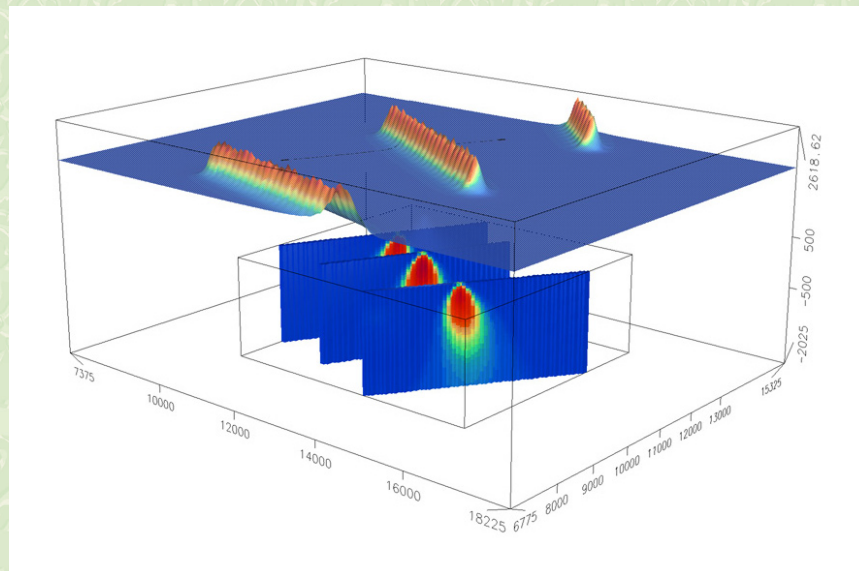




Apparent magnetic models with "upward continuation filter"



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FoU projektnr 35132

APPARENT MAGNETIC MODELS WITH "UPWARD CONTINUATION FILTER" (UCF).

FAST PROCESSING OF AIRBORNE DATA TO CREATE MAGNETIC PSEUDO-SECTIONS

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ABSTRACT

The method uses gridded flight-line data and processes them based on the parameters selected by the user. The method is based on the paper by Pedersen (1991) and uses the concept of equivalent sources and tries to estimate the distribution of magnetization at depth. We have made a program that calculates the magnetization in equally thick layers that are located at different depths. The estimation is carried out over the surfaces equal to the original data grid. The final results can be shown as pseudo magnetic sections along the selected directions. The method is first evaluated by generating various synthetic data sets from the models of well-defined geometry. The pseudo magnetic sections from dipping thin dikes show the same dip direction but as we expected with a much smoother variation and wider anomaly signature. The sharp variations of magnetization at depths were comparable to the real structure depth within 10-15% of accuracy. The final picture is very much dependent on the correct choice of structural index. The method was then applied to the real data from south of Ragunda. The results were also shown in 3D using the voxel model in Oasis Montaj.

THEORY

Pedersen (1991) derives equations for the magnetic potential and magnetic field due to thin sheet source distribution. As a result, the potential and the field can be conceived as superposition of double- and single-layer distributions related to the sheet magnetization. This can be written as

$$\Delta H_e = -\frac{1}{4\pi} \int_S [\nabla_t \cdot (J_{ns} e_t) + (\nabla_t \cdot J_{ts}) e_n] \frac{\partial}{\partial n} \left(\frac{1}{R} \right) dS + \frac{1}{4\pi} \int_S [-\nabla_t^2 \cdot (J_{ns} e_n) + \nabla_t \cdot ((\nabla_t \cdot J_{ts}) e_t)] \frac{1}{R} dS \quad (1)$$

In which the quantities shown in the equation are defined as:

S = The surface that confines the magnetic volume, V .

∇_t = Horizontal gradient operator within the volume V .

J = magnetization density vector within the source region.

\hat{e} = The measurement direction of the field.

$$J_{ns} = \lim_{n_+ \rightarrow n_-} \int_{n_-}^{n_+} J_n dn$$

$$J_{ts} = \lim_{n_+ \rightarrow n_-} \int_{n_-}^{n_+} J_t dn$$

$R = |\mathbf{r} - \mathbf{r}_0|$ is the distance between the observer & the integration point.

For a uni-axially magnetized half-space it can be shown that using equation (1) in the Fourier domain the magnetization can be described in terms of measured field by

$$\tilde{J} = \frac{2}{e_z} \frac{1}{V(\mathbf{k})} \Delta \tilde{H}_e = \frac{2}{e_z} \Delta \tilde{H}_z \quad (2)$$

Where

$$V(\mathbf{k}) = \frac{1}{|\mathbf{k}|} \hat{e} \cdot i\mathbf{k} + |\mathbf{k}| \hat{z} \quad (3)$$

and the tilde represents Fourier transformation. In equations (2) and (3) e represents a unit vector in the direction the field is measured and defined as

$$\hat{e} = (\cos I \sin D, \cos I \cos D, \sin I) \quad (4)$$

with I and D as the inclination and declination of the ambient magnetic field, respectively. These equations express the magnetization where the equivalent surface is parallel to plane of measurements at $z_0 = 0$.

For a composite model consisting of sandwiches of M sheets in which magnetization is of induced type and varies just as a function of x and y we find

$$\Delta\tilde{H}_e(\mathbf{k}) = \frac{1}{2} V^2(\mathbf{k}) \sum_{i=1}^M [e^{-|\mathbf{k}|h_i} - e^{-|\mathbf{k}|h_{i+1}}] \tilde{J}_i(\mathbf{k}) \quad (5)$$

where h_i s are the depths to the top of each thin sheet. What we are after is to make a sandwich model and try to estimate the magnetization at each layer interval. We have used the method proposed by Pedersen (1991) that is first based on the filters obtained by Jacobsen (1987) to estimate the part of total magnetic field measured at the surface which derives from a particular layer in the sandwich distribution. They assume that the magnetizations in layers are uncorrelated and the magnetization energy distribution is independent of depth. A least square method is then used to minimize the differences between the expected values of the measured and estimated fields due to the magnetization in the i^{th} layer. This can be written as

$$E \left[\tilde{F}_i \Delta\tilde{H}_e - \Delta\tilde{H}_e^i \right] = \text{minimum} \quad (6)$$

and $\tilde{F}_i, \Delta\tilde{H}_e, \Delta\tilde{H}_e^i$ are the Fourier transforms of filter, total magnetic field and the magnetic field due to the sandwich layer i , respectively. Using equations (5) and (6) the filter can be defined as

$$\tilde{F}_i = \frac{E \left[\Delta\tilde{H}_e^i \right] (e^{-|\mathbf{k}|h_i} - e^{-|\mathbf{k}|h_{i+1}})^2}{E \left[\Delta\tilde{H}_e \right] \sum_{n=1}^N (e^{-|\mathbf{k}|h_n} - e^{-|\mathbf{k}|h_{n+1}})^2} \quad (7)$$

Using equations (5) and (7) one can calculate the magnetization in layer i according to

$$\tilde{J}_i(\mathbf{k}) = \frac{2}{V^2(\mathbf{k})} \frac{e^{-|\mathbf{k}|h_i} - e^{-|\mathbf{k}|h_{i+1}}}{\sum_{n=1}^N [e^{-|\mathbf{k}|h_n} - e^{-|\mathbf{k}|h_{n+1}}]} \Delta\tilde{H}_e(\mathbf{k}), i=1, N \quad (8)$$

In our application we have used a simple case where infinite numbers of layers ($N \rightarrow \infty$) with the same thickness (d) are assumed. In such a case equation (8) is reduced to

$$\tilde{J}_i(\mathbf{k}) = \frac{2}{V^2(\mathbf{k})} (e^{-|\mathbf{k}|h_i} + e^{-|\mathbf{k}|h_{i+1}}) \Delta\tilde{H}_e(\mathbf{k}) \quad (9)$$

Equation (9) is the base for the approach we have used in this project to make a magnetic pseudo-section over the target anomalies in a proper direction. This provides a possibility to make magnetization pseudo-sections and even 3D pseudo models very quickly. For a given layer thickness of d , at a depth between h_i and h_{i+1} the magnetization density is calculated using equation (9) in the Fourier domain and the same procedure is repeated for all layers selected. At the final stage the data are transferred into the space domain and saved in the gxf grids that are ASCII Oasis Montaj grids.

PROCESSING PROGRAM

A user interface in Oasis Montaj in the form of a loadable menu, so-called GX, is made to ease the use of program. In the following we deliver a rather detailed description of the program and the reader can find the body of programs in appendices A and B.

GX CODE IN OASIS MONTAJ

The GX code can be loaded in the standard Oasis Montaj menu bar. The menu is called PseudoMag and resides in “C:\Program Files\Geosoft\Oasis Montaj\omn” (see figure 1a). The menu is then added in the Oasis Montaj menu bar (figure 1b).

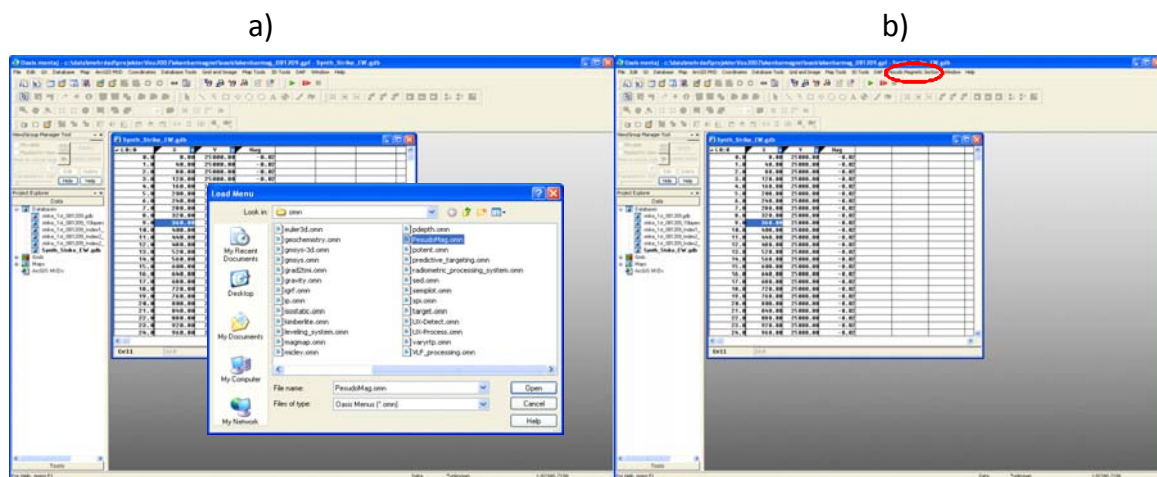


Figure 1. a) Selection and b) loading of the PseudoMag program in the Oasis Montaj environment.

To run the program you have to grid the data into a gxf grid format using the first item in the Pseudo Magnetic Section menu as shown in figure 2. NOTE: you have to make a **text gxf** format not a compressed gxf.

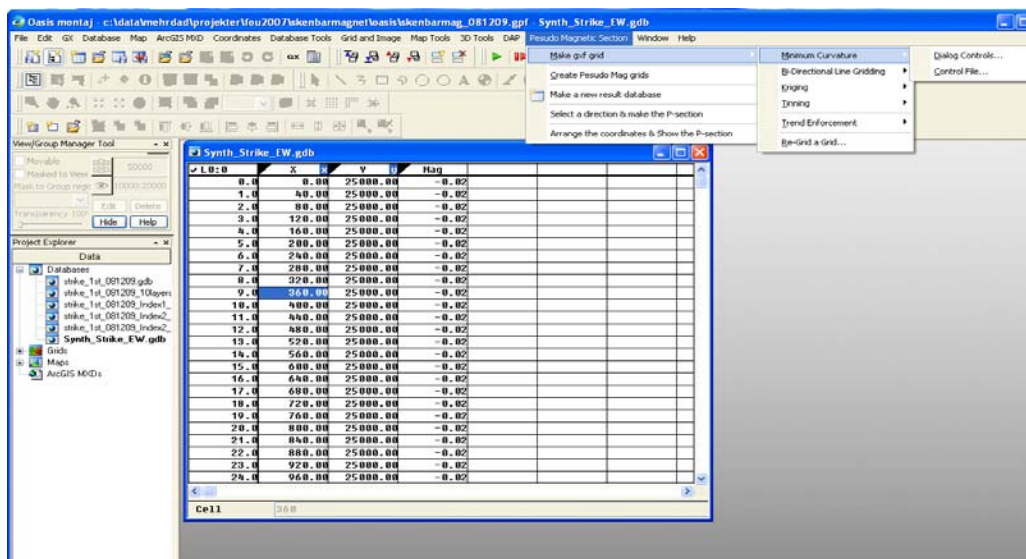


Figure 2. Data preparation into a gxf grid from a database.

One can specify the type of gridding, grid name and grid cell size. Note that the grid name is the last name for the last program execution (see figure 3).

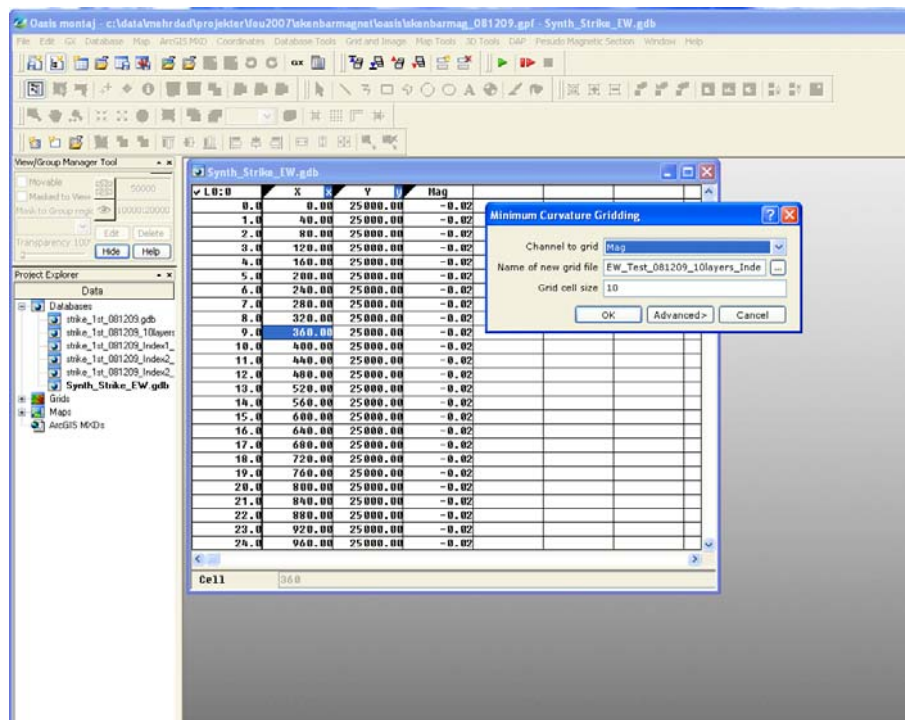


Figure 3. Grid specification in step 1.

The main process runs in the next stage by selecting the “Create Pseudo Mag grids” from the list (see figure 4).

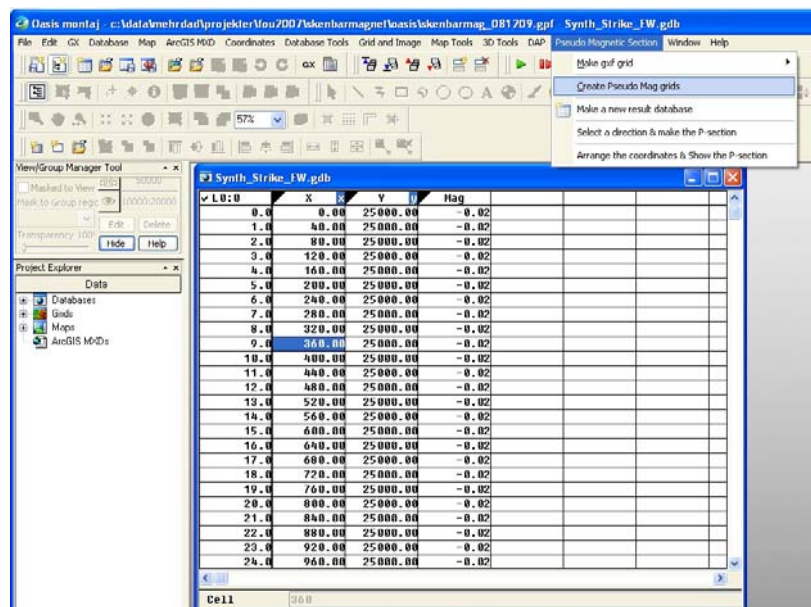


Figure 4. Activation of the main process in Pseudo Mag menu.

Then a dialogue box shown in figure 5 pops up and the user has to specify the processing parameters that are partly described in the theory section. The parameters are

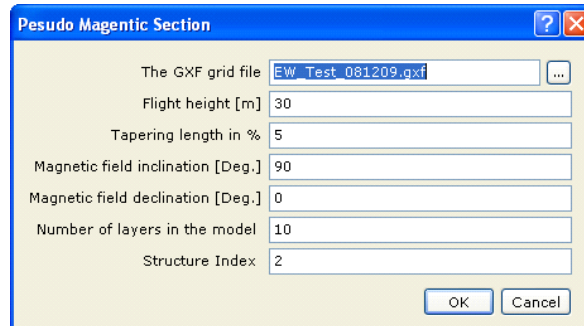


Figure 5. The dialogue box for setting up the processing parameters.

- Name of the generated gxf grid file. Note that an old grid file can also be selected for processing to skip the first step.
- Flight height in case of airborne data analysis
- Tapering length is given in percent of data in each profile side. The tapering is done using a cosine taper that prevents the Gibbs phenomena
- Magnetic field inclination (degrees)
- Magnetic field declination (degrees)
- Number of layers in the model determines the maximum depth. The depth resolution is determined by the grid cell size. If the grid cell size is 10 m for example, and the number of layers is selected equal to 10, then the maximum depth shown in the model is 100 m only. On the other hand more number of layers required it adds up the processing time. One must consider also that the processing is performed once and the results can be used in several directions for a given dataset or study area.
- Structural index (0-contact, 1-infinite thin sheet, 2- horizontal cylinder, 3- sphere). One can even use non-integer values for the intermediate shapes like a thicker vertical dike that can have an index of about 1.5. We use this parameter to account for the distance between source and measuring point.

You have to remember an important point. The program calculates the magnetization density for a given specific type of structure and therefore an attention must be paid when selecting the index parameter. If you are after dike-like anomalies an index of 1.5 must be proper. The Matlab executable file runs and processes the data. An MS-DOS like window shows the stages taken in the processing (figure 6).

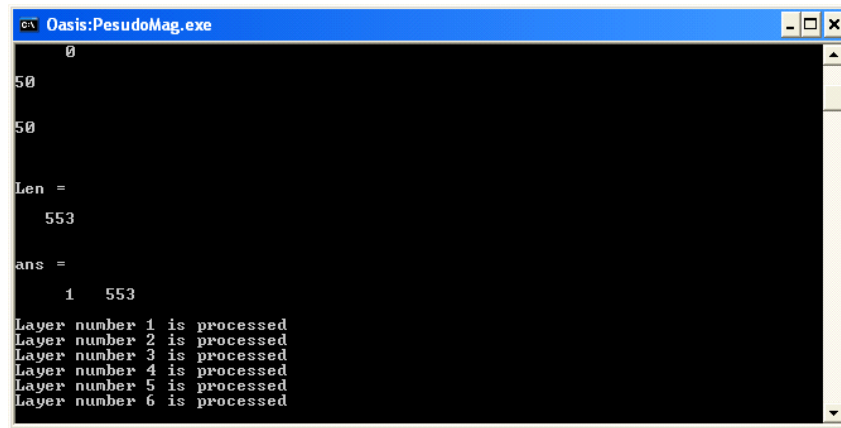


Figure 6. Matlab processing output window while the Pseudo Mag program runs.

The processed data can then be transferred into a database for visualization. A new database is then needed for each selected direction. One can make a new database via using the 3rd item in the dropdown list and completing the dialogue box shown in figure 7.

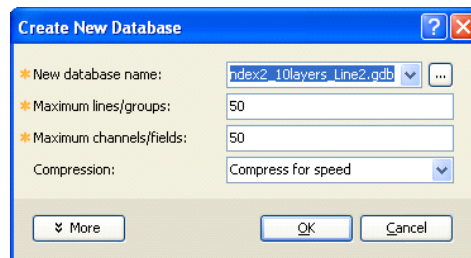


Figure 7. The dialogue box for making a new database to store new results along a selected direction.

The data for each layer are registered in a separate gxf grid, gxf_i , $i=1,N$ where N is the number of layers given as the input parameters to the code (see figure 5). In order to visualize the results one has to select the desired anomaly and also the direction. This means that the magnetic anomaly map has to be selected as the active map and a good assessment about specific anomaly (or structural index) and preferred direction has to be made. One can also gain such knowledge by trial and error. The selection can be made by using the item number 4 in the drop-down list of the application as shown in figures 8 and 9. A popup menu provide the possibility of selection of number of layers to show in the pseudo selection that controls the maximum depth. One has to be careful not using a number of layers greater than the original one given at the beginning of the processing.

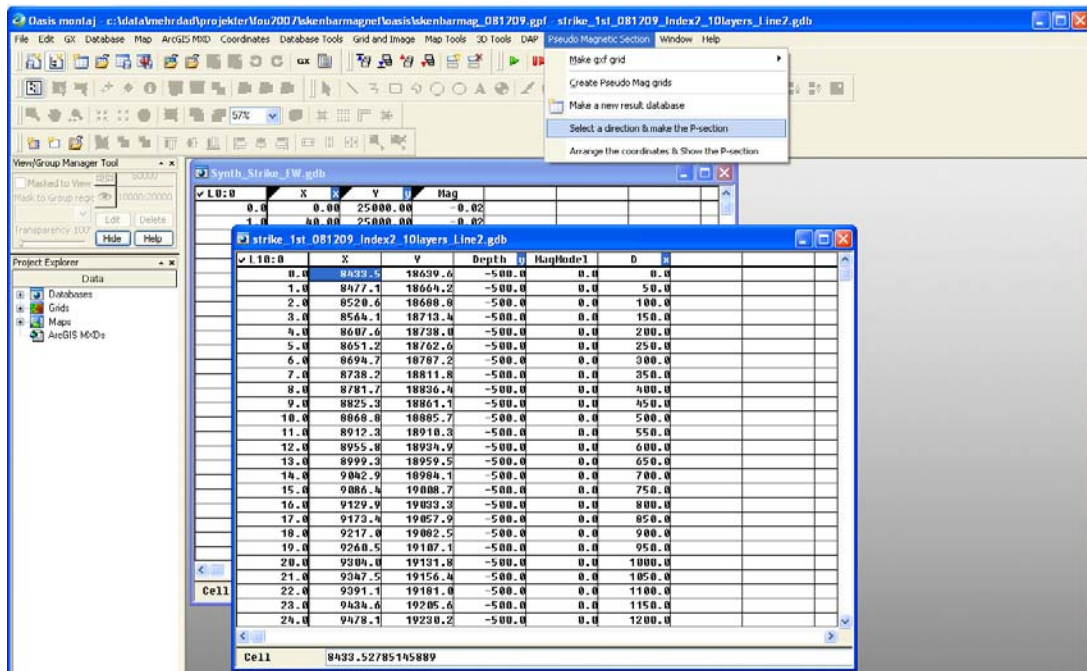


Figure 8. Selection of preferred anomalies and directions.

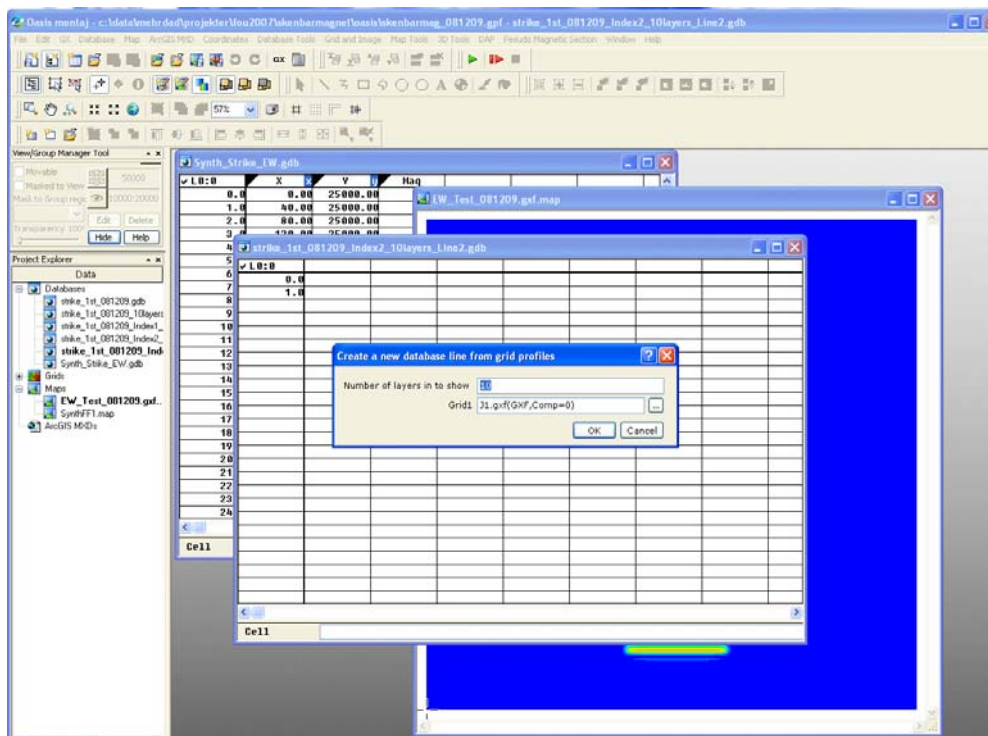


Figure 9. The popup menu that controls the number of layers to use when making the section. This parameter controls the maximum depth and must not be greater than the original number of layers given at the beginning of the processing.

A message box labelled “Extract profile” appears on the screen (figure 10) that informs about the selection of profile and how to terminate the selection procedure.

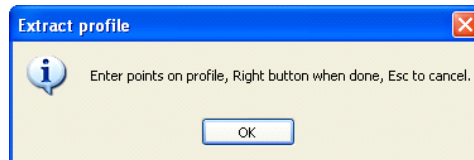


Figure 10. Message box showing the selection choices.

At this stage the active map is the one that you can select the target anomaly and desired direction. Therefore selection of original magnetic/gravity anomaly maps as the target map would help to save some time and to reduce erratic selection of anomalies using improper active maps. Figure 11 shows an example of magnetic anomaly map from the synthetic models we made to test the method. The model consists of a set of thin dikes with changing strikes. The map is chosen as the reference to select the target anomalies. The line in the map shows the selected anomaly and direction.

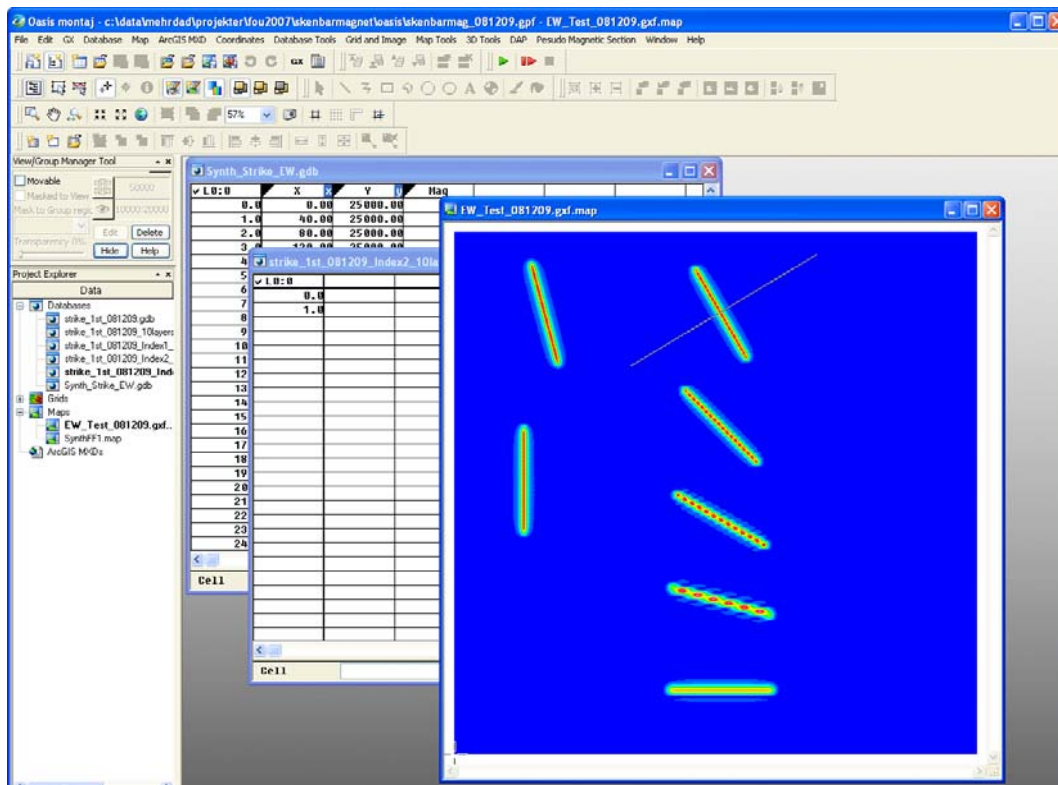


Figure 11. An example of selection of anomaly and direction. With a left mouse click the points are selected and at the end a right mouse click terminates the selection and data are transferred to the database.

The selected data from the grid are then saved into the database that the user has created. Each layer is saved as a line in the database and later is used to make the pseudo-section. The last step is to rearrange the coordinates in the database so that the depth and distance along the selected direction are set as the x and y and then visualize the results. Figure 12 shows how the rearrangement can be achieved using the last item in the list. The last step selection will run a GX routine that activates a dialogue box to create the distance channel (figure 12). The defaults are given in the dropdown lists and can be changed if needed.

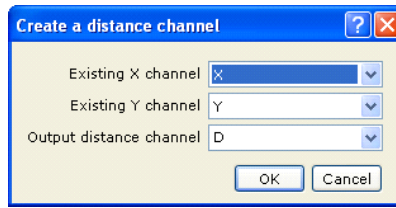


Figure 12. The dialogue box to create the distance channel.

The distance channel is created and added to the database. Another dialogue box is then shown to set the resulting output model grid in GXF format (figure 13). One must also set the grid cell size and also the channel to grid. The default channel name is MagModel that holds the results. One may want to filter the results prior to visualization and save them in another channel other than MagModel.

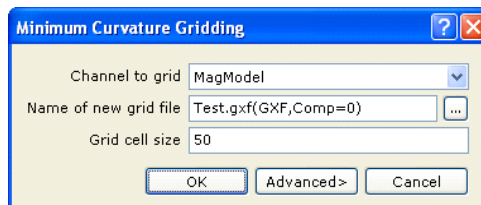


Figure 13. Dialogue box to select the result channel, output result filename and the grid cell size.

By feeding in the parameters the selected data are gridded and visualized in a map. The map shows the magnetization density pseudo-section along the selected direction. Figure 14 shows the final results (magnetization density pseudo-section) from the selection shown in figure 11.

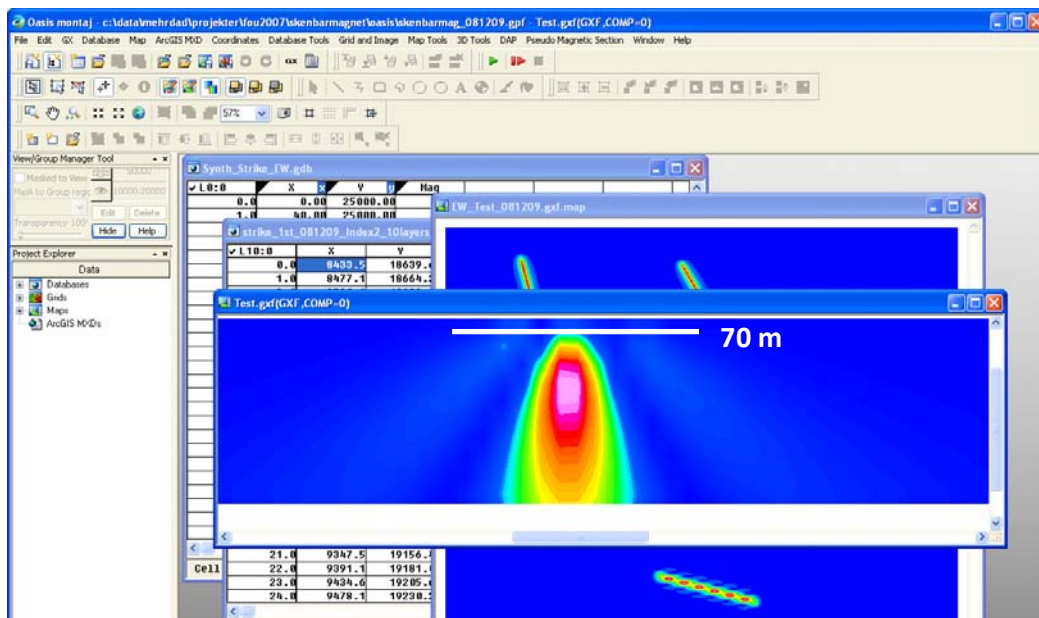


Figure 14. Pseudo section of magnetization density for the selection made in figure 11.

TEST WITH SYNTHETIC DATA

We applied the proposed method to a number of synthetic datasets to check the resulting sections with the true models. We show two examples in this document.

- **Thin dikes with changing strikes:** The model shown in figure 15 is a combination of seven thin dikes each having a different direction.

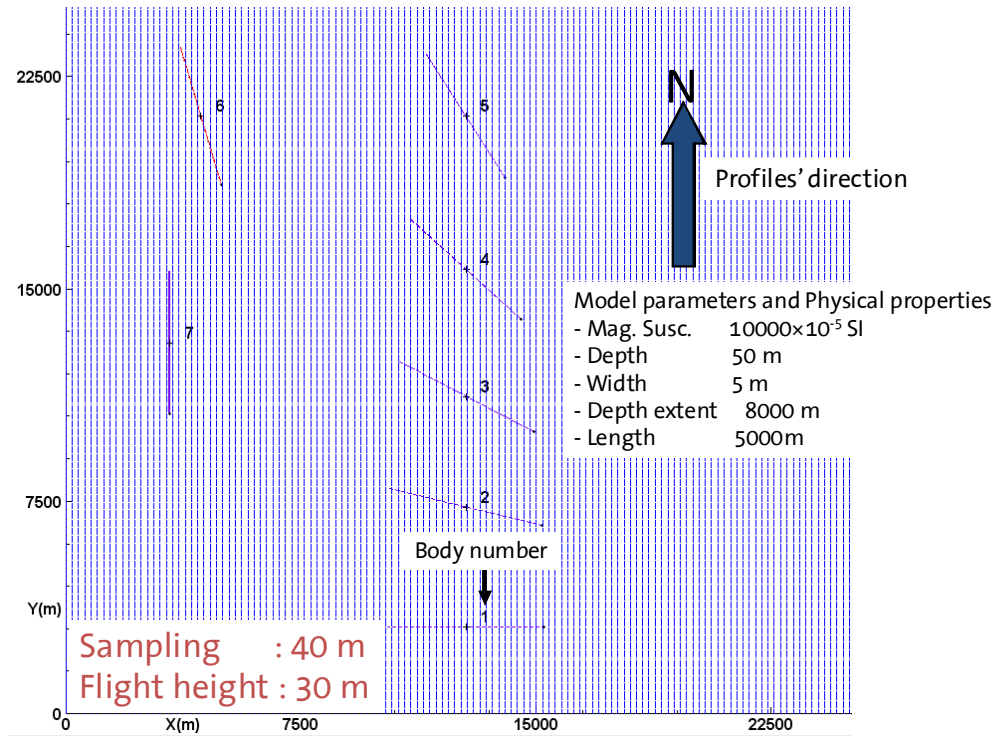


Figure 15. The synthetic dike models with changing strikes used to test the pseudo magnetic method.

In figure 14 we have already shown the results of pseudomag processing along the selected direction (figure 11) on dike number 5. The physical parameters of dike are given in figure 15. It is vertical, located 50 m below the surface and is 5 m wide. The white horizontal line in figure 14 indicates the depth to the top of body causing this anomaly. It shows a depth of about 70 m and a vertical distribution of magnetization. The width is of the order of 100 m which is extremely overestimated. But the dip and the depth are rather well-determined.

- **Spheres at different depths:** The second synthetic dataset is the total magnetic field from two spheres with the same physical specifications but located at different depths. Table 1 contains the details about the spheres.

Body	Diameter (m)	Depth of centre (m)	Magnetic sus. (SI)
1	2000	1300	0.01
2	2000	1500	0.01

Table 1. Source parameter of spheres in the model shown in figure 16a&b.

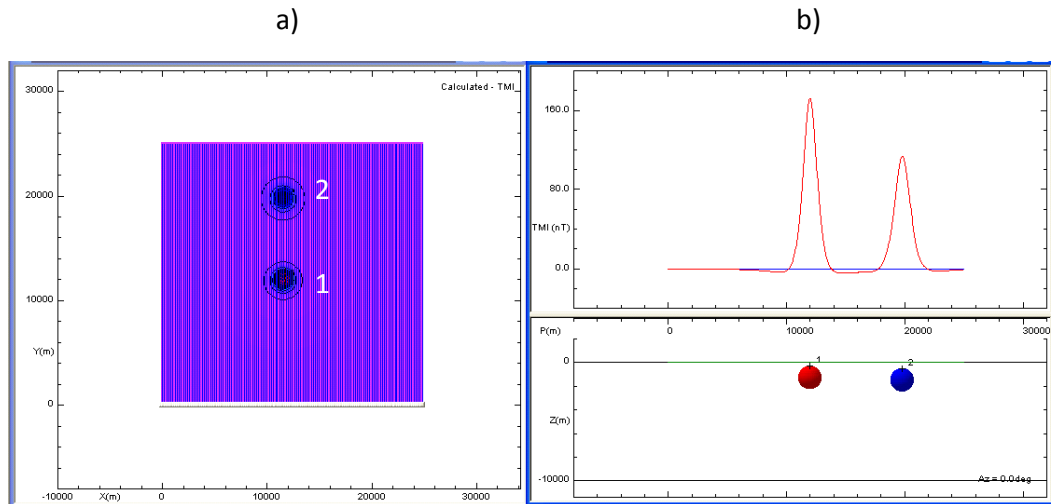


Figure 16. The second synthetic model consisting of two identical spheres located at different depth. a) map view, b) the section view.

The data are generated in a way to resemble a real airborne measurement condition. The model responses are calculated along flight lines with 200 m separation and sampled at 40 m distance along each line. The modelling has been done in POTENT. The map view and section view of the model are shown in figure 16a&b. The model response along line 11400 is also shown on top the section view in figure 16b. The data are then imported to a xyz text file with a Oasis Montaj compatible format. The map of model response at 30 m above the ground was created using Oasis Montaj and is shown in figure 17 where two distinct circular magnetic highs are observed. We applied the method to this dataset along two profiles shown in figure 17. The results are presented in figures 18a and 18b.

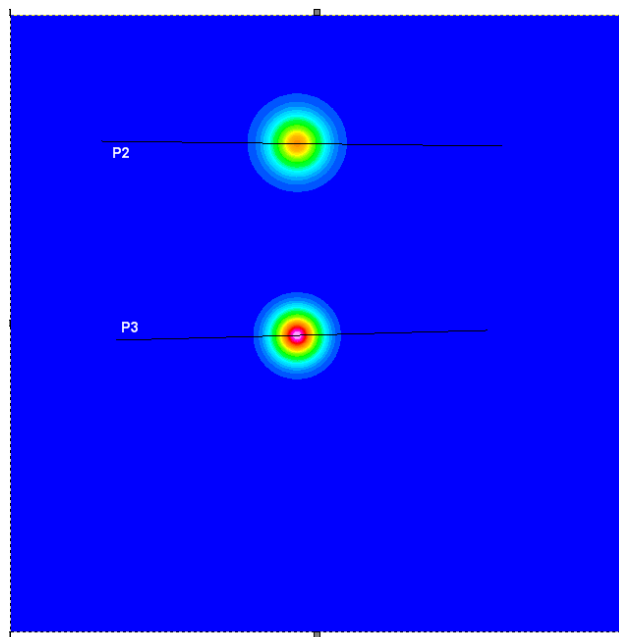


Figure 17. Total magnetic anomaly map of the model shown in figure 16

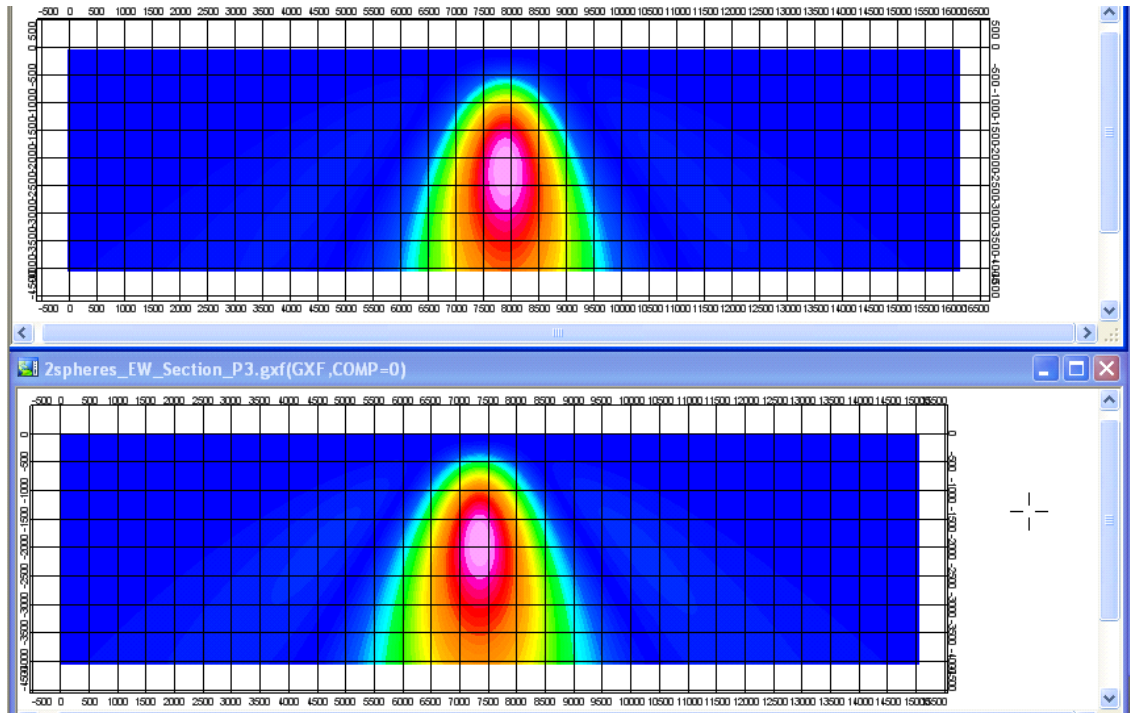


Figure 18. Pseudo magnetization sections along top) profile P2, bottom) profile P3 shown in figure 17.

The estimated depths are rather overestimated for both anomalies and it might be due to the large depth compensation (cubic power of layer depth). Our experience shows that for a sphere a structural index of 2.5 will give the best answer.

- **Dikes models and 3D visualization:** We have also tried to present the models from the process in 3D using voxel models in Oasis Montaj. Such an example is shown in figures 19 to 21.

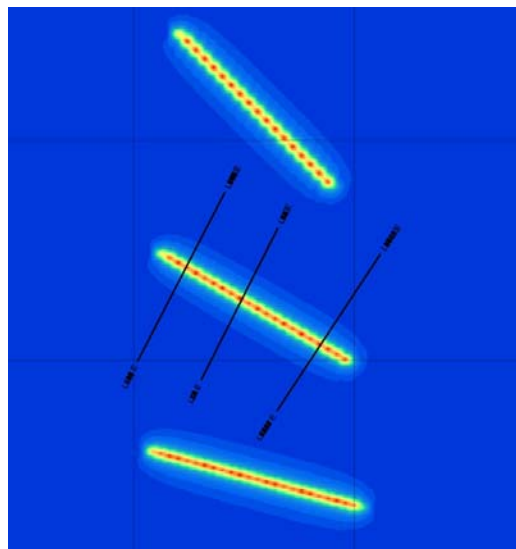


Figure 19. Location of three profiles selected to make a 3D visualization of the results on body number 4 shown in figure 15.

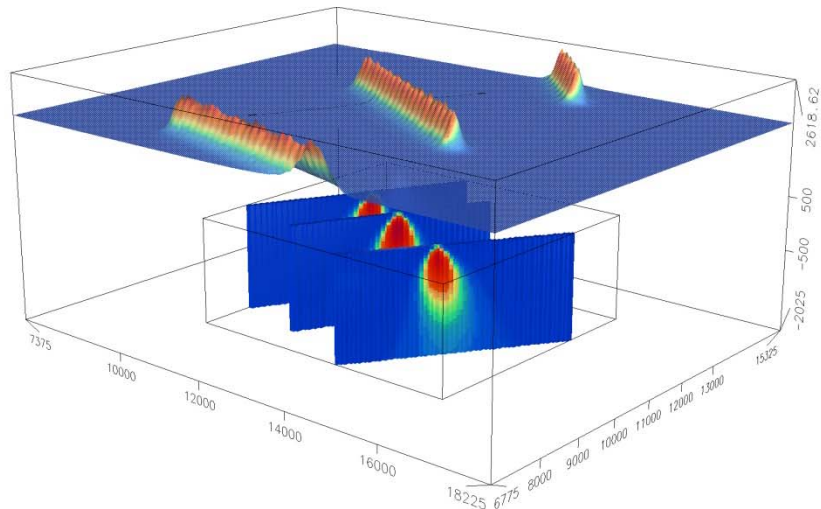


Figure 20. 3D visualization of the pseudo sections from the processing along three selected directions shown in figure 19. On top the 3D view of total field is illustrated.

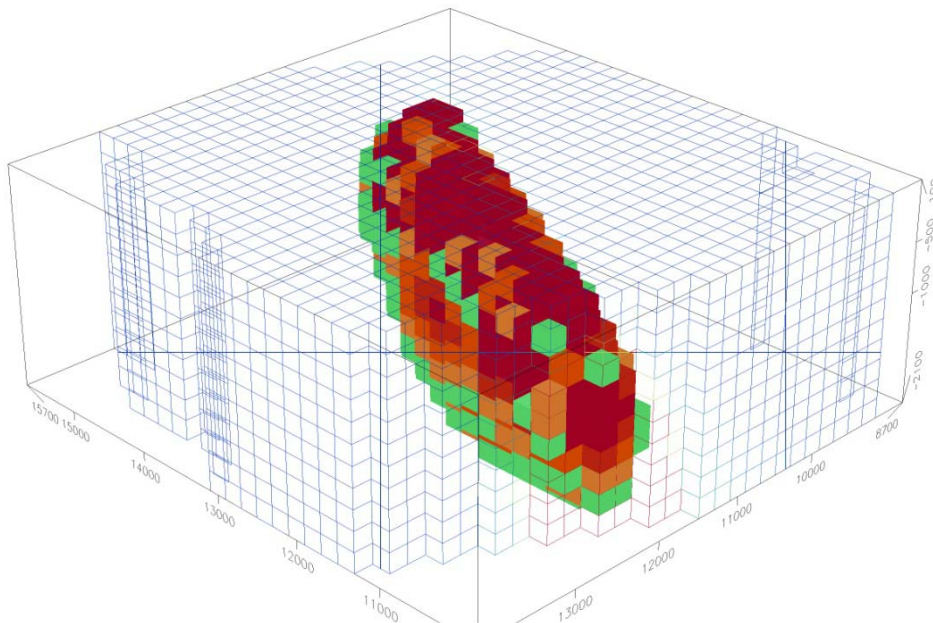


Figure 21. Voxel model from the results shown in figure 20.

TEST WITH REAL AIRBORNE MAGNETIC FIELD DATA

The airborne data from Ragunda area in Sweden were selected to process with the pseudomag method. The area is well studied and we also have a good control and knowledge about the magnetic susceptibility on some outcropping rocks. The location of area is shown in figure 22 with the black square that is superimposed on the magnetic anomaly map. The anomaly is situated south of the Ragunda batholiths and it is interpreted to belong to the Rapakivi kompleks of the Subjotnian period which comprise a number of batholiths, smaller plutons and dyke swarms (Andersson, 1997).

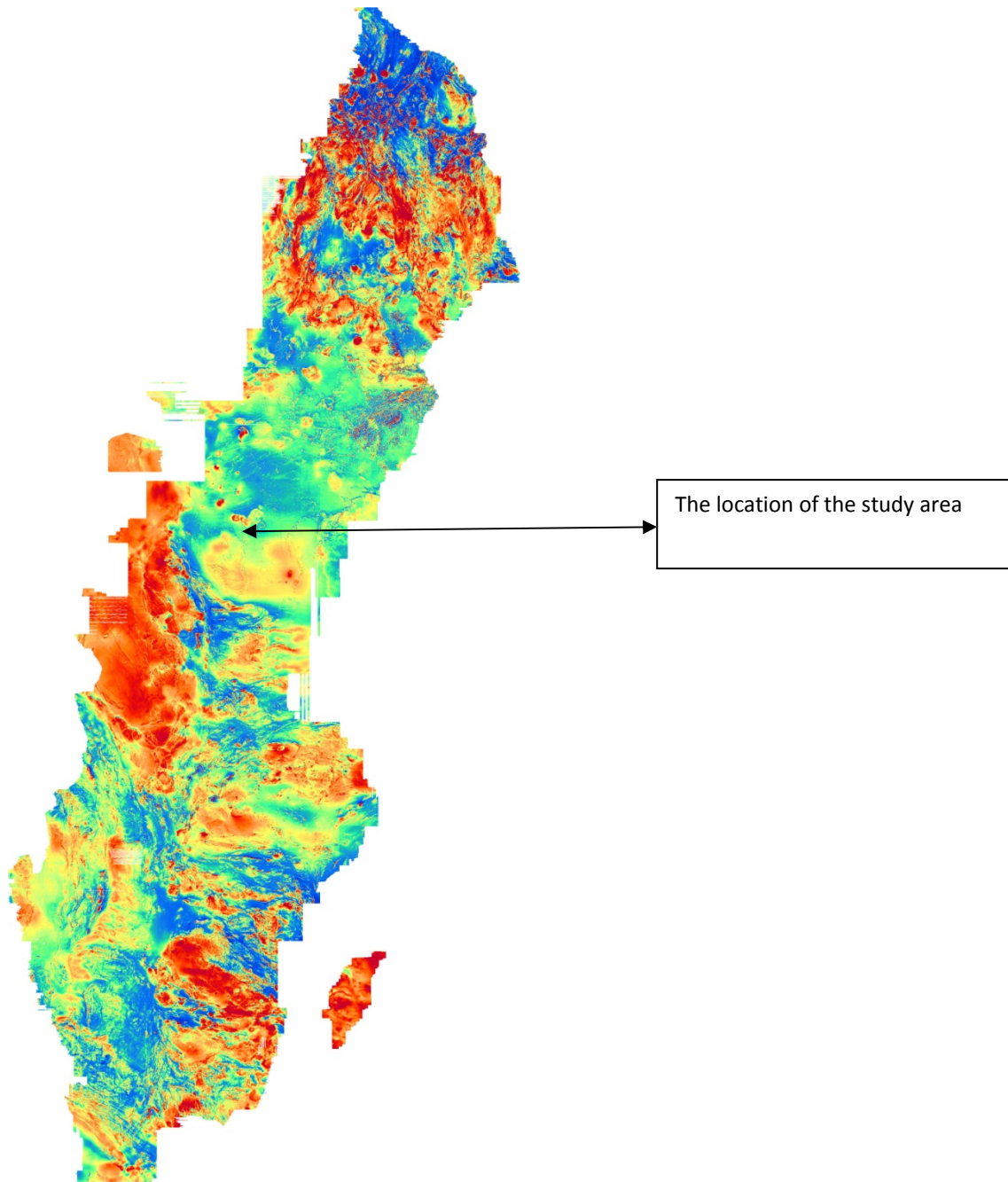


Figure 22. The location of the area

The data are acquired year 1978 with a flight line spacing of 200 m and a sampling interval of about 40 m. In the first step we selected a single anomaly that is known to be due to the mafic rock with a susceptibility of about 0.04 (SI units). The data were then sampled along three profiles to carry out forward modelling using POTENT software. The profiles are shown figure 23. We have selected one example to show that is along profile L2N.

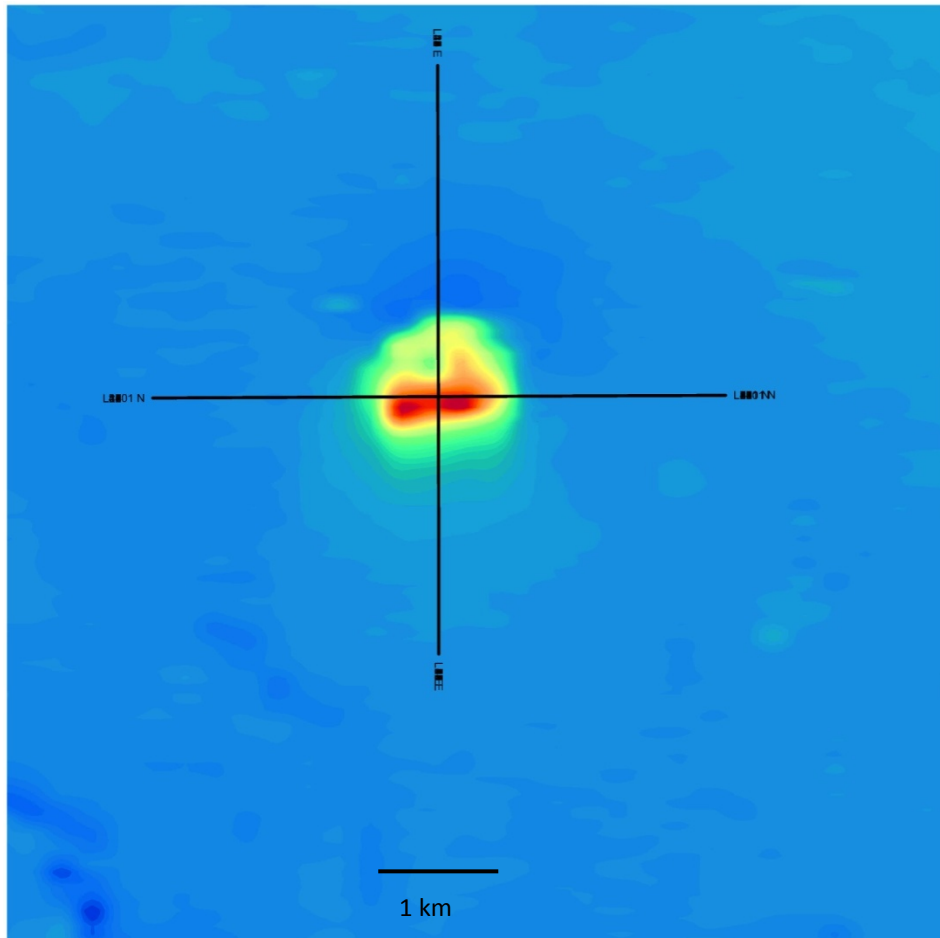


Figure 23. Location of selected profiles for data analysis. The background shows the total magnetic field anomaly.

The data are exported to POTENT and modelled using different available body shapes, e.g. sphere, ellipsoid and polygon. We found a polygon model that fits the measured data best. The model together with the measured and estimated data is shown in figures 24 and 25.

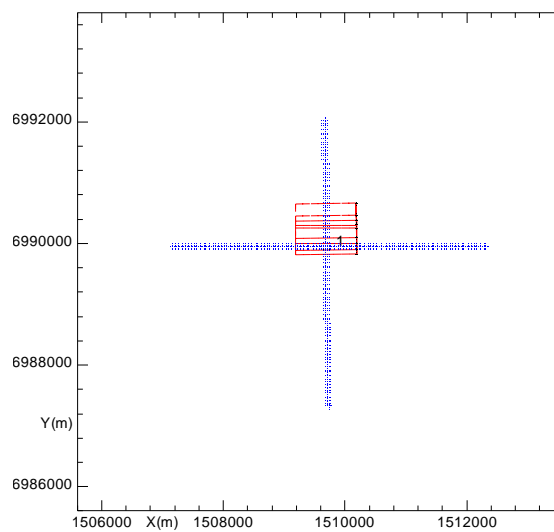


Figure 24. The map view of the polygon model and the selected profiles for modelling.

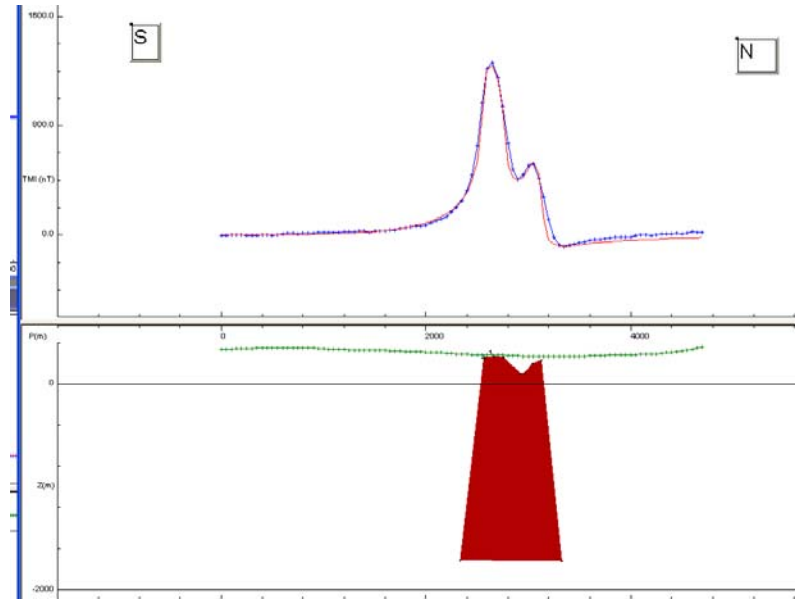


Figure 25. Voxel model from the results shown in figure 20. On top the 3D view of total field is illustrated.

The data were then processed with the pseudo magnetic program using a structural index of 2.5 that is a structure between horizontal cylinder and a sphere. The results are shown in figure 26.

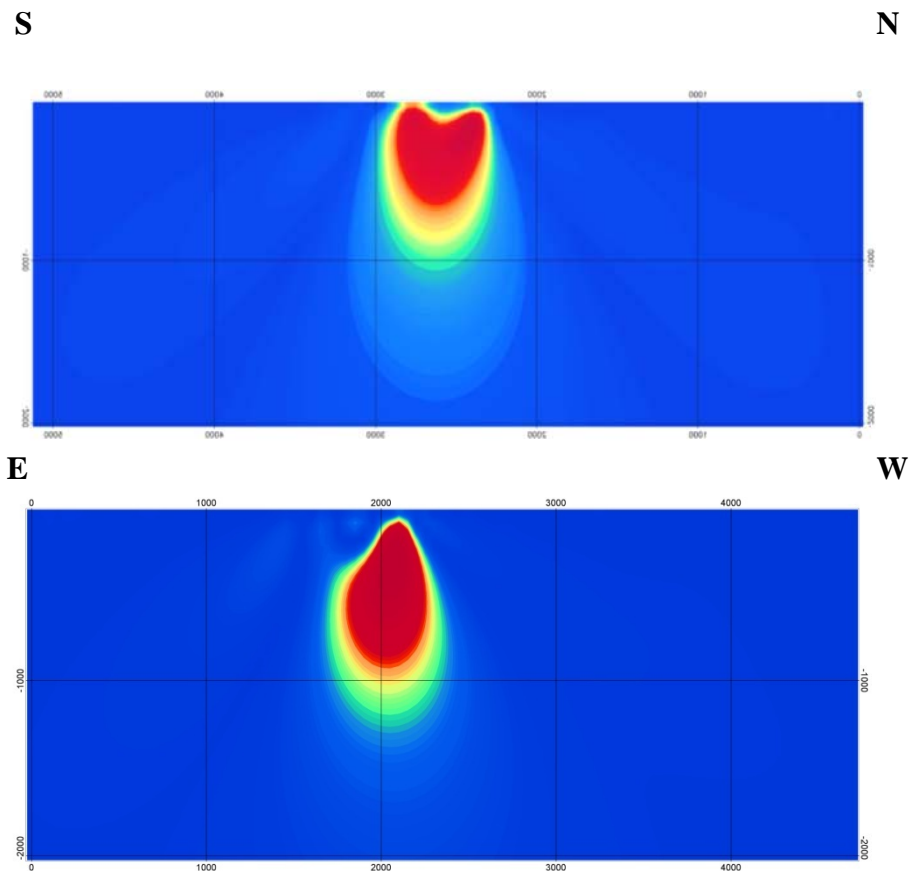


Figure 26. Pseudo sections of the anomaly in figure 20.

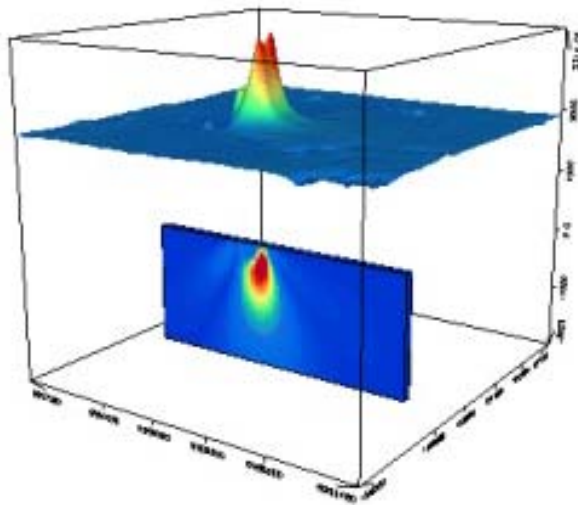


Figure 27. Visualization of the pseudo section along one selected direction.

CONCLUSIONS

A method for fast processing of large amount of airborne magnetic data acquired by SGU has been developed and tested.

The method was first evaluated by generating various synthetic data sets from the models of well-defined geometry and then was applied to the real data from south of Ragunda. The results were also shown in 3D using the voxel model in Oasis Montaj.

A user interface in Oasis Montaj in the form of a loadable menu, so-called GX, is made to ease the use of program

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