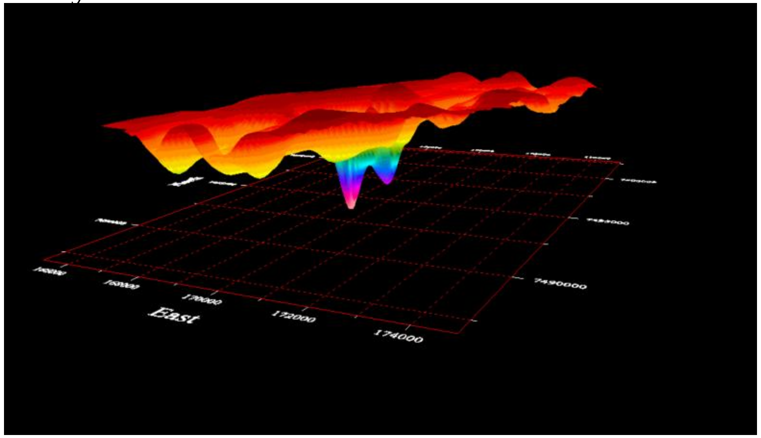
Magnetics 7 Use of Derivatives

The vertical derivative is a strong indicator of depth. Here, we see some 3D images of the vertical derivative of the upward continued data exhibiting the strength and depth of the anomaly.

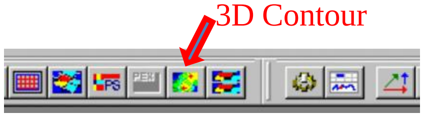


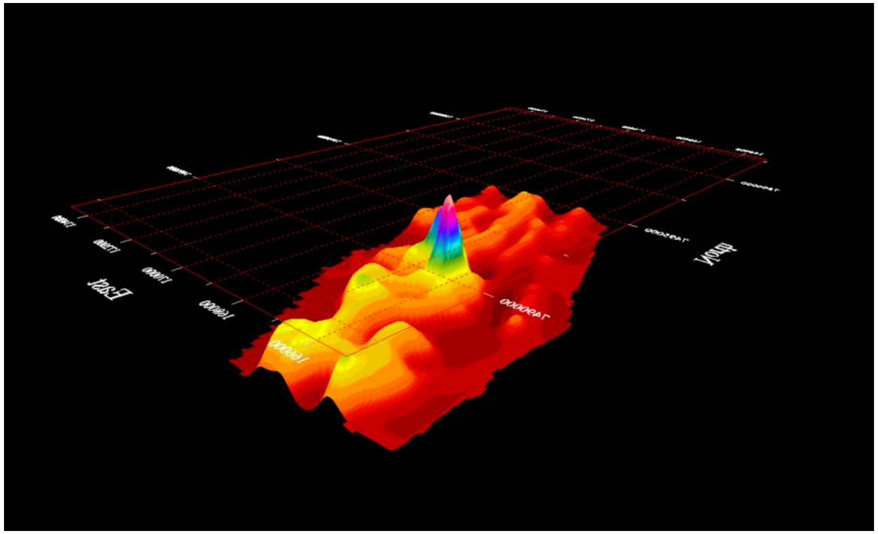
View from South





View from East

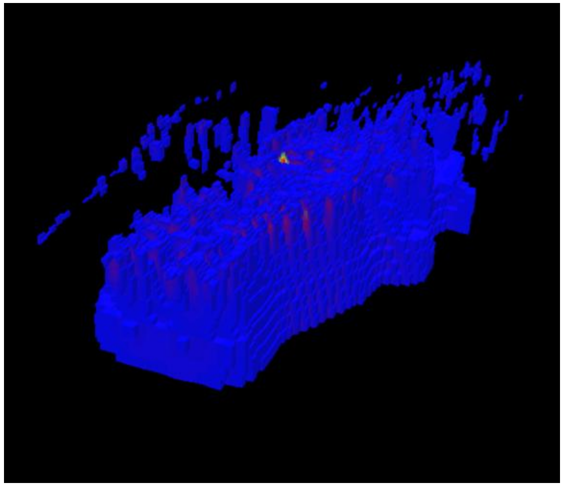

3D Contour



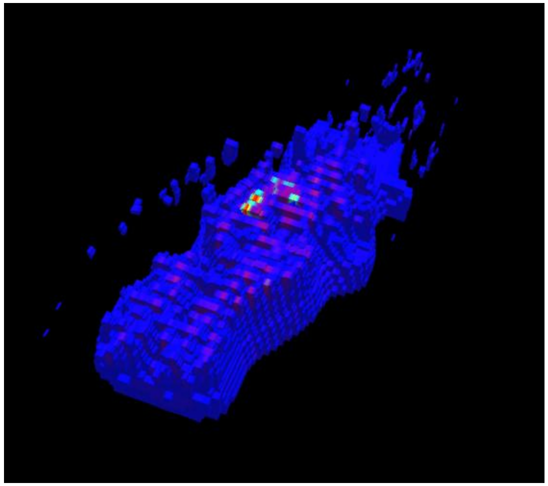
View from below

Magnetics 8 3D Inversion

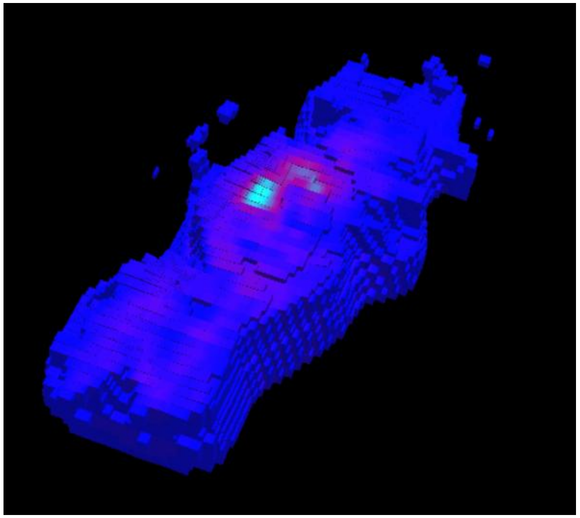
Here, we show the inversion grid with weak cells removed and then sliced to 2 depths. Blue cells are approximately 0.25 susceptibility and red cells about 1.8 susceptibility.



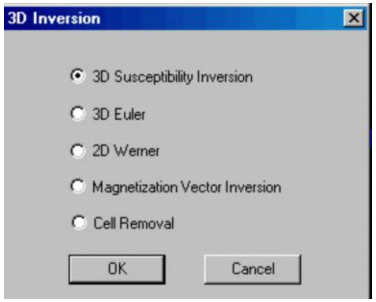
View from South



Sliced to 350 GPSZ
about 120m depth



Sliced to 100 GPSZ
about 370m depth

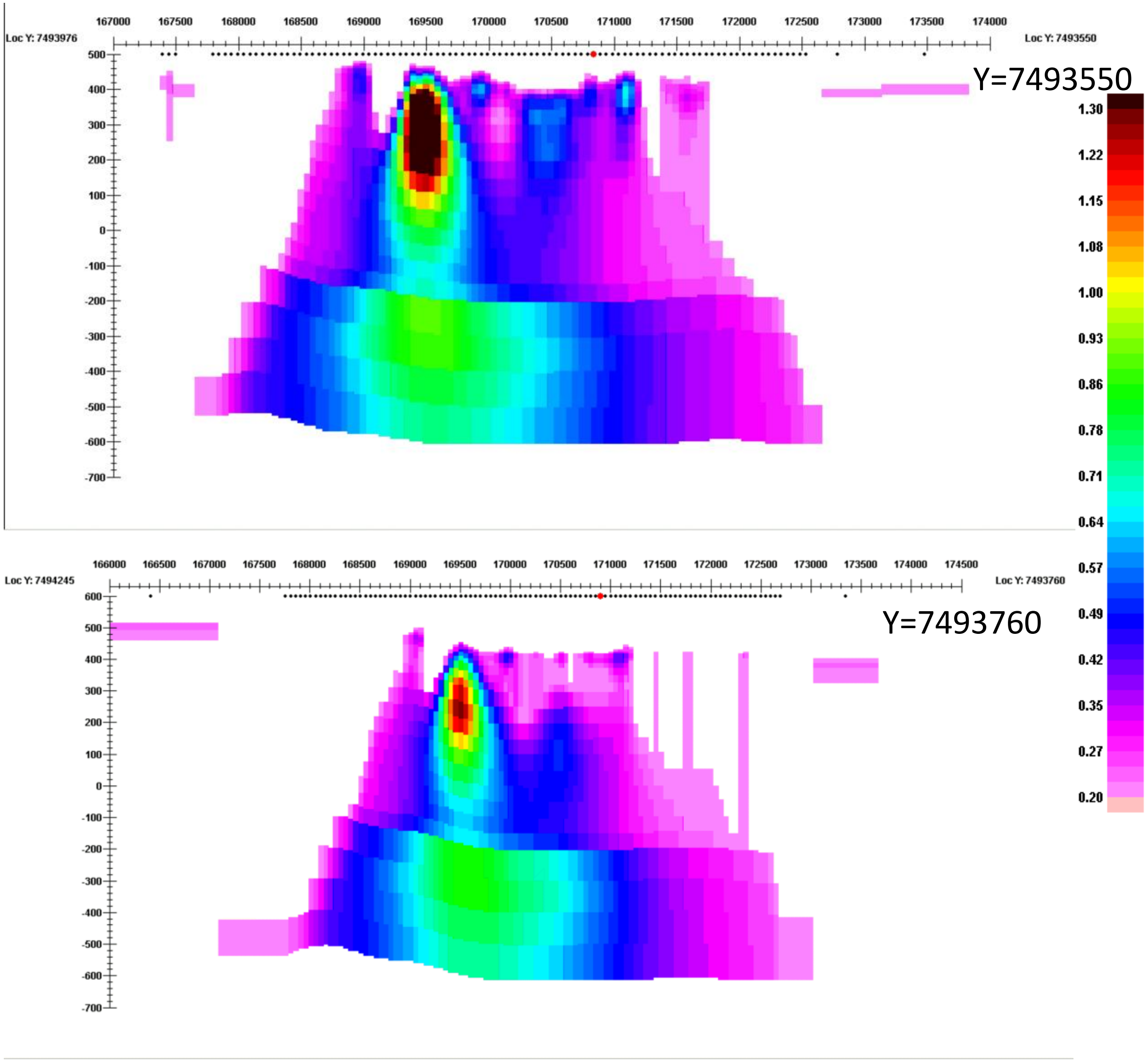


3D Inversion

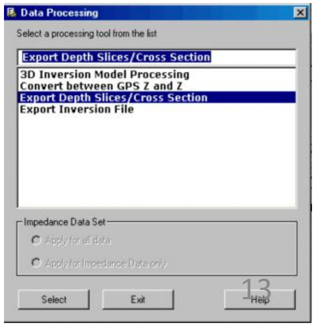
- ● 3D Susceptibility Inversion
- ○ 3D Euler
- ○ 2D Werner
- ○ Magnetization Vector Inversion
- ○ Cell Removal

Magnetics 9 3D Inversion

Another way to view is by creating cross sections through the Inversion processing tools. Here, we show 2 slices through the grid.



The Y indicators at either side show the northing at each end of the section cut.



Data Processing

Select a processing tool from the list

Export Depth Slices/Cross Section

- 3D Inversion Model Processing
- Convert between GPS Z and Z
- Export Depth Slices/Cross Section
- Export Inversion File

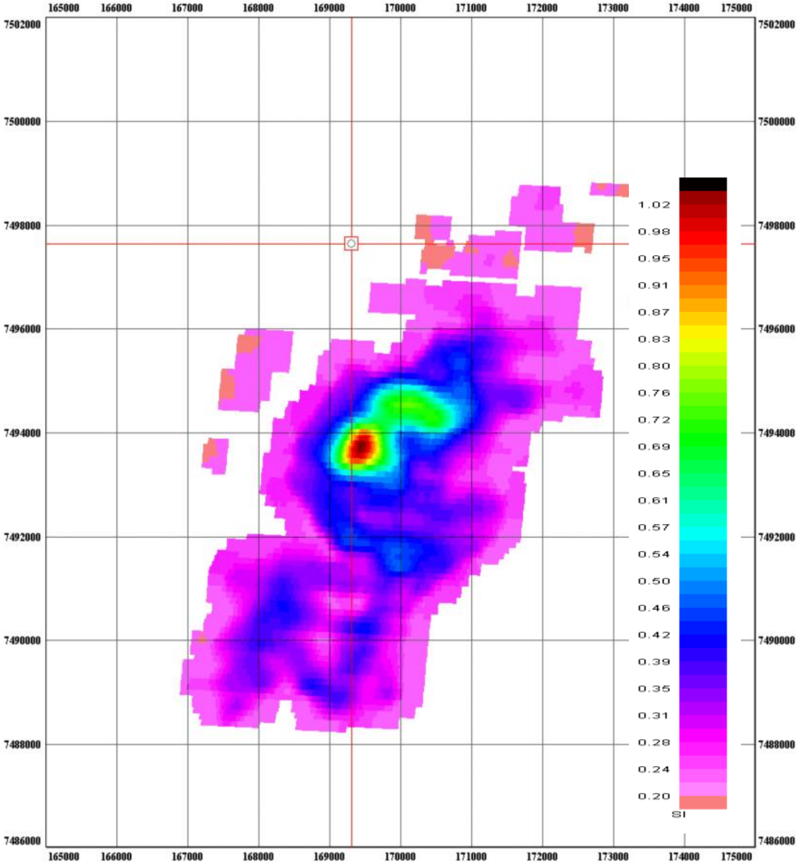
Impedance Data Set

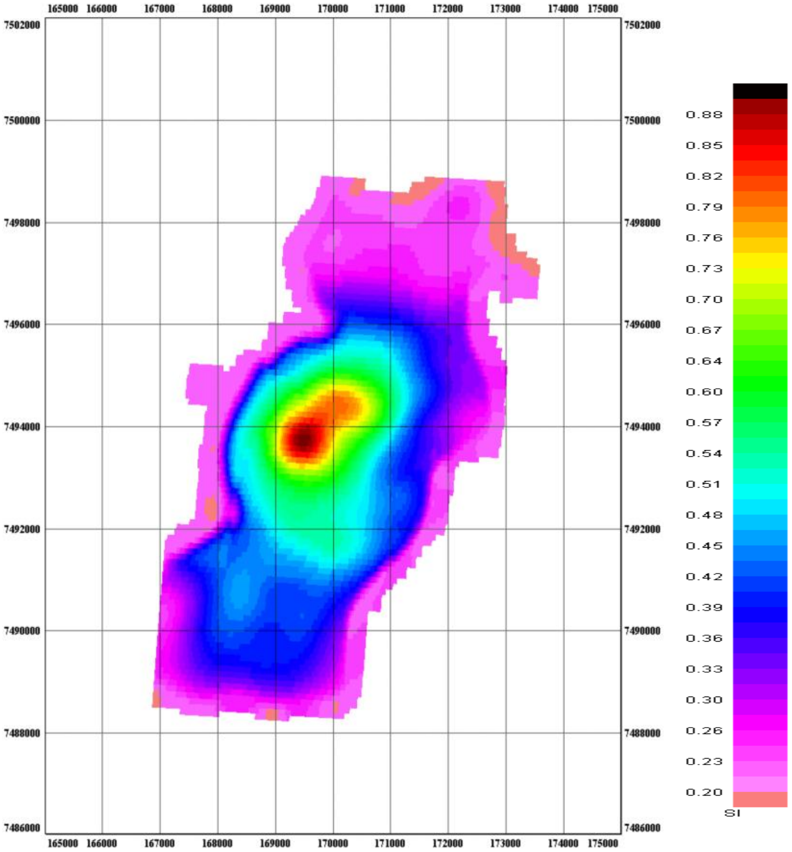
○ Apply for all data

○ Apply for Impedance Data only

Magnetics 10 3D Inversion

Another way to view the inversion grid is to export the inversion into cuts in the XY plane at each depth. Here, we see cuts at GPSZ depth of 92m and -262m (left) or about depths of 380m and 730m (right).



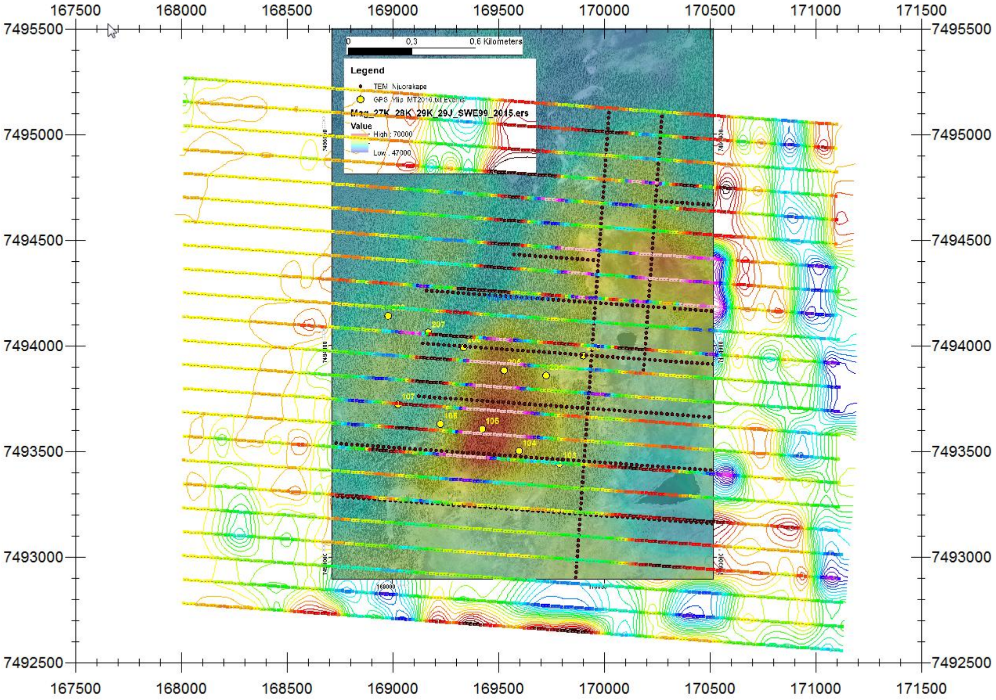


Magnetics 11 Focus Njuorakape Area

Now, we turn to a more detailed examination of the ground TEM and MT survey area. Our objectives are to a) more detail the magnetic structures in this area, b) to determine if the magnetic structures can be interpreted via conventional Born techniques and c) to see if an anomaly can be found which could be used to investigate the airborne TEM data from the SkyTEM survey.

With these objectives in mind, we cut the aeromagnetic survey area down to enclose our ground TEM survey and extract the magnetic derivatives to use in our modeling exercises.

Below, we see the gridded data extracted to a survey which includes all 3 derivatives. The vertical magnetic field is shown both in contour but also as values at the new survey points on the profiles. A map provided by LKAB is underlaid. This map is made in GridPresentation.

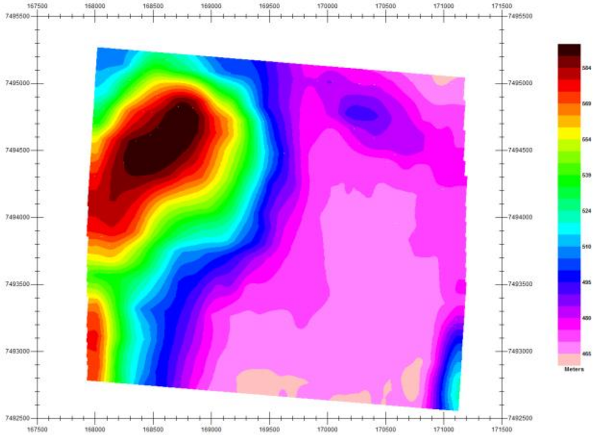


EMIGMA survey of TMI plus derivatives

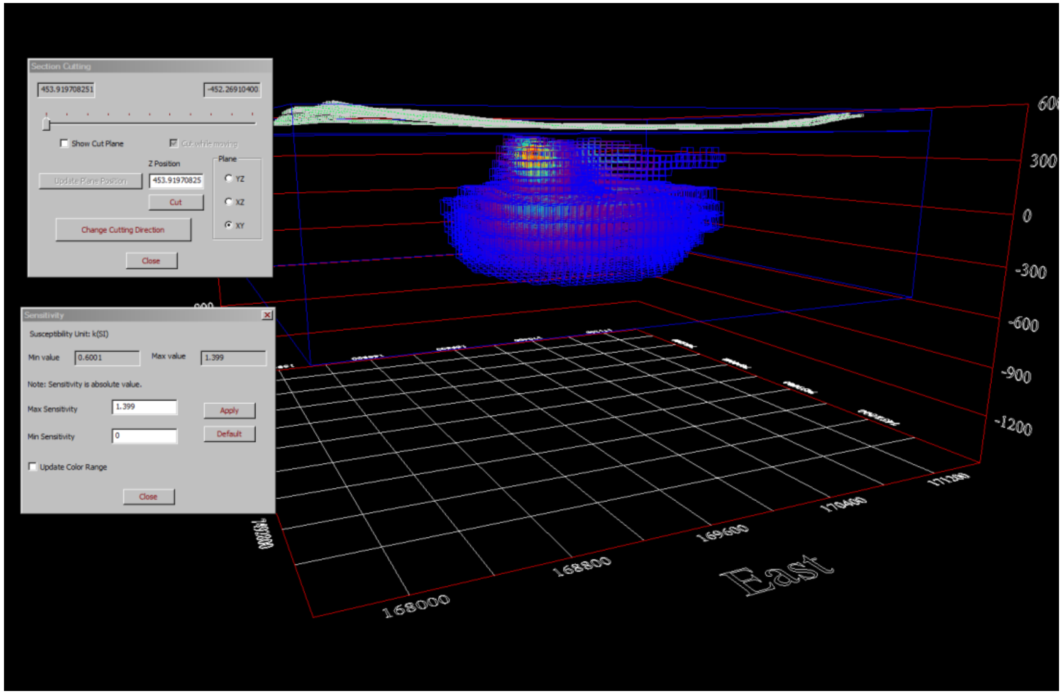
Magnetics 12 Aeromagnetic Inversion Focus: Njuorakape Area

A inversion is performed on the survey derived from the gridded data using the TMI and the vertical derivative, jointly. Cells with small susceptibility have been removed to focus on the stronger materials.

The derived model has these properties:
- 4900 cells
- GPSZ of top cell: 454m (DEM ranges from 463 to 595)
- GPSZ of bottom cell : -450m
- cells susceptibilities – 0.6 to 1.4



DEM model derived from gridded data



Section Cutting

453.919708251 -452.26910400

☐ Show Cut Plane ☑ Cut while moving

Z Position: 453.91970825

Plane: ○ YZ ○ XZ ● XY

Sensitivity

Susceptibility Unit: k(SI)

Min value: 0.6001 Max value: 1.399

Note: Sensitivity is absolute value.

Max Sensitivity: 1.399

Min Sensitivity: 0

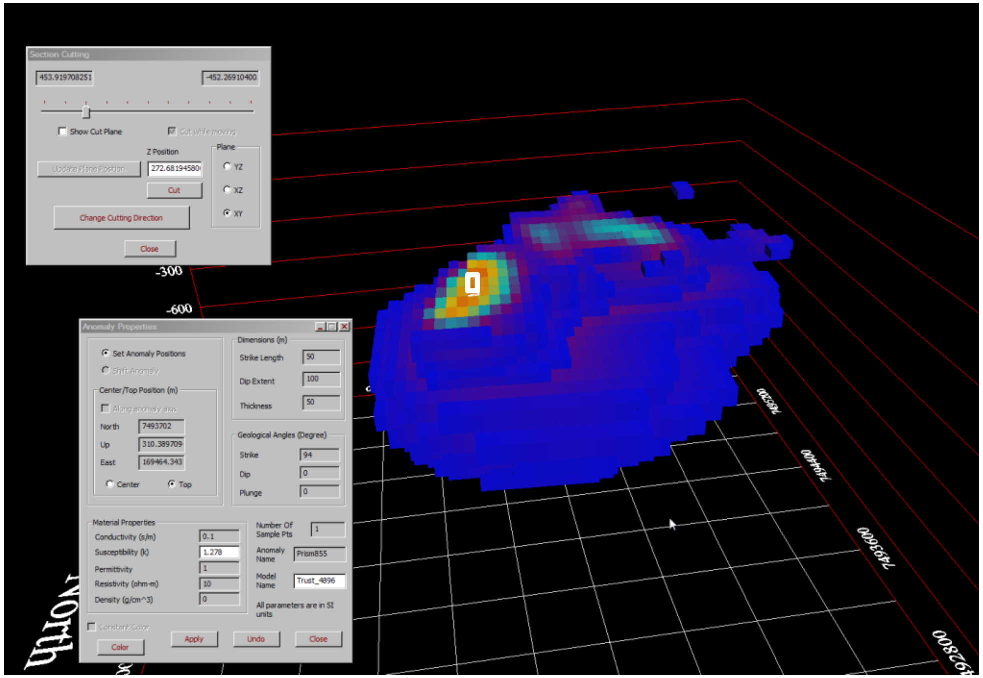
☐ Update Color Range

Note: Altimeter and GPSZ are included in the interpolated grids and thus can be exported to the new survey derived from the gridded data.

Magnetics 13 Aeromagnetic Inversion Focus: Njuorakape Area

A inversion is performed on the survey derived from the gridded data using the TMI and the vertical derivative, jointly. Cells with small susceptibility have been removed to focus on the stronger materials.

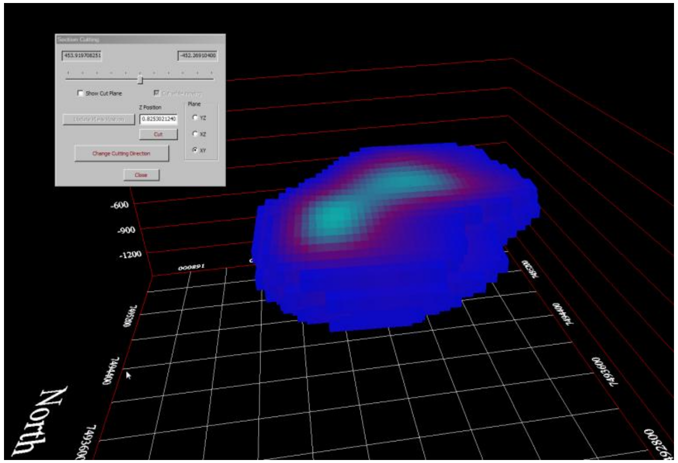
Sliced to an elevation of 273m (gps).
The properties of the selected cell are shown in the Anomaly Properties box.



Section Cutting: 453.919708251 | -452.26910400
☐ Show Cut Plane ☑ Cut while moving
Z Position: 272.68194580
Plane: ○ YZ ○ XZ ● XY

Anomaly Properties
● Set Anomaly Positions
○ Shift Anomaly
Center/Top Position (m)
☐ Along anomaly axis
North: 7493702
Up: 310.389709
East: 169464.343
○ Center ● Top
Dimensions (m)
Strike Length: 50
Dip Extent: 100
Thickness: 50
Geological Angles (Degree)
Strike: 94
Dip: 0
Plunge: 0
Material Properties
Conductivity (s/m): 0.1
Susceptibility (k): 1.278
Permittivity: 1
Resistivity (ohm-m): 10
Density (g/cm^3): 0
Number Of Sample Pts: 1
Anomaly Name: Prism855
Model Name: Trust_4896
All parameters are in SI units
☐ Constant Color

Sliced to an elevation of 0m (gps).

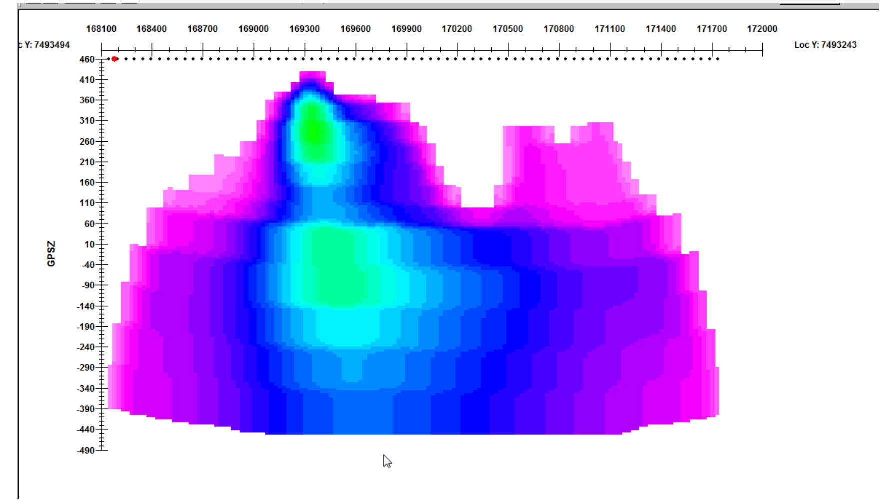


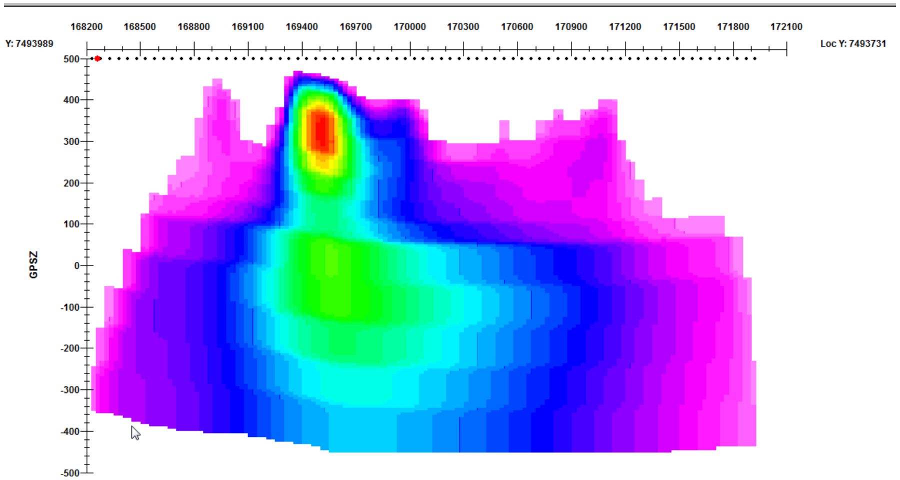
Section Cutting: 453.919708251 | -452.26910400
☐ Show Cut Plane
Z Position: 0.8253021240
Plane: ○ YZ ○ XZ ● XY

Magnetics 14 Aeromagnetic Inversion Focus: Njuorakape Area

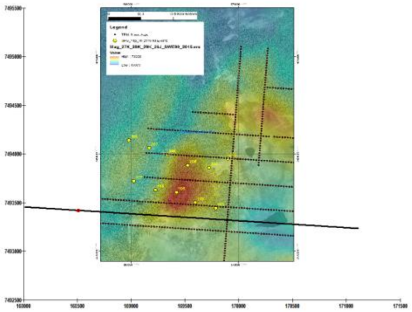
The magnetic structure consists of a large very deep component and a shallower, thinner object with a much stronger inverted susceptibility.

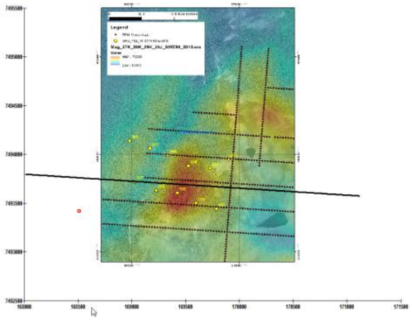
Inversion Section





Inversion Section Location





Addendum 2

Modeling and Inverting Magnetic data

Of course, there are 2 possible sources of the magnetic response,

a) an induced magnetization
b) a remanent magnetization

Both effects may be forward modeled in EMIGMA but we wish to consider here the modeling of induced magnetization. All magnetic modeling software except for EMIGMA assumes only one type of algorithm. That algorithm being that the induced magnetization is parallel to the local earth's field which is primarily the earth's dipole field. However, this is not strictly correct because magnetics is not gravity as there is an additional equation which governs the magnetic response and that is Gauss' law which is namely that

$$\nabla \bullet B = 0$$

and since the curl of B is also zero for DC magnetics then the boundary conditions for magnetics are the same as resistivity. In other words, the magnetic field bends around a magnetic anomaly.

The assumption that the Magnetization is parallel to the earth's field is a Born scattering assumption. EMIGMA offers both Born and a non-linear solution, ie. the nonlinear approximator (LN) solution for the complete solution.

Additional issues which EMIGMA addresses is the interaction between magnetic bodies which is not considered in other software.

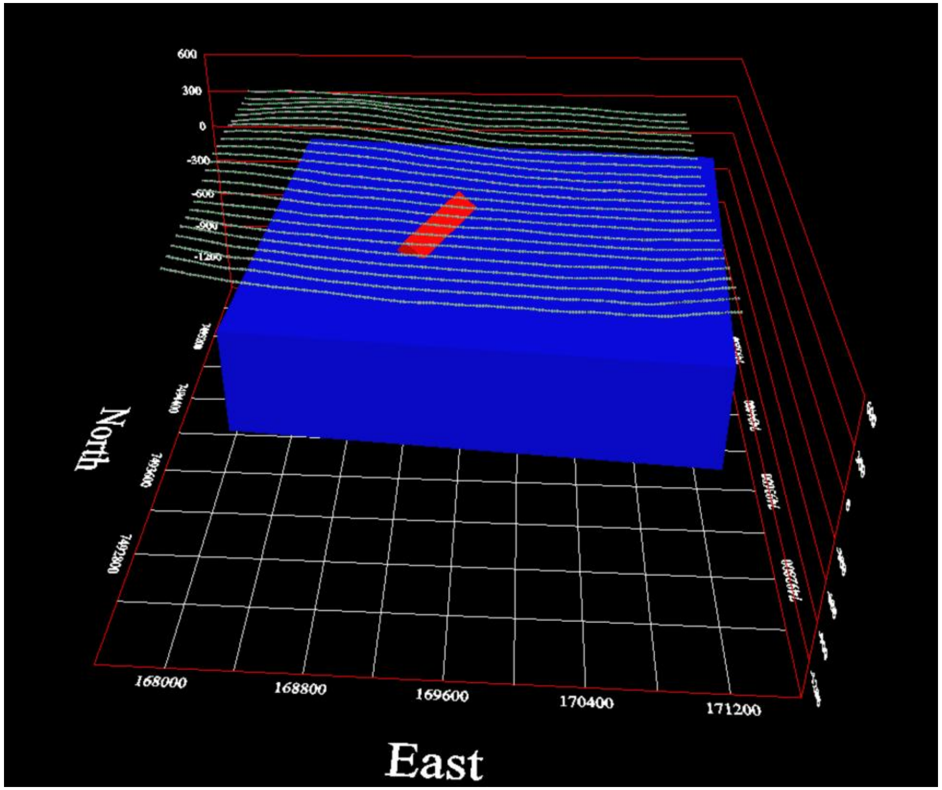
However, inverting under the non-linear assumption is a very long computation compared to the Born approach and thus it is common to invert assuming Born and then check the susceptibility by forward modeling under the non-linear assumption.

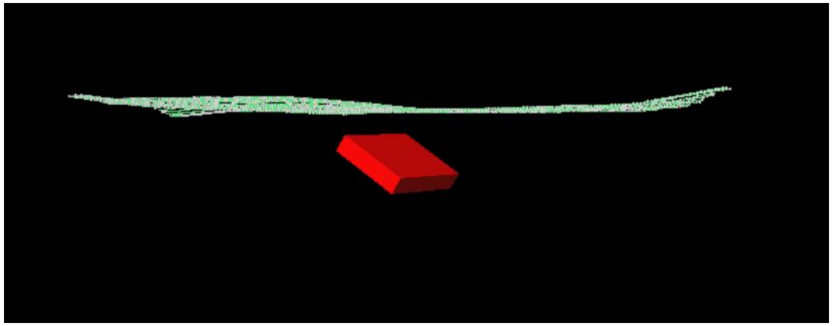
Magnetics 15

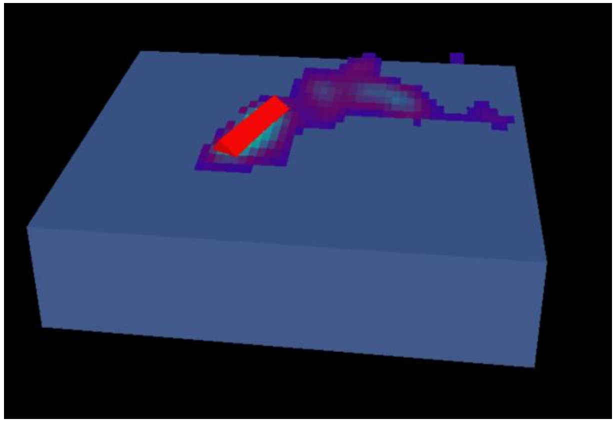
Model from 3D inversion

The inversion indicates a large block of higher magnetic susceptibility which causes a general overall increase in the magnetic field response over the area. This is model in simplicity as a single block of size 2400x2800x700 with a depth to top of 300m (gpsz) and a susceptibiliy of 1 SI. The shallower anomaly is modeled as an anomaly of 700m x 400m x100m striking at 25 degrees east of north and dipping at 35 degrees with a susceptibility of 10 SI, with a depth to top of 390 (gpsz). The figures below indicate the model.

The model is constructed in the Visualizer using the inverted model as a background.

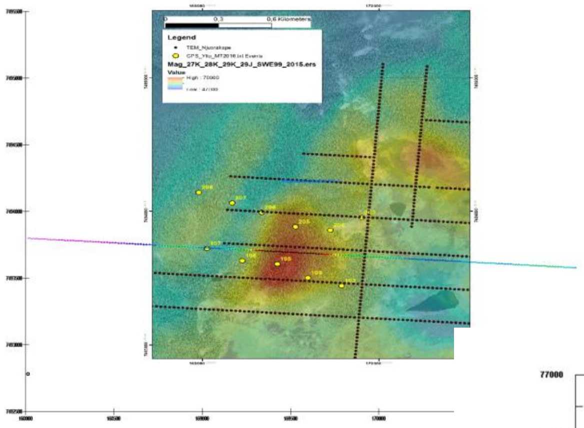




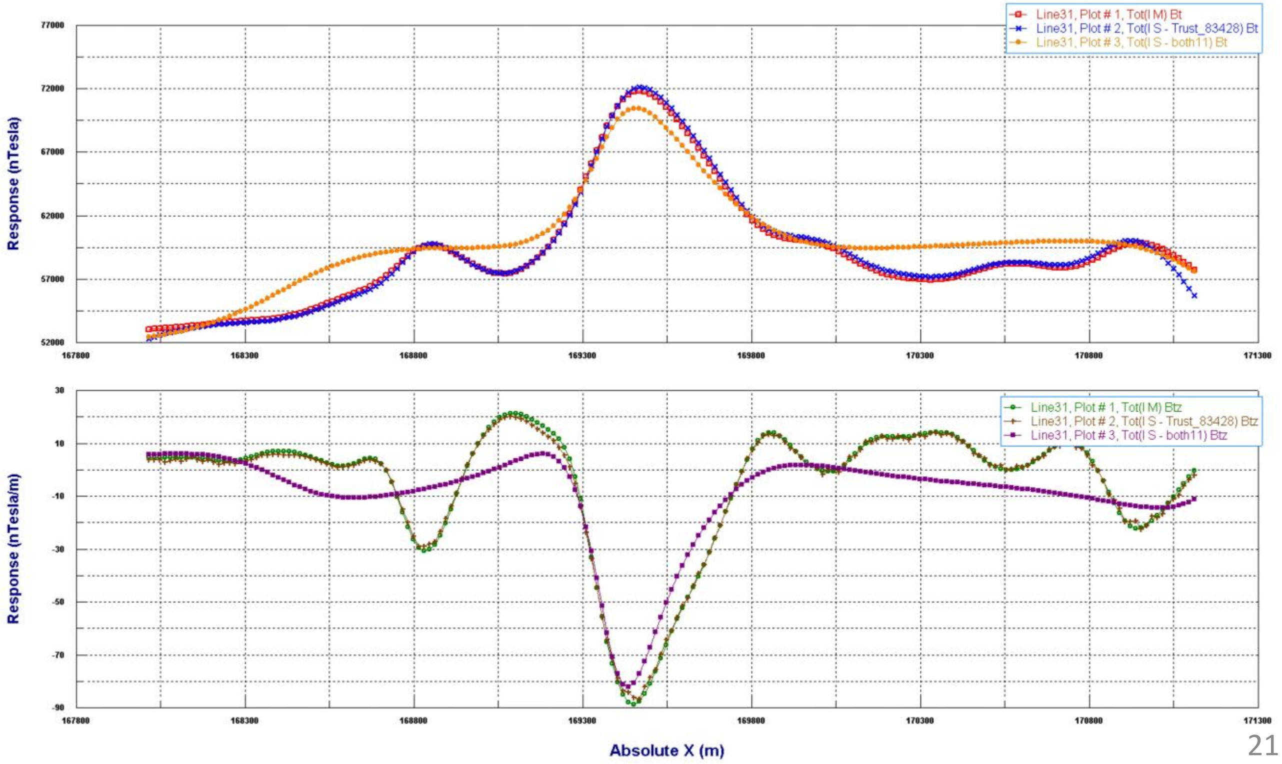


Magnetics 16 Model from 3D inversion

The principle purpose is to determine if a non-linear simulation is required to determine the magnetic properties. Thus, for example, we compare out data (TMI and d Bt/ dz) with the inversion results and an estimated simple model.



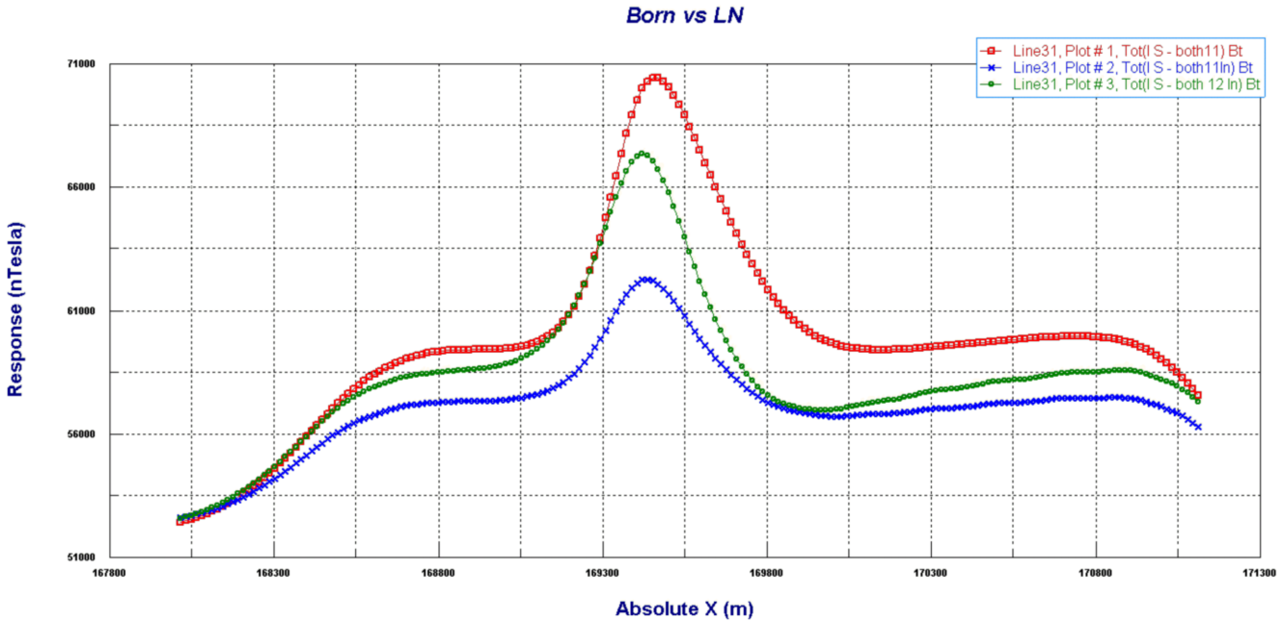
TMI and Vertical Derivative Comparisons
top figure: TMI, red (measured), blue (inverted), orange (model)
bottom figure: dz , green(measured), brown (inverted), purple (model)



Magnetics 17 Determining Susceptibility

We will now compare the simulation under the Born vs LN and then proceed to determine the correct susceptibility.

Below, we see a comparison between the estimated model using Born susceptibilities derived from the inversion.
Red: target k=2.7 , block basement: 0.7
Blue is the response of the same model but using a full solution non-linear algorithm. This indicates for the size of the objects and their susceptibilities that this weak magnetization approximation is not appropriate.
Green is a closer estimate: target k=10 , block basement: 1



TMI for the Estimated Model
red: linear, blue: LN and green: LN increased susceptibility

Conclusions

1: First, we now have some indications of the large geological features which will be critical to at least the interpretation of the magnetotellurics if not the airborne and ground TEM.

2. We have isolated a highly magnetic target which would imply a metal and thus a conductor. Having this model, we can utilize this model to evaluate the SkyTEM airborne EM data.