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Abstract

DSIM3D provides a rapid, unconstrained 3D inversion of gridded magnetic data. It is a Geosoft GX implementation of an inversion approach (Pilkington, 2009) that produces a 3D susceptibility distribution from observed magnetic anomaly data. The GX accepts gridded magnetic data as input and produces a subsurface 3D distribution of magnetic susceptibilities due to an equally spaced array of dipoles. Input parameters include the depth of the model, the distance from the observation plane to the model, the maximum allowable number of iterations, an RMS error limit to terminate iterations, options for grid preconditioning, the initial model susceptibilities, the data noise level, the ambient magnetic field, and the magnetization inclination and declination. The output is a Geosoft voxel model.

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1. Introduction

DSIM3D is a Geosoft GX implementation of an inversion approach (Pilkington, 2009) that determines a 3D susceptibility distribution from input magnetic anomaly data. The GX accepts gridded magnetic data as input and produces a subsurface 3D model of the magnetic susceptibilities of an equally spaced array of dipoles. DSIM3D provides a rapid, unconstrained 3D inversion of gridded magnetic data.

2. GX DSIM3D

The original inversion software DSIM3D was written as FORTRAN code (Pilkington, 2009). A Geosoft GX implementation of the original code is presented here. The inversion incorporates depth weighting of the solution and is posed in the data space, leading to a linear system of equations with dimensions based on the number of data, *N*. This contrasts with the standard least-squares solution, derived through operations within the *M*-dimensional model space (*M* being the number of model parameters). Hence, the data-space method combined with a conjugate gradient algorithm leads to computational efficiency by dealing with an $N \times N$ system versus an $M \times M$ one, where $N << M$. For more information on the algorithm, see Pilkington (2009).

2.1. Input Parameters

DSIM3D accepts the following input parameters:

Input grid file:

The name of the input residual total magnetic field data grid, in Geosoft GRD format.

The input grid must contain **no** dummy values. Presence of dummies can be determined using GRIDSTAT GX. To ensure no dummies are present, extract the input grid from a larger grid using GRIDWIND GX or interpolate grid dummy values using GRIDFILL GX

DSIM3D uses Fast Fourier Transform (FFT) processing to achieve computational efficiency. As a result, input grids are padded to the next power of 2 using code from the USGS GX FTPREP (Phillips, 2007). The minimum padding is 15% of the input grid resulting in a larger input dataset and subsequent increase in processing time.

DSIM3D can also invert the vertical gradient of gravity (T_{zz}). This requires the scaling of the ambient magnetic field strength to the gravity field and setting the ambient magnetic field inclination to 90^o.

Output voxel model file:

The name of the output 3D model in Geosoft voxel file format. The output voxel model will be trimmed in X and Y dimensions to those of the input grid.

Output Voxel Z Cell Size (m):

The size of each voxel cell in the Z direction. The dimensions in the X and Y directions are those specified in the input grid.

Output Voxel Model Depth in Cells:

The number of voxel cells, NZ, in the Z direction. The voxel model will have dimensions NX x NY x NZ cells.

Distance from Observation Plane to Top of Model (m):

The distance from the magnetic sensor to the top of the model in metres. This is usually the mean terrain clearance of the magnetic survey aircraft. DSIM3D assumes measurements are made on a horizontal plane.

Maximum Number of Main Iterations:

The maximum number of main iterations. A maximum of 10 iterations is usually acceptable, however, if convergence is slow and RMS error is still decreasing this number can be increased.

Maximum Iterations to Solve Linear System of Equations:

The maximum number of iterations within the CG (conjugate gradient) algorithm which solves the linear system of equations. As a rule of thumb, set this maximum to twice the number of grid cells in X or Y, whichever is larger:

IGMAX = 2*MAX(NX,NY)

If the RMS error is only slowly decreasing, increase the maximum number of iterations. For example, 150 iterations may be reasonable for a 64x64x20 voxel model.

RMS Error Limit to Terminate Iterations (nT):

The minimum RMS error allowed in both the main and CG iterations. If the RMS error is less than this limit, then the iterative process will finish. This limit should reflect the expected error in the input data. Such a value, however, may be too small as the final RMS error may include components in the observed field that cannot be modelled completely, e.g., regional fields and remanence effects. Also, setting the limit to a small value will lengthen processing time. Larger values can be used to get a quick solution which can then be refined later. Often a value of 50 or even greater is acceptable.

Grid Preconditioning:

Type of grid preconditioning. Use either no preconditioning or precondition the grid using inverse diagonal matrix elements. Faster convergence of the CG algorithm is possible using preconditioning.

Initial Susceptibility (SI) for all Output Cells

The initial value of susceptibility, in SI, for all model cells. This should be kept small. A value of 0.00125 is acceptable.

Data Noise Level (nT):

The estimated input data noise level in nT. Estimating a noise level may be difficult. A value from 1 to 10 is usually acceptable.

Ambient Magnetic Field Strength (nT):

The total magnetic intensity of the earth's magnetic field at the time of acquisition and at the location of the input magnetic data. This can be calculated using the Geomagnetic Field Calculator from Geomagnetism Canada of Natural Resources Canada:

http://www.geomag.nrcan.gc.ca/calc/mfcal-eng.php

Ambient Magnetic Field Inclination (degrees):

The inclination of the earth's magnetic field at the time of acquisition and at the location of the input magnetic data. This can be calculated using the Geomagnetic Field Calculator from Geomagnetism Canada of Natural Resources Canada:

http://www.geomag.nrcan.gc.ca/calc/mfcal-eng.php

Ambient Magnetic Field Declination (degrees):

The declination of the earth's magnetic field at the time of acquisition and at the location of the input magnetic data. This can be calculated using the Geomagnetic Field Calculator from Geomagnetism Canada of Natural Resources Canada:

http://www.geomag.nrcan.gc.ca/calc/mfcal-eng.php

Magnetization Inclination (degrees):

The inclination of the magnetization of the source body. If magnetization is assumed to be due to induction, the inclination will be the same as that of the ambient field. If the magnetization is affected by remanence, enter the inclination of the resulting magnetization.

Magnetization Declination (degrees):

The declination of the magnetization of the source body. If the magnetization is assumed to be due to induction, the declination will be the same as that of the ambient field. If the magnetization is affected by remanence, enter the declination of the resulting magnetization.

2.2. Output Files

Inversions of typical size (256 x 256 x 20) on simple anomalies performed on a standard desktop computer are usually completed in approximately 2 to 2.5 hours. Three output files are generated; a log file describing the RMS errors of the iterations, the 3D model in Geosoft voxel file format, and a grid of residuals (difference between computed magnetic field and the input magnetic data).

The GX creates a log file that shows the iterative process as the inversion proceeds. The log file is named using the root of the output voxel file name with the extension '.log'. The main iterations and the associated RMS error between the input data and the model signal are shown as:

```
iteration  rms error
     5       45.3456
```

Within the main iterations two additional processes are computed. First, if the RMS error does not decrease the susceptibility updates are multiplied by a factor, Alpha, with a value less than one to try to decrease the RMS error. If this does not produce a decrease in RMS error, Alpha is divided by three for the next iteration. For example:

```
iteration  rms error
     1       157.9229
iteration  rms error
     2      7139.4990
Alpha =   0.3333333
iteration  rms error
     2       691.9530
Alpha =   0.1111111
iteration  rms error
     2        59.4056
```

Here, the initial RMS error at iteration 2 is larger than for iteration 1, so the factor, Alpha, is applied. As the next iteration's RMS error is greater than the initial RMS error, Alpha is divided by three and re-applied. Alpha is applied until the RMS error decreases to a value less than the initial error (from 157.9229 to 59.4056).

Second, the error (err) for the solution of the linear system of equations at each main iteration (ig) is shown:

```
iteration  rms error
     2        59.4056
 ig=          10  err=   30.25865
 ig=          20  err=   17.29380
 ig=          30  err=   23.91518
 ig=          40  err=   12.34971
 ig=          50  err=   10.36094
```

```
iteration  rms error
     3        41.7094
```

The error is displayed every 10 iterations and may not necessarily decrease. These iterations are terminated when the value of the input parameter "Maximum Iterations to Solve Linear System of Equations" is reached or the error is less than the input parameter "RMS Error Limit to Terminate Iterations".

The output voxel model is automatically displayed using Geosoft's 3D Viewer. Clipping of magnetic susceptibility data in the viewer allows for visualization of higher susceptibilities representing magnetic bodies at depth.

A grid of residuals between final model signal and input magnetic data are stored in a file named using the root of the output voxel file name with the extension '_residuals.grd'.

Note: Running DSIM3D.GX using the Geosoft Oasis montaj Viewer has two limitations. The grid of residuals will not be created and the final voxel model will not be trimmed to the X-Y extent of the input grid.

3. Inversion Example

Figure 1 shows the residual total magnetic field over an area in the northern Athabasca Basin, Saskatchewan. The magnetic data displays a large broad anomaly, elongated to the northeast and southwest. The anomaly is intersected by a pair of long linear anomalies trending northwest.

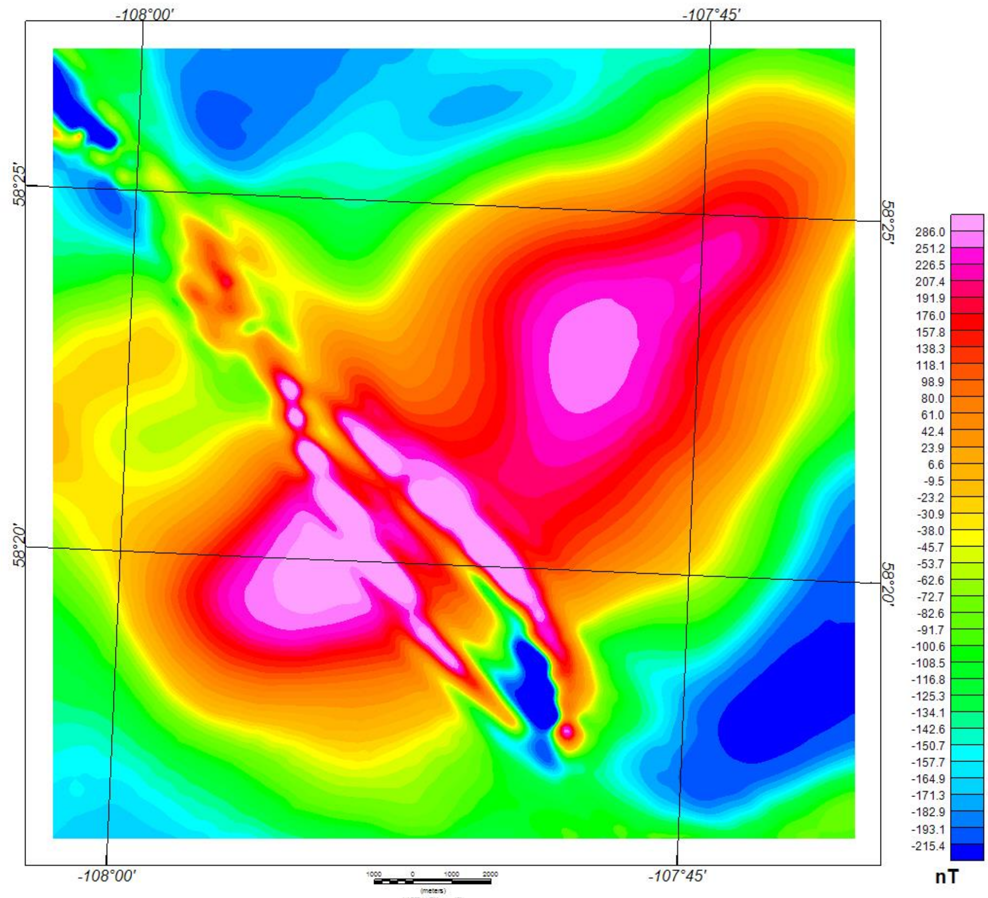


Figure 1. Aeromagnetic data from the NW Athabasca Basin, Saskatchewan survey (Fortin et al., 2011).

Figure 2 displays the mapped geology of the example area. Sedimentary sequences of the Athabasca Group (PAob) unconformably overly metamorphosed Archean supracrustal and granitoid rocks. Two northwest-trending dikes (PMd) cross-cut the basin and basement geology (PMd).

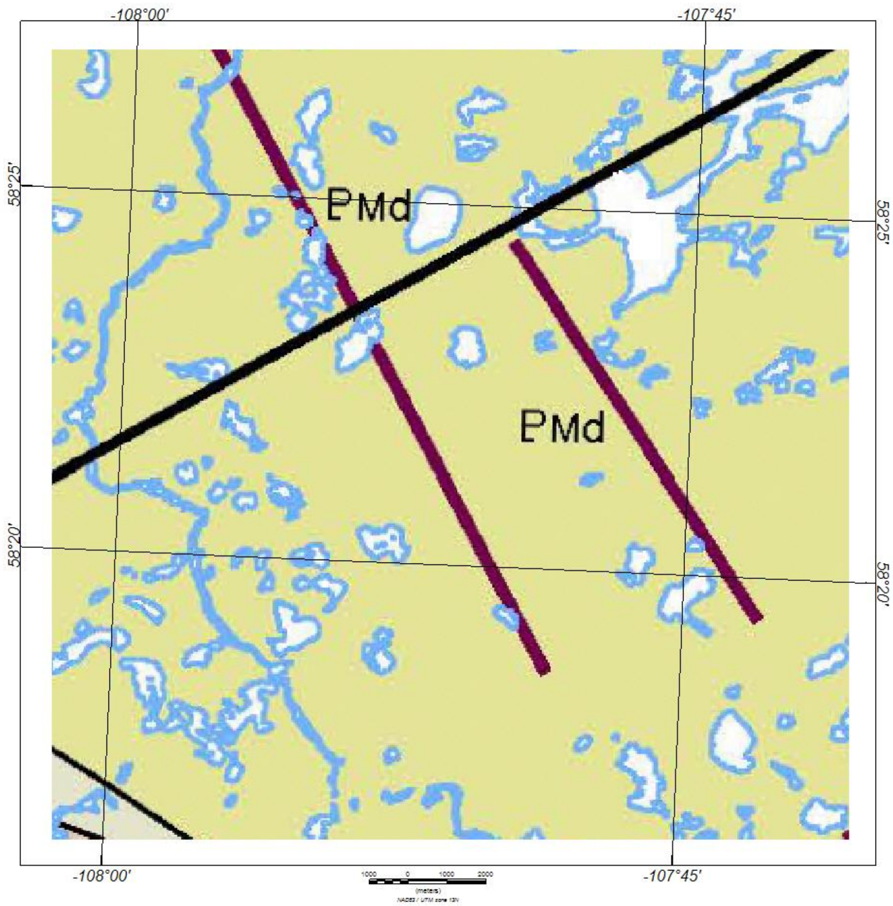


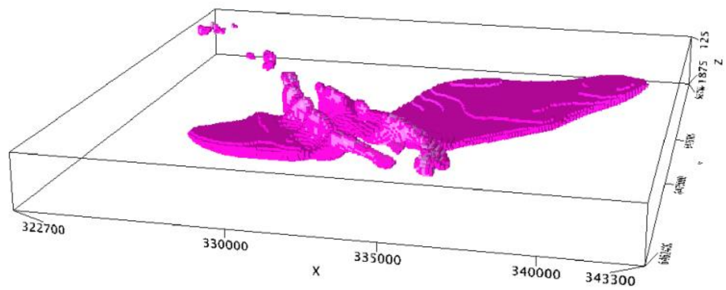
Figure 2. Geological map of example area from Pehrsson et al., 2014.

The magnetic data used in the inversion example were acquired in 2010 along a drape surface with a nominal terrain clearance of 125 m (Fortin et al., 2011). The traverse line spacing was 400 m and the control line spacing was 2400 m. The data were gridded to a 100 m interval using minimum curvature. The area shown in Figure 1 consists of 206 by 203 grid cells. These data were used as input to the DSIM3D routine. The following parameters were used:

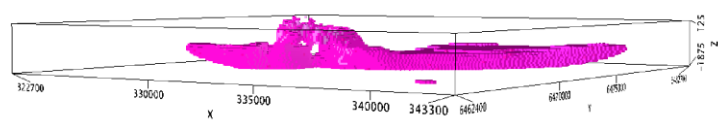
Input grid file: basin.grd
Output voxel model file: basin.geosoft.voxel
Output residuals grid: basin_residuals.grd
Output Voxel Z Cell Size (m): 100
Output Voxel Model Depth in Cells: 20
Distance from Observation Plane to Top of Model (m): 125
Maximum Number of Main Iterations: 10
Maximum Iterations to Solve Linear System of Equations: 412
RMS Error Limit to Terminate Iterations (nT): 1.0
Grid Preconditioning: Inverse Diagonal Matrix Elements
Initial Susceptibility (SI) for all Output Cells: 0.00125
Data Noise Level (nT): 1.0

Ambient Magnetic Field Strength (nT): 59122
Ambient Magnetic Field Inclination (degrees): 79.6
Ambient Magnetic Field Declination (degrees): 13.3
Magnetization Inclination (degrees): 79.6
Magnetization Declination (degrees): 13.3

The inversion was performed on a standard desktop computer and was completed in approximately 2.5 hours. Figure 3 presents the results of the inversion with magnetic susceptibilities clipped to 0.0075 SI. A 3D Portable Document Format (.pdf) of the output voxel is attached as Appendix 1.



a)



b)

Figure 3. Unconstrained 3D inversion of aeromagnetic data from the NW Athabasca Basin, SK (Fortin et al., 2011). a) View of model with inclination 17^o and azimuth 13.4^o. b) View of model with inclination 2.4^o and azimuth 33.8^o. Both views have magnetic susceptibilities clipped to .0075 SI.

The voxel model in Figures 3a and 3b show two subparallel, linear bodies trending northwest. They have slight curvilinear form and coincide with magnetic anomalies mapped as dikes (Pehrsson et al., 2014). The bodies widen only slightly with increasing depth, preserving their geologic integrity. The southernmost body is subvertical, while the northern body appears to dip to the northeast. Both bodies extend to a depth of 700 to 800 m where they intersect a large flat-topped, elliptical body elongated to the northeast. The depth of this body suggests it occurs within the Archean basement. The flat top may represent the unconformable surface between basin sedimentary sequences and crystalline basement.

4. Conclusion

DSIM3D computes unconstrained inversions of magnetic data. The GX implementation is straightforward and easy to use. It allows the user to input aeromagnetic data in a widely-used, industry standard format (Geosoft GRD). There are a limited number of variable input parameters, allowing the user to set up and run inversions quickly. The routine automatically pads input grids to allow the use of FFT processing, as well as minimizing edge effects in the input data. The output 3D model voxel is automatically displayed in Geosoft's 3D viewer for ease of visualization. The model voxel can be printed, saved, or converted to other 3D formats (GOCAD, UBC, XYZ). The simplicity of the GX implementation is due to the unconstrained nature of the inversion. While unconstrained inversions are relatively easy to initiate and run, they are inherently non-unique as there is no consideration of known constraints (contacts, rock properties, borehole data etc.). Care must be taken when setting values for variable parameters that affect inversion performance and accuracy (main iterations, system of equation iterations, RMS error limit, preconditioning, and data noise level). Selecting too few iterations will result in a poor fit of the model to the data. RMS error limits and data noise levels that are too high will similarly result in models that are excessively smooth with poor fit to the input data. RMS error limits that are too low may be excessively noisy.

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Appendix 1 – Inversion Example Voxel Model as a 3D PDF (Portable Document Format) File

The following page contains a 3D PDF (Portable Document Format) file of the output voxel model for the inversion example.