Gravity and magnetic data interpretation with non-linear transforms

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Abstract

Program MMATrans (Magnitude Magnetic Transform) available by the *Society of Exploration Geophysicists* (Gerovska and Arauzo-Bravo, 2006) implements a series of non-linear transforms to process grid magnetic data. Processing tools in MMTrans aim anomaly centering over causative sources as a tool to improve geological mapping. Program MDRMI (Mendonca and Meguid, 2008) jointly processes gravity and magnetic data to obtain rock physical parameters, namely: magnetization to density ratio (*MDR*) and magnetization inclination (*MI*). Here we present real data applications with MMATrans and MDRMI using a regional data set from the *Minnesota Geological Survey* (MGS). Comparison of results with available geological maps and previous published geophysical studies points out to possible contributions that such transforms can bring in interpreting a regional data set.

Introduction

Linear and non-linear transforms can be applied to process potential field (gravity and magnetic) data to improve geological mapping of bodies with density and magnetization contrast. Reduction to the pole (a linear transform) is usually applied to magnetic data because anomalies evaluated at the south or north poles are better centered over sources. This transformation, however, requires a known magnetization direction and in low magnetic latitudes is numerically unstable. A non-linear transform producing the analytical signal for magnetic anomalies (Nabighian, 1972; Roest *et al.* 1992) also seems effective in centering fields over sources but requires no knowledge on magnetization direction and gives useful results in low magnetic latitudes. Numerically, the amplitude of the analytical signal (AAS) is obtained from the square root of the squared anomaly-derivatives, which means it can be regarded as the magnitude of the anomaly gradient. For 2D sources AAS is invariant with magnetization direction and assigns maxima over the center of elongated sources or over the edges of large bodies. For 3D sources maxima are slightly distorted over sources but AAS still is useful to identify source position and contacts.

Non-linear transforms in MMATrans (Gerovska and Arauzo-Bravo, 2006) attempt to produce better skilled centering transforms meanwhile lowering interference from juxtaposed bodies, a main problem in interpreting AAS. As in AAS, transforms in MMATrans do not require a known magnetization direction but instead of involving only first order derivatives also second order derivatives are employed in calculating intensity fields. Program MMATrans was implemented in MATLAB making use of optimized grid partition in computing Fourier transforms, which allows its application to large data sets. Non-linear transforms in MDRMI were implemented in FORTRAN (Mendonca and Meguid, 2008) based on previously published routines to process potential field data (Blakely, 1995).

Our objective in applying MMATrans and MDRMI to a real data set is to verify if their products help anyway the identification of geological contacts and discontinuities as well as general characterization of geological unities. Analysis in this context is somewhat arbitrary since no 'true model' are available to check results. Nevertheless, by analyzing results from different processing routes, the interpreter can realize what a sort of information each transform may give according to specific interest on geological structures or targets. Actually, both programs have been tested with synthetic data (Gerovska and Arauzo-Bravo, 2006; Mendonca and Meguid, 2008) but not analyzed in the ground of a common data set as developed here.

Theoretical Aspects

Let us write the magnetic total field anomaly, T_t as

$$T_t \approx X_a cos(D_0)cos(I_0) + Y_a sen(D_0)cos(I_0) + Z_a sen(I_0), \quad (1)$$

where X_a, Y_a, and Z_a are the x, y, and z-components of the anomalous magnetic field ($\mathbf{T}$), I_0 and D_0 are the inclination and declination of the local magnetic field, its direction represented by an unitary vector $\mathbf{t}$. Total field anomaly may be written as $T_t = \mathbf{t} \cdot \mathbf{T}$ (e.g., projection of anomalous vector $\mathbf{T}$ onto the main field). In terms of components X_a, Y_a and Z_a of the vector field $\mathbf{T}$, field intensity T is

$$T = (X_a^2 + Y_a^2 + Z_a^2)^{\frac{1}{2}}. \quad (2)$$

Transform T in MMATrans stands for $T \equiv |\mathbf{T}|$. From which the following transforms are implemented (Gerovska and Arauzo-Bravo, 2006): $R \equiv |\nabla T|$, $E \equiv 0.5\sqrt{\nabla^2 T^2}$, $L \equiv \nabla^2 T$ and $Q \equiv \sqrt{T\nabla^2 T}$ such that

$$R = \frac{1}{T} \mid X_a \nabla X_a + Y_a \nabla Y_a + Z_a \nabla Z_a \mid \quad (3)$$

$$E = (\frac{\mid \nabla X_a \mid^2 + \mid \nabla Y_a \mid^2 + \mid \nabla Z_a \mid^2}{2})^{\frac{1}{2}} \quad (4)$$

$$L = \frac{1}{T}(\mid \nabla X_a \mid^2 + \mid \nabla Y_a \mid^2 + \mid \nabla Z_a \mid^2 - \mid \nabla T \mid^2) \quad (5)$$

and

$$Q = (|\nabla X_a|^2 + |\nabla Y_a|^2 + |\nabla Z_a|^2 - |\nabla T|^2)^{\frac{1}{2}}. \quad (6)$$

Transforms in MDRMI evaluate rock properties MDR (magnetization to density ration) and MI (magnetization inclination) from processing gravity and magnetic data. The processing line evaluating MDR and MI can be regarded as non-linear transforms because, respectively, involve a field intensity ratio and a normalized scalar product. MDRMI relationships are derived from Poisson's theorem (Blakely, 1995). MDR (r) can be obtained (Mendonca & Meguid, 2008) as

$$r = G\frac{|\mathbf{T_m}|}{|\nabla g_z|} \quad (7)$$

and MI (α) as

$$\alpha = asin\frac{\mathbf{T_m}.\nabla \mathbf{g_z}}{|T_m||\nabla g_z|}. \quad (8)$$

In equations 7 and 8 $\mathbf{T}$ is written as $\mathbf{T_m}$ with subscript m assigning a field generated from uniformly magnetized sources with magnetization direction $\mathbf{m}$. Vector ∇g_z is the gradient of the gravity anomaly g_z meaning that $|\nabla g_z|$ can be regarded as the gradient intensity for the gravity anomaly (equivalent the amplitude of the analytical signal for g_z); G is the gravitational constant.

Geological Information & Data Sets

Minnesota State geology is composed by igneous and metamorphic rocks covered by quaternary glacial sediments (Figure 1). Magnetic anomalies can be associated to volcanic belts and iron-formation sequences earlier mined in the years of 1940 to and 1950 (Spector & Lawler, 1995). The metamorphic zones composed by migmatites are magnetically weak but host dyke-like inhomogeneities with magnetization contrast (Spector & Lawler, 1995). Some granodiorites are magnetic and form "tear-shaped" structures (Spector & Lawler , 1995). Pre-Cambrian geology has been prospected for several mineral resources (e.g., iron, copper and nickel) and some geological structures conditioning the formation of mineral deposits have expression (or 'signatures') in gravity and magnetic maps. Granodiorites may appear either as positive and negative density contrast. Regional gravity and magnetic data from Minnesota State were made available on the Internet by the Minnesota Geological Survey (Chandler et al., 2004). The compiled data sets encompass surveys from 1979 to 1991. Data were leveled to a common datum and disclosed in separated files, either as 'raw data' (gravity and magnetic anomalies) as well as products from standard processing (field derivatives and RTP field). Non-linear transforms next discussed were applied to a data window approximately covering the region previously investigated by Chandler(1985) and Spector & Lawler(1995). Gravity and magnetic entering MMTrans and MDRMI processing are shown in Figure 2.

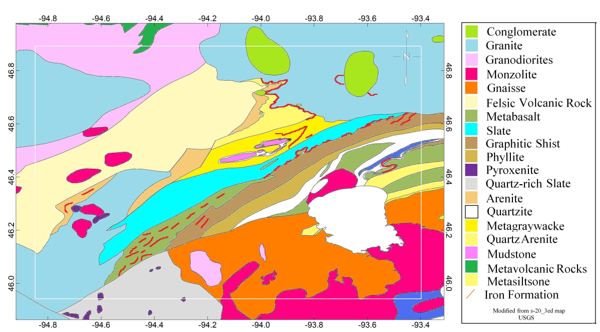

Figure 1: Data window (white rectangle) and geological map (adapted from s-20_3ed map-USGS).

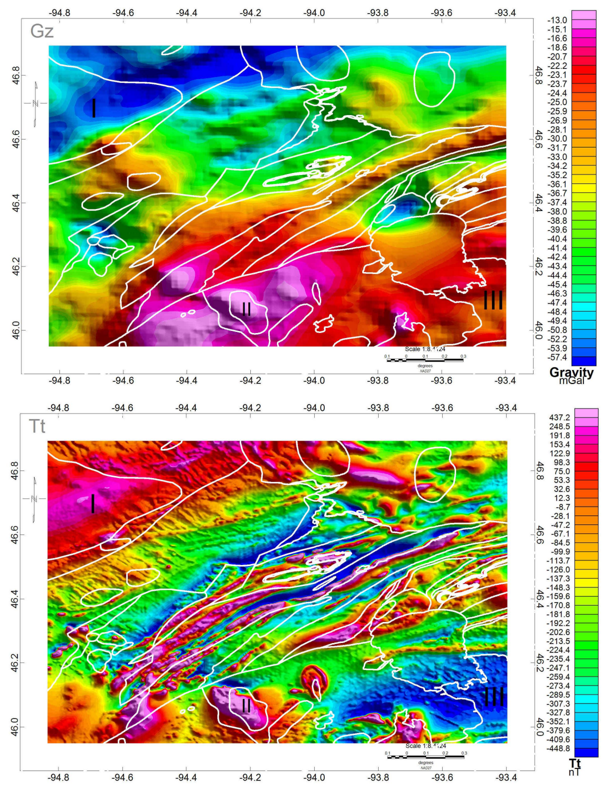

Figure 2: Gravity anomaly (g_z) and total field magnetic anomaly (T_t). Geological elements in the background (white).

MMTrans and MDRMI Products

Before introducing MMTrans and MDRMI results, we present in Figure 3 two processing products: intensity field ($T \equiv |\mathbf{T_m}|$) of the anomalous vector magnetic field, $\mathbf{T_m}$, and the analytical signal amplitude, $|\nabla T_t|$, for the magnetic anomaly T_t. As shown in equations 2 to 8, vector field $\mathbf{T_m}$ is included in all MMTrans and MDRMI transforms but actually not used as an interpretative tool. The magnetic anomaly AAS, otherwise, can be regarded as a standard product in magnetic data interpretation and for this reason is presented to allow comparison with other transforms.

Transformed intensity fields R, E, L and Q from MMTrans are presented in Figure 4. Apparent physical property values from MDRMI are presented in Figure 5. To support discussion on MDRMI results, first vertical derivative of the gravity anomaly and its AAS were included in Figure 5.

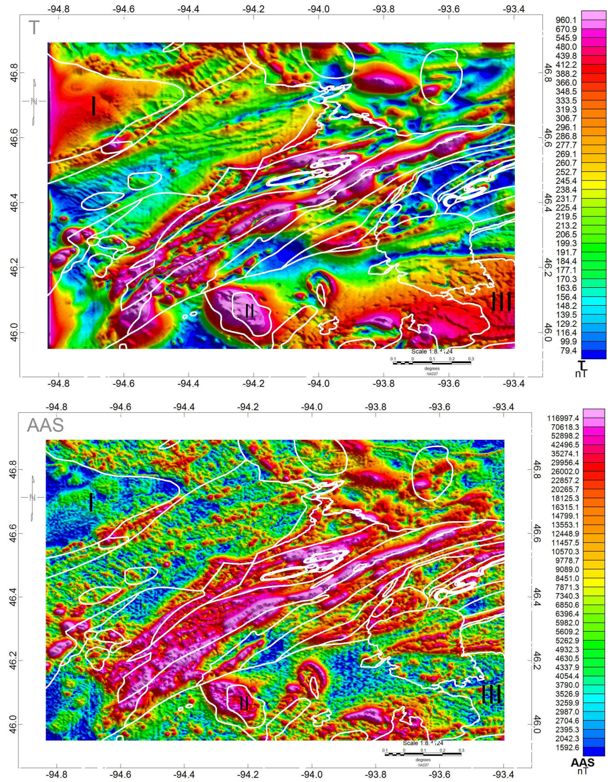

Figure 3: Intensity fields from processing magnetic data: field intensity $T = |\mathbf{T_m}|$ and magnetic anomaly amplitude of the analytical signal (AAS).

Discussion

As previously mentioned, comparison of processing products with real data sets is somewhat subjective because most elements in the geological map can not be regarded as perfect representations of the subsurface geology. In addition, different criteria can be deployed according specific exploration or research objectives. For this reason, we opted to present results in side-by-side columns to give interpreters some elements to support their own conclusions. For us, a surprising result was that no substantial difference was noticed between 'standard' AAS transform and non-linear R, E, L and Q transforms. It does not mean that similar results can be expected in other geological settings. Numerical simulations with shallow sources suggest that R, E, L and Q are not equally skilled as edge mappers but it is possible their performance becomes similar for fields from deeper sources. Results from field intensity T deserve further attention since it seems able to recognize fields from both shallow and deep sources. In some sense the T-transform complements the AAS interpretation, which enhances the expression from shallow sources.

To illustrate interpretation with MDR and MI we discuss specific structures labeled as `I`, `II` and `III` in the maps. Structure `I` is covered by sediments, has magnetic expression and a negative gravity anomaly (negative density contrast). In the MI map the average value of -80^o must be multiplied by -1 because equation 8 is derived under assumption that density contrast is positive. It gives a MI estimate of about +80^o, higher than expected if magnetization was induced only (regional field of about +55^o). MI is rather uniform over `I` suggesting a constant magnetization direction. MDR, however, increases northwestern suggesting a trend in composition lowering density contrast (in absolute value). Field T is observed over `I` but its high order derivatives vanish, a kind of response expected from wider than deeper sources. Structure `II` is associated to a granodiorite emplaced in a complex gnaissic terrain. The structure has positive density and magnetization contrasts and MDR and MI are rather constant. This can be interpreted as body with rather uniform composition and magnetization direction. For many intrusive bodies uniform MI can be associated to fast cooling rates, usually in shallower crustal levels. Structure `III` groups many lithological unities with variable MDR and MI, a kind of response from mixed or complex terrains. For elongated sources apparent MDR and MI assign true physical property values. MDR of about 150 mA.m^{2}kg^{-1} for lithological unity marked as 'slate' in Figure 1, for example, can be regarded as a true physical property estimate. Over the same unit MI is variable, suggesting magnetization disturbances (heating?) from superposed geological events.

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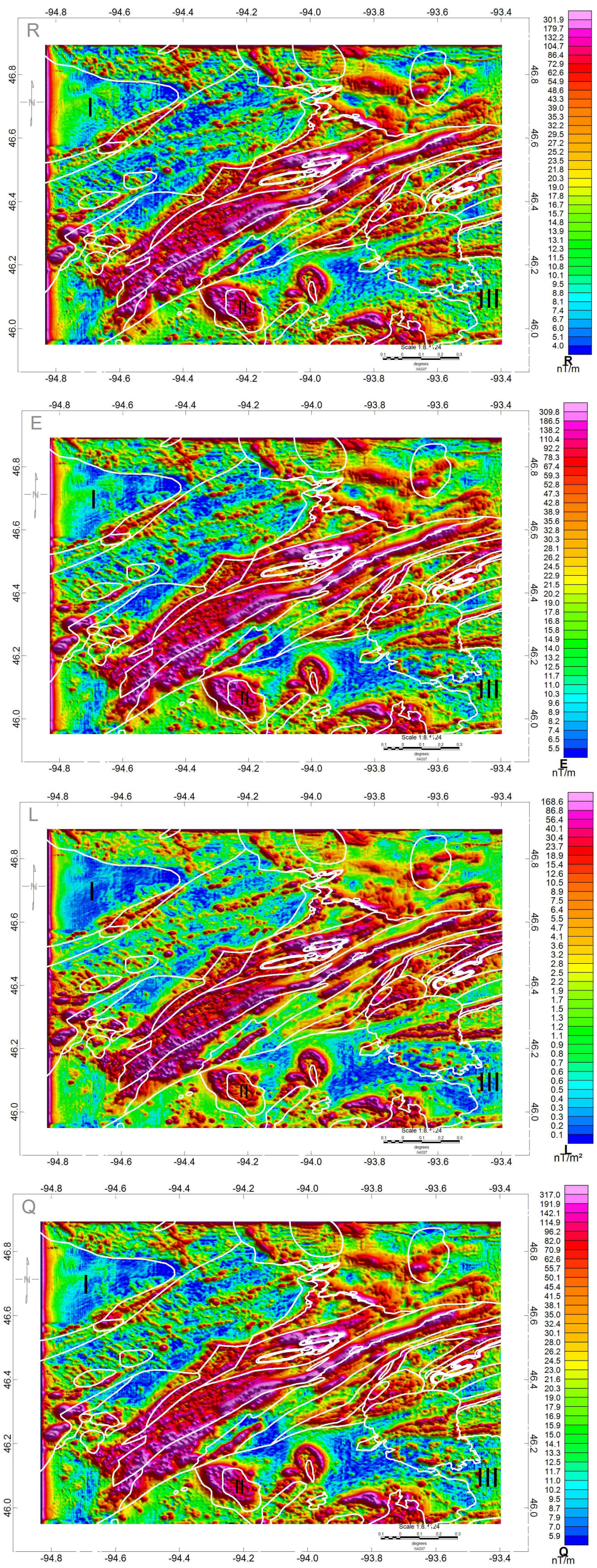

Figure 4: Products from MMATrans: transforms R, E, L and Q.

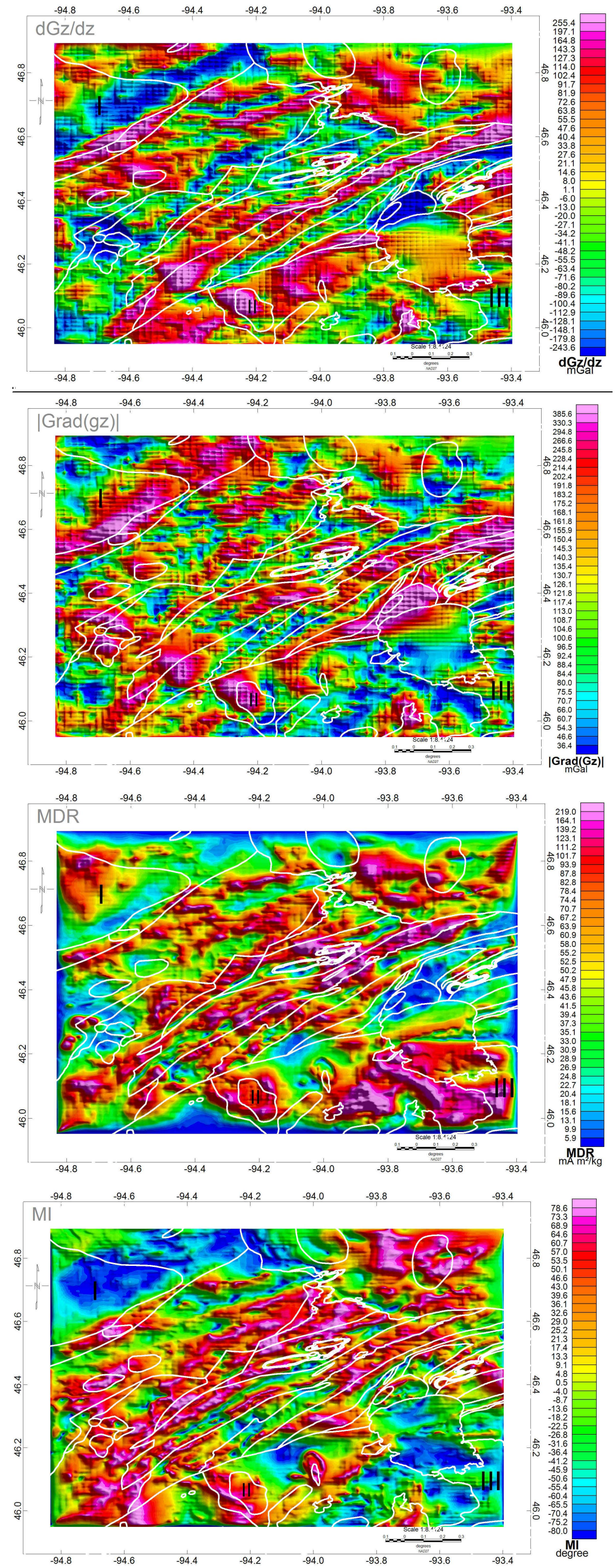

Figure 5: Gravity vertical derivative (dg_z/dz); gradient intensity of the gravity anomaly ($|\nabla g_z|$) and MDRMI parameters: magnetization to density ratio (MDR) and magnetization inclination (MI).