

Reconciling high resolution airborne gravity gradiometry surveys with 3D mine geology models: Sensitivity testing and new approaches ready for greenfields exploration

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Summary

Direct detection of high density bodies and faults in greenfields exploration via Airborne Gravity Gradiometry (AGG) is now a practical reality because of successful test-casing of known resources at producing open pit and underground sites. First approaches have tested AGG technology together with integrated 3D modelling methods where complimentary data sets are abundant.

Several case studies in Australia, North America and Brazil including mine site data from heliFalcon and Bell FTG (some confidential) have been undertaken. From this work we conclude current best-possible resolution is for orebodies with lateral extents up to 200 m. This is achievable with careful processing and data integration, and can be reconciled against current drilling, assays and lithological records, EM surveys and high resolution digital terrain models (DTMs). Further improvements to this resolution will come about by end 2015, with anticipated deployment of further improved technology.

Acquisition of AGG surveys for greenfield exploration has distinct advantages over ground gravity surveys because they can be acquired more rapidly, over larger areas and hence are more cost-effective.

Introduction to new workflow approaches

AGG is routinely available from several contractors either from Falcon or Full Tensor Gradiometry (FTG) systems. The typical use has been in exploration of basin settings. However to achieve wider applications, extra effort needs to be applied during acquisition to ensure the useable wavelengths of around 200m or less are produced. Vale in Brazil have duplicated both Falcon and FTG surveys over the same mine sites. This work published by Braga et al 2014 takes an iron ore perspective. Other work by the non-ferrous division of Vale has also been completed, the latter has helped form the workflows reported in this paper which can be summarized as occurring in three main stages:

- Dealing with topography and weathering profiles
- Processing and interpretation of all geophysical data
- 3D geology model building

Topography and weathering: Very useful AGG data for mining targets can result from helicopter borne instruments flying relatively slowly and at a nominal altitude of 50m above the terrain. Additionally though, to achieve sensible

outcomes we advocate detailed knowledge must be available for the following:

- High resolution Digital Terrain Models (DTMs)
- Knowledge of the weathering profiles (regoliths)
- Information on large transitory water masses, such as in pit water and waste dump volumes and densities

This is because the largest density anomalies observable from an airborne platform come from terrain effects or topography, up to 80%, followed by weathering anomalies, another 6%. Hence corrections are critical to see the deeper density anomalies from faults and orebodies.

Also the effects of water saturation and other near-surface sources need to be resolved using hydrogeological and geological data derived from drilling and shallow EM. Later these effects can be accounted for in the 3D modelling leaving the “ore bodies” as the remaining source of signal.

DTMs are required around mines for the application of terrain corrections prior to further processing. These can be LIDAR or from careful ground surveys. They need to be temporally coincident with the timing of AGG surveys, particularly in the light of changing dimensions of mine pits and water storages.

Australia is known for its relatively conductive shallow regolith cover making it less likely, compared to Canada, that Electromagnetic (EM) surveys will be routinely used around mine sites. However, with proper planning, significant useful information about near surface conductors and depth of weathering or cover are obtainable using these methods, even without the aid of information from surface drilling.

Processing and interpretation of all geophysical data

The next stage involves processing and preliminary interpretation of all geophysical data sets including AGG data. Processing and interpretation should include determination of:

- Shape, depth and location of bodies of interest (e.g. anomalies, sills, plugs, dykes)
- Dip/Strike of faulted contacts and structures
- Thickness of flat lying strata
- Material property contrasts

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High resolution conventional gravity, magnetic gradiometry and EM data can contribute this required information, as well as AGG data. Historically, the vertical component of gravity or G_z , has been the main workhorse for geophysical interpreters. McGrath, 1991, developed a technique for estimating dip across a fault using conventional gravity. This method has been adapted to AGG data, automated and now it fits into the workflow for worming (see below).

Most interpretation methods for AGG data currently ignore the true nature of the measured signal and fall back to inversion of the G_z , using a "checkerboard" of point sources. Having paid for a full tensor survey, it seems only reasonable to try and devise methods that use all the measured components to help find buried sources and delineate sub-surface faulting.

Electrical Methods: In the context of brownfields auditing of shallow, dense bodies that are potential targets, EM survey is essential. There are around 10 airborne systems for EM in common usage. Of these SPECTREM, VTEM, TEMPEST and SKYTEM are most commonly used for near surface mapping of geology and delineation of bodies.

Depth to source determination: The aim is to find body edges and "hot-spots", and to estimate the Structural Index (SI) for buried shapes, or decay curve fall-off rate (for example, a pipe shape has an SI value of 3). The first code development using Full Tensor Gradiometry (FTG) data for this purpose was an Euler Deconvolution extension.

Dykes Determination: Holstein, FitzGerald and Anastasiades (2009) showed a novel method for finding 2D sheet-like bodies directly from FTG data. Further development of this work exploits inherent dimensionality of most geology bodies, as this is also reflected in the full set of curvature gradients and its local Eigen system. The outcome of this work is an automated system for identification of dyke-like bodies.

Faults Determination: Further new algorithms have followed to deliver explicit 3D shapes that are predicted and so can be tested. A recently developed technique gives good estimates of the dip, throw and density contrast across faults in FTG survey data (FitzGerald and Holstein, 2014). The method requires a central location and strike of the feature to be identified first. Then at least 10 FTG observation points on a profile at right angles to the fault, and in close proximity, are used to create a characteristic curve using a least squares best fit. Once the closed curve is established, dip, throw and density contrast are directly implied. This innovation also involves applying implicit function technology to create fault, dyke, sill and granite bodies directly from the geophysical data. In the first

instance 3D faults that are sheet-like can be derived in strongly expressed structural settings.

Multi-scale edge detection (worming): Interpreters wanting to work in 3D prefer properly registered 'contact' surfaces in 3D as can be supplied by mine models, not simply 'worms' solved for depth of source corresponding only to their upward continued level. Therefore, the current push to identify methods and techniques more successful in exploring undercover, has resulted in improvements to the original "worming" approach. In particular, 2D seismic section interpretation can be greatly assisted by 3D fault networks from gravity (FitzGerald and Milligan, 2013).

3D Mine geology and orebody model building

The final stage of an integrated workflow for getting the most from AGG data involves modelling with all data combined (drilling, assays, lithological logs, and EM), and the geophysical interpretation outcomes. This should include implicit 3D structural geology modelling and property models so that geophysical responses can be calculated directly from modelled geology, including gravity curvature estimates. Furthermore, litho-constrained stochastic inversion can be used to predict the size and location of ore bodies. This workflow presents a continuum towards eventual review of resource tonnage estimates, and definition of structurally controlled ore body geometries.

Best practice for creating 3D models relies upon the emerging use of "implicit functions" constrained by geology observations. A good starting point is a drilling database and detailed topography. Using the steps below, a lithology model of the ore zones, each having density anomalies, are rapidly built using GeoModeller software:

1. define a project modelling space
2. use digital terrain model
3. create a simplified geological pile
4. assemble existing drill hole databases
5. review and simplify the lithology logs
6. import and digitize the surface geology map
7. add constraints for weathering profiles/regolith
8. import mapped/interpreted geology sections
9. compute the mine geology model, with faults
10. add density property laws for each formation
11. compute the gravity forward model response, including the predicted FTG

Case Study – Pilbara, Australia

Using the above workflow, a Pilbara case study has demonstrated how sensitive an AGG survey needs to be to compete with the accuracy and usability of ground based gravity acquisition (FitzGerald, Chilès and Guillen, 2009). In this study, modelling thin beds of the iron ore formations

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(BIFs) over an extensive area (5 km x 2 km x 1 km) undercover, was a key objective.

The Pilbara 3D model (Figure 1) was realized through rule based modelling honouring a stratigraphic pile and fault network chronology. Calculation of each group of concordant geological units occurs independently and then onlap/erode rules apply to resolve the final implicit 3D geology/structure model. The predicted gravitational response is easily computed for any desired component, using a table of densities per lithology expressed as a population with a given Probability Distribution Function.

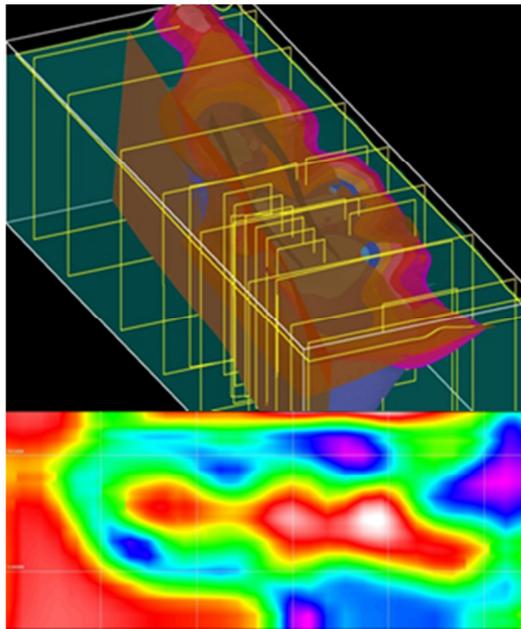


Figure 1, upper: Pilbara model of BIF (vertically exaggerated 3:1) used to capture geological uncertainty in grade-tonnage estimates, using a potential field method of interpolating implicit 3D surfaces. Lower: Computed forward response of the gravity gradient G_{zz} from 3D geology. Units are Eotvos.

Case Study – Nevada, USA

In 2005, Montezuma Mines Inc, commissioned further studies on the geology and structural controls of their prospect in northern Nevada. This included FTG acquisition and commissioning an interpretive study which was later revisited in the light of new interpretation techniques for FTG data (Mataragio & Hogg, 2011).

The Montezuma project is located in the eastern margin of the northern Nevada Rift. Rift-associated tectonics and volcanism dominate the geology including near-surface Tertiary basalt and andesite flows. Deep intrusive bodies

comprise the sources for Miocene volcanism (Stewart and Carlson, 1978). This Carlin-style trench setting has yielded many profitable mines, but exploring for new extensions, often hosted in limestones, continues to be challenging.

A seismic line crosses part of the rift. Drill holes, mapping and FTG data were all available for the study. The rift zone is characterized by N20W striking, parallel boundary faults and several NE striking cross-cutting faults. These are prominent in the FTG signal. Thus, an ideal opportunity to calibrate the ability to estimate the dip and throw of the faults directly from FTG data was presented.

Tensor Gradient Data: The Bell survey data contained the components of a terrain corrected signal. These were combined into a tensor field and gridded, ready for interrogation. Figure 2 shows a tensor phase pseudo-colour image. This enhancement was chosen as it shows the main rift features most clearly, namely the near linear N20W bounding fault and the NE cross-fault. In this case, the density contrast for the cross-cutting fault is much stronger than the density contrast for the main bounding rift faults.

Worming step: The workflow to derive 3D faulted surfaces depends upon multi-scale edge detection, or “worming”. The extension to support FTG data and to generate 3D fault networks has been much requested from multiple resources industries. Figure 3 shows a perspective view of the SRTM terrain and the upwards continued edges for the Montezuma project. In this case, 3 levels of upwards continuation were used to generate edges that are biased to be linear. These edges were clustered in 3D to isolate strong features for transformation into 3D surfaces. The strike/dip calculation step is necessary to allow an implicit function to be solved for each fault’s geometry.

Discussion

A progression towards a viable upgrading of geology and geophysics techniques has been occurring steadily over several years. This is not being done in isolation, but by leveraging upon several new technologies in related fields.

In data rich environments, many aspects of modelling 3D geology and structure can be well constrained. Beyond data-rich zones and into greenfields exploration areas, we recommend using a stochastic geophysical inversion code to predict geology-geometry including orebodies, to optimize for properties, and importantly to gain uncertainty limits for both. By this approach, difficult-to-explore-for orebody settings, such as those hosted in limestones, become less challenging.

The possibility to improve resolution to sub-200 m bodies using AGG technologies will come about by late 2015 with anticipated deployment of further improved technology for

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enhanced resolution and detectability in gravity surveying. This was announced in 2013 by Lockheed Martin in respect of their Eotvos sensitive instrument (essentially a “Falcon” style instrument, but in triplicate). Again careful processing of the recorded signal will likely be recommended, to maximize its useable portion.

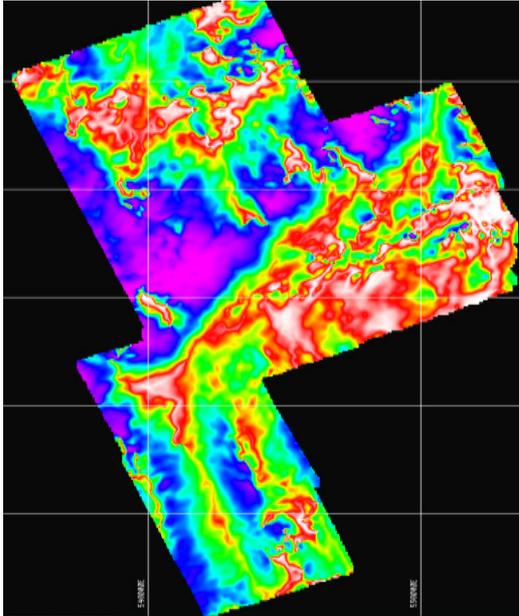


Figure 2: Montezuma gridded tensor data with a phase enhancement derived from rotating each tensor to solve the Eigen system (hence like an AGC filter), histogram equalised. The NE cross-cutting fault and N20W rift bounding fault are clear.

Conclusions

Gravity gradiometry has an important role to play in exploration in the coming years. Good progress is demonstrated for high resolution modelling in 3D that can count for all geological and structural constraints, drillhole logs, resource modelling and geophysical datasets.

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Figure 3: A perspective view of the SRTM terrain and the upwards continued multi-scale edges, derived from the FTG data. The white lines have a stronger amplitude.

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