# Retrieving geological signal from full tensor gravity gradiometry data using source body migration

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## Summary

Interpreting full tensor gravity gradiometry data (FTG) depends on clear delineation of signature patterns arising from sub-surface geology. However, challenges presented by depth uncertainty and the presence of a noisy anomalous overprint characterized by a high frequency, low amplitude anomaly field arising from the overburden can prevail; leading to less clear interpretations. We describe a method to overcome this challenge. Source body migration is used to identify the depth sensitivity of dominant signal and a self-steering directional filter applied to extract clear signal associated with geology.

## Introduction

FTG data are routinely used for discriminating detailed sub-surface geological complexity exhibiting density contrast. Data processing generates maps displaying the field across all tensor components that when combined, reveal anomalous character associated with density change (Gravity and Tzz), structural change (Txx, Txy and Tyy mapping the horizontal curvature of the field), and contact lineament information (Txz and Tyz mapping the horizontal gradient). The total horizontal curvature (THC) and total horizontal gradient (THG) fields are invariant representations of the tensor and are calculated from final processed data (Murphy and Brewster, 2007). However, as these are depictions of the gradient of the field, and often more sensitive to shallow geological complexity yielding high amplitude, high signal strength anomalies, then their anomalous character often prevents imaging of deeper, more subtle geological complexity. An added challenge with gravity gradiometry is the persistent presence of a noisy anomalous overprint in final processed data. This is most evident in survey data where the dominant signal is arising from deeper geology and where the overburden geology generates more subtle responses. The noisy overprint degrades the signal limiting the ability to map clear signal from the subsurface.

FFT based filtering methods are routinely used to overcome such challenges, where separating the signature according to frequency content is a useful first step in depth estimation. However, choice of cut-off frequencies often results in either removal of too much signal or not enough. This is particularly the case when separating good signal from signal containing the noisy overprint of similar bandwidth, or when signal strength arising from the overburden is excessive that it needs a wide bandwidth filter to be dampened. The resultant outputs only capture a portion of the desired signal for effective geological interpretation.

Brewster et al (2014) introduced a self-steering directional filter (SSDF) that separates good signal from noise induced signal when of a similar bandwidth. SSDF looks for linear anomalies following self-defined strike orientations independent of FFT based filtering. It achieves this by exploiting the full tensor to look for higher frequency, narrow width, linear anomalies that are continuous from line to line. Resultant maps show significant improvement in delineating coherent signal from geology.

Signal separation for estimating depth from FTG data is best achieved using a means other than frequency filtering. Source Body Migration (SBM) uses a depth-density approach. Brewster and Murphy (2020) describe SBM as a depth filtering method that performs signal separation by modeling a density field retrieved from the tensor data to identify a depth relationship independent of frequency content. The benefit of such an approach is that it not only images directly beneath the noise infused signal causing the signal degradation but also beneath high signal strength sources in the data.

This paper describes usage of the SBM method to a public domain FTG data set acquired over the Midcontinent Rift System for the USGS in NE Iowa (data available from https://mrdata.usgs.gov/ ). The selected parameters not only image beneath the degraded signal in the data but identify a clear, high resolution, depiction of the sub-surface geology. In addition, we employed the SSDF to identify definitive linear shaped anomalous patterns from the migrated data to map the geological character of the area.

## Methods

SBM is a fast, robust, unconstrained inversion method that identifies depth sensitivity producing meaningful depth interval anomaly fields from FTG data. SBM transforms the final processed tensor data to a 3D density field for a mass distribution of point sources at survey altitude. Forward models are automatically calculated from the density distribution and evaluated for estimated relative, mean depth sensitivities. Maximum and minimum depth sensitivity is identified and used to construct depth interval anomaly maps. Nominated parameters include top of model, maximum depth of model, and voxel size.

SSDF simultaneously uses all tensor components. It works by first identifying strike lineaments of different orientations associated with elongate anomaly patterns. The filter is next designed to incrementally extract source anomaly for the strike directions. SSDF works first on long linear strike lengths before iteratively adding increasingly shorter strike lengths. The iterative outputs are summed together to reproduce the tensor field.

The final output from these methods is a data set minus the degraded signal resident in final processed data.

## Procedure

The adopted procedure is to first run SBM to separate the signature according to depth and then to employ SSDF to interrogate the signature pattern evident in each Depth Interval for geological character.

SBM works on final processed FTG data. Parameter selection is key, and is set to target optimal retrieval of clear signal. Voxel size is set to be less than the survey traverse line spacing to ensure adequate signal is worked. The shallow most depth layer retrieved corresponds to the top of model minus the voxel size. If too shallow, then we either reset the top of the model or change the voxel size to optimally work the data.

The automated modeled depth solution is assessed by generating a depth profile that maps modeled tensor signal intensity against modeled depth. Zones of high intensity identify the depth sensitivity and depth interval maps are generated for nominated depths. The collective output is the final SBM, or migrated, tensor.

SSDF is run on the tensor field for each depth interval to identify coherent signature patterns related to geological character. The key parameter is specification of the starting strike length for retrieval of elongated anomalies. This strike length is then reduced to match the average length of elongated anomalies in the residual map. The process is repeated until no more discernible signal remains.

Individual SSDF iterations are key for identifying lineament information. The THG is calculated for each iteration by combining the Txz and Tyz and worked to reveal the lineaments. The collective SSDF iterations for each depth interval are summed and the Txx, Txy and Tyy components are combined to calculate the THC. This is, in turn, evaluated by following Li (2015) to map the maximum and minimum curvature, working their ratio, and outputting a shape index, or structure map. The outputs are subjected to geological reasoning and their impact evaluated.

## Data Example – NE Iowa FTG survey

The NE Iowa FTG survey was acquired with a 400m line spacing and 4000m tie line spacing with traverse lines orientated E-W. The final processed data contains shallow sourced signal characterized by a dominant high frequency, low amplitude signal preventing confident interpretation of the more subtle deeply sourced geological signal. Figure 1 (a) shows the delivered terrain corrected Tzz. A reduction density of 2400 Kg/m$^3$ was assumed for the terrain corrections. SBM was run for 100m voxel spacing thus allowing us to retain sufficient high frequency signal. The improvement in signal coherency is noted with the SBM output (Figure 1b) showing greater clarity amongst the higher frequencies.

Drenth et al (2015) in their comprehensive paper on the Precambrian in the Iowa Minnesota area describe an interpretation of the FTG survey data identifying several key anomalies. The horseshoe shaped anomaly ‘A’ on Figure 1a is the Decorah Complex, an inferred alkaline ring intrusion likely comprising gabbro-troctolite rocks; Anomaly ‘B’ is a metagabbro; and, Anomaly ‘C’ is interpreted as a silicic s-type granitic pluton. The narrow, circular shaped, Anomaly ‘D’ is identified as sourced by an impact crater buried at c.150m below surface and described by French et al (2018).

## Depth analysis

The interpretative work described by Drenth et al (2015) relied on the application of a matched filter to make their interpretation restricting detailed description of the anomalous sources. The SBM Tzz map shows more discernable information is now available for interpretation.

Analysis on the SBM output identifies three depth intervals. Figure 1c displays a depth profile summarizing the depth analysis. The positive peaks on the curve point to greatest depth sensitivity, at 500m and 2150m below ground. The local minima facilitate construction of the depth interval anomaly (DIA) maps. Figures 1d to 1f display the three DIA maps with DIA1 showing signal sensitive to geology from ground to 250m depth, DIA2 from 250m to 1000m below ground and DIA3 at depths greater than 1000m with greatest sensitivity at 2150m below ground.

It is clear from the DIA maps that more pertinent information is now available from the FTG data. DIA1 (Figure 1d) confirms the shallow presence of the impact crater (Anomaly ‘D’) and indicates the intrusive complex (Anomaly ‘B’) is heavily structured at a shallow interval. The subdued anomaly pattern displayed probably results from the 400m line spacings, that if acquired with tighter spaced lines, then we would expect a higher signal strength anomaly. DIA2 (Figure 1e) indicates the Decorah Complex (Anomaly 'A') has a more complex geometry facilitating a more complete construction of its geological significance than that modeled by Drenth et al (2015) (Figure 1g). A similar case can be made for the granitic intrusion (Anomaly 'C'). DIA2 points to the presence of a lower density rim partially bordering the pluton. DIA3 (Figure 1f) is dominated by longer wavelength signal arising from the deeper geology. However, geological implications are noted where the deeper section of the Decorah Complex is interpreted as possibly dipping more to the east than that depicted in the model section in Figure 1g.

## Structures and Lineaments

Structures depicted in FTG data are captured in the THC, the combination of the Txx, Txy and Tyy component data. High amplitude anomalies locate geological structures that show curvature. Lineaments are interpreted as the maximum amplitude on THG maps (combination of Txz and Tyz) and associated with geological contacts between geological sources generating density contrasts.

SBM DIA2 is selected for the mapping exercise. SSDF was employed to interrogate the signal for geological character. The starting strike length was set to 1600m with subsequent iterations set with strike lengths of 800m. Three iterations were required to complete the analysis. The iterations were summed to produce the final anomaly display as shown in Figures 2a, c and d. The warm colored anomalies on the THC (Figure 2c) are interpreted as structures. Correlation with the Tzz is revealing. The western and eastern sides of the granitic intrusive indicate presence of a localized structure that is lower in density than the granite or country rock. The maximum peaks on the THG (Figure 2d) map contact lineament information. The near circular shape to the granitic pluton is easily mapped. Other notable trends in the THG are WNW, NW, N and NE.

Figure 2(b) combines the THC and THG. The THC is displayed as a structure map that is produced by taking the ratio of its maximum and minimum curvature and applying a color scale. The red colors represent localized higher density structural highs, blues represent lower density structural lows. The result is dimensionless, being a ratio of two curvature gradients, but the colors are revealing. We clearly see excellent correlation, and complexity, associated with the horseshoe shaped Decorah Complex. The linear overlay are the contact lineaments identified from the THG and they add perspective helping to map the structural complexity.

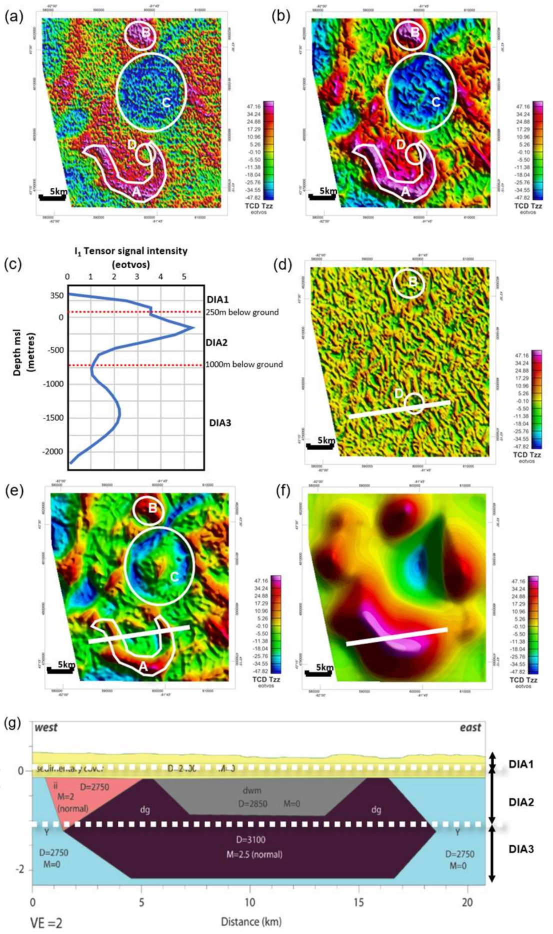

Figure 1: (a) Delivered final processed terrain corrected Tzz, (b) SBM Tzz, (c) SBM depth analysis showing signal intensity for 3 depth intervals, (d) SBM Tzz for Depth Interval Anomaly 1, (e) SBM Tzz for Depth Interval Anomaly 2, and (f) SBM Tzz for Depth Interval Anomaly 3. Lettered and encircled anomalies as described in text. Profile is line of section shown in (g), (g) geological model from Drenth et al (2015). White dashed lines locate depths where SBM DIA maps transition from shallow to deep. Densities in model denoted as values of 'D', units in Kg/m$^3$. Magnetic susceptibilities in values of 'M', SI units.

## Discussion

SBM extracts high confidence, high quality signal from final processed FTG data. The added benefit of determining depth sensitivity directly from the data facilitates a direct means of separating signature patterns into depth intervals; allowing a more efficient interpretation of target geology. The example presented in this paper directly extracts key signature patterns sub-cover and above those associated with deeper geology. Added value is revealed using the SSDF to interrogate the geological significance of mapped anomalous patterns. This work points to a more complex geometry for both the Decorah Complex and the granitic pluton than previously envisaged.

The latter is more intriguing in the sense the low-density zones mapped on the edges of the granite are coincident with localized positive curvature responses (Figures 2a & 2c). One interpretation for this is a possible pegmatite vein proximal to the silicic, s-type granitic pluton. Pegmatites are often lower in density than country rock and often associated with s-type granites, particularly if they are lithium bearing. However, such an interpretation needs to be followed up for confirmation.

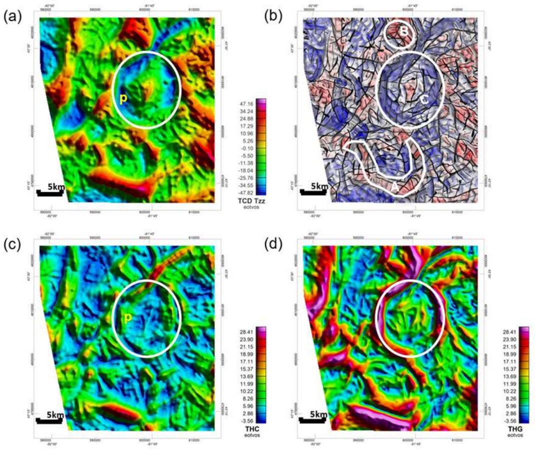

Figure 2: Interpretative maps for SBM Depth Interval Anomaly 3. (a) Tzz, (b) Structure and Lineament map, (c) THC and (d) THG. Lettered and encircled anomalies as described in text. Symbol ‘p’ locates low density structure. See text for details.

Nonetheless, the fact that we have been able to extract such signature patterns from what is a noisy dataset, and from sources beneath sedimentary cover is testament to the FTG data and usage of SBM. Being able to discriminate subtle anomalous patterns from geophysical data is of increasing relevance when exploring for mineral deposits or pursuing energy transition activity in areas where the targeted depths are overlain by variable thickness sedimentary cover, and the need to retrieve high coherency, high quality signal is imperative.

## Conclusions

This paper describes usage of a combined depth-filtering approach, SBM, and SSDF to address challenges when geologically interpreting FTG data. Imaging beneath a noisy response from sedimentary cover and identifying depth intervals hosting source geology is described from final processed FTG data acquired in NE Iowa.

SBM identifies three depth intervals, the second of which maps clear informative signal extracted between depths 250m and 1000m below ground. The mapped anomalous patterns are associated with deeply buried rocks of the Decorah Complex and a granitic pluton. Additional analysis identifies complexity on the granite locating localized zones on its periphery interpreted as a potential for lithium bearing pegmatites.

The significance of this approach to interpreting FTG data is of increasing importance when exploring for metals or energy related geological complexity, particularly where such target zones are buried beneath complex overburden.

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