Flexible approaches to gravity and magnetic inversion at regional and continental scales.

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SUMMARY

Magnetic and gravity data have great potential to inform us about regional-scale features. Major fault zones, basin geometries, basement character, Moho, intra-crustal boundaries etc can all be imaged. However, modelling results are inherently non-unique and often highly uncertain. This feeds into the reliability of the method and its usefulness in resource exploration. Following Occam's razor, traditional methods have usually sought to find the simplest model possible, through use of maximum smoothness regularization (e.g. UBC-GIF), or through simplifying the model to an analytically unique problem (e.g. Parker-Oldenburg). More recent software packages allow the process to be constrained by lithology and the explicit incorporation of geological knowledge into the process. This increased degree of freedom leads to greater flexibility, but also greater ambiguity in results. A single result is clearly not adequate in these cases. Here we present some examples at regional and continental scales where the inclusion of variability measures has greatly increased the usefulness of the inversion process to understand 1) the features of interest and 2) the robustness of the solution.

Key words: Inversion, gravity, magnetic, variability

INTRODUCTION

Magnetic and gravity data have immense potential to inform us about regional to continent scale features, including fault and basin geometries, basement characteristics, the Moho and intracrustal boundaries and properties.

However, the physics of these fields is such that a model can never be uniquely constrained, and only in rare circumstances can a high-certainty result be achieved with just the geophysical data.

Several modelling approaches have been derived that seek to minimise the uncertainty involved in the modelling process, and to maximise the usefulness of the results.

The traditional approach is to follow Occam's razor, and degrade model complexity to the point where a high confidence and repeatable result can be achieved. Such is the case with, for example, a Parker-Oldenburg (Oldenburg, 1974; Parker, 1972) layer geometry inversion, which for a single layer is unique in the analytical sense. UBC-style inversions with default settings are close to this approach also, through the penalising of strong gradients in 3 dimensions (Li and Oldenburg, 1996; Li and Oldenburg, 1998; Li and Oldenburg, 2003). In these approaches, the implicit goal is to find THE answer, i.e. a single model that fits the geophysical data.

These simple models can be geophysically robust, but they are often at odds with geology known to be more complex, and so their usefulness is limited somewhat. More recently developed approaches allow integrated lithological constraint, and the opportunity to, either simultaneously or iteratively, change the geological structure, as well as the property distribution within units (Fullagar et al., 2008; Guillen et al., 2008).

This flexibility allows greater opportunity to generate useful, geologically believable models. However, it also provides greater opportunity for the results to be completely wrong. Our tasks therefore are, firstly, to capture this flexibility in the final result, to control the modelling to avoid erroneous results, and ultimately, to settle on the most representative model given these factors.

The Geomodeller™ inversion method (Guillen et al., 2008) provides this capability by default, as it involves the sampling of a large selection of geophysically acceptable candidate models. For other software packages, e.g. VPmg™ (Fullagar et al., 2008) this sort of analysis is not "included" but can be achieved using a simple workflow. Here we demonstrate two examples at regional to continent scale where such an approach has been applied.

Regional Case Study

The regional example is taken from the west Musgrave Province in central Australia. The crustal structure of this region predominantly represents Mesoproterozoic rift architecture (Giles Event), overprinted in the Neoproterozoic by the intraplate Petermann Orogeny. The geometry of this region is highly 3D and thus a 3D model was produced (Fig

1). This formed the initial model for gravity and magnetic inversions.

In this case, we applied several styles of 3D magnetic and gravity inversion using VPmg™ (Aitken et al., 2013a). Here, we will focus on the combined geometry/property inversion style.

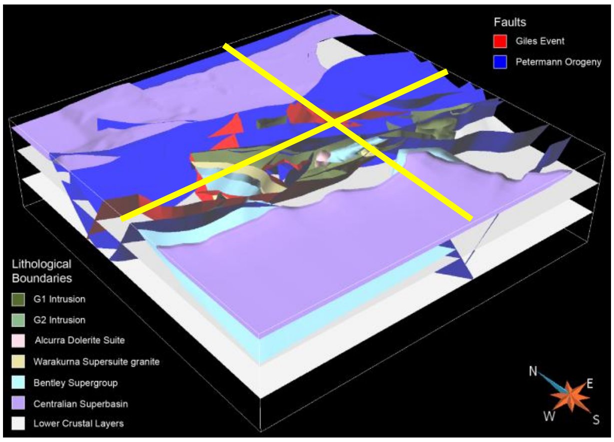

Figure 1: Initial west Musgrave province 3D model. Yellow lines indicate sections in Fig. 2.

In an iterative combined approach, a trade-off must be imposed, so as to control the relative influence of property changes vs geometry changes in resolving misfit. In the case of VPmg this can be achieved using "per-iteration" constraints on the permissible change to the model. This must be imposed upon inversion, and it therefore introduces bias into the solution.

A simple approach therefore, is to apply sufficient different constraint systems such that the range of potential solutions is mapped.

For the west Musgrave Province, the inversions proved highly sensitive to density changes, and geometry changes were the limiting factor in all inversions. Initial RMS misfit was 28.3 mGal, and target misfit was 0.5 mGal. It is clear that, with large permitted geometrical changes, capability is "maxed-out" in the early stages, while with more gradual change, effectiveness persists longer, but involves very minor changes at every step.

Max ρ change (kgm^{-3})	Max depth change (%)	Num iterations (to GII)	RMS Misfit at GII (mGal)	Final Misfit (mGal)
20	0.25	55	1.29	1.23
20	0.5	37	1.84	1.77
20	1	19	2.87	1.84
20	2	13	4.10	1.95
20	5	9	5.15	2.15

Table 1: Inversion Proceedings. GII demarcates the property inversion preceding the first geometry inversion that was ineffective in reducing misfit. Except for the first example, which ran for 60 iteraions, the final misfits after 40 iterations are similar.

From these inversion results, it is straightforward to calculate the lithological mode for each cell, and the mode order – i.e. how many times the mode lithology occupied the cell (Fig. 2). Not surprisingly, the geometrical variation in these models is focused at the boundaries with the greatest petrophysical contrast. A subsequent property model using the modal lithology provided the final result (Fig.2).

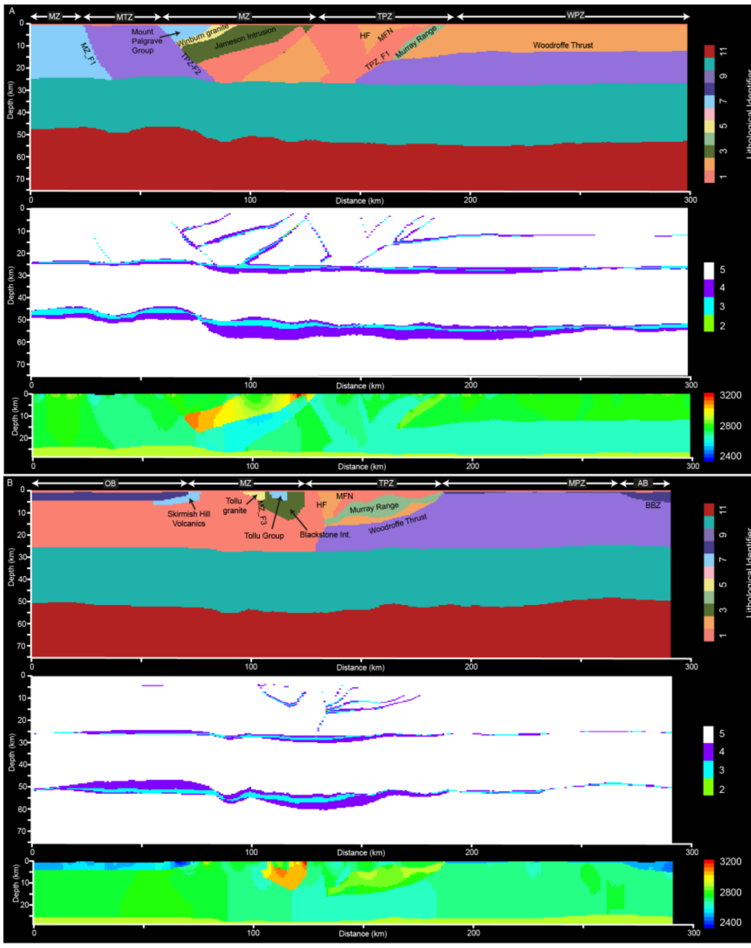

Figure 2: Mode, mode order, and modal model density for an E-W (top) and N-S section (bottom) through the 3D inversion result.

Continental Case Study

A similar approach can be applied at the continental scale to understand Australia's Moho geometry, and the crustal density required to balance this. Previous gravity Moho models for Australia have produced only a single result (Aitken, 2010). While interesting and useful, and effective in resolving key structures in greater detail, this model will provide bias due to the choice of a single trade-off parameter.

This model commences with the network of Moho estimates recently mapped by Kennett et al (2011). A layered crustal model was developed using simple geometrical relationships, the SEEBASE sedimentary thickness map (Frogtech pty ltd, 2005), and a mantle density map (Aitken, 2010; Aitken et al., 2013b). 23 inversions were then carried out varying maximum density change per-iteration between 0 and 150 kgm^{-3}, and with permitted geometry changes ranging from 0% to 50% per iteration.

Of these 23 inversion results, 12 were rejected, either because they failed to produce an adequate fit to the data (RMS misfit >10 mGal), because they produced an unbelievable Moho geometry, or because the misfit evolution was identical to another inversion. The last stable iterations of the remaining

11 models (Fig. 3) were used to calculate the mean Moho and its standard deviation (Fig. 4).

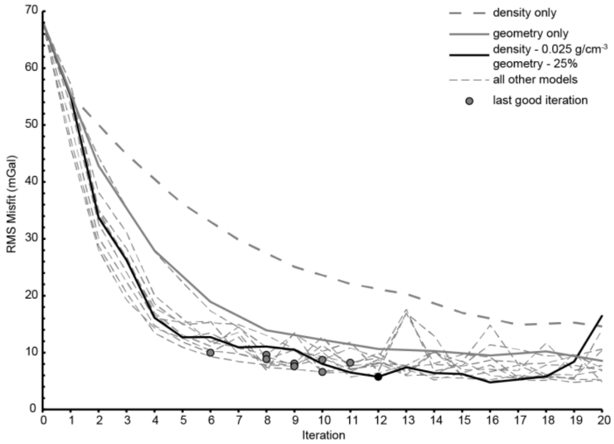

Figure 3: Misfit curves for the 11 accepted models. Note how, unlike the previous example, geometry changes (even numbered iterations) are more effective at reducing misfit. Dots indicate the last stable iteration in each case.

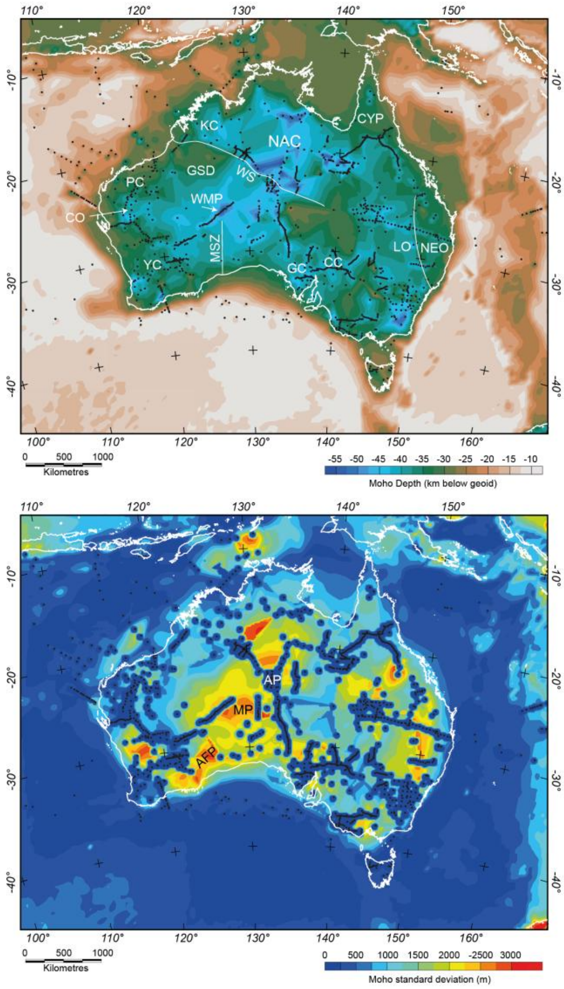

Figure 4: The mean Moho elevation for the continent (top), and the standard deviation of Moho depth in the inversion results (bottom). Generally, 2σ errors are less than 3 km, but can reach upwards of 6 km.

This map, in particular the standard deviation map, highlights areas where the Moho geometry remains poorly constrained. We note that this does not exactly map out areas with the least seismic constraint.

We choose the model closest to the mean result as our "final" model (black curve in figure 3) and apply property only inversion, to derive a map of crustal density variations (Fig 5). This map is a vertically integrated estimate of the percentage change in crustal density from the initial model.

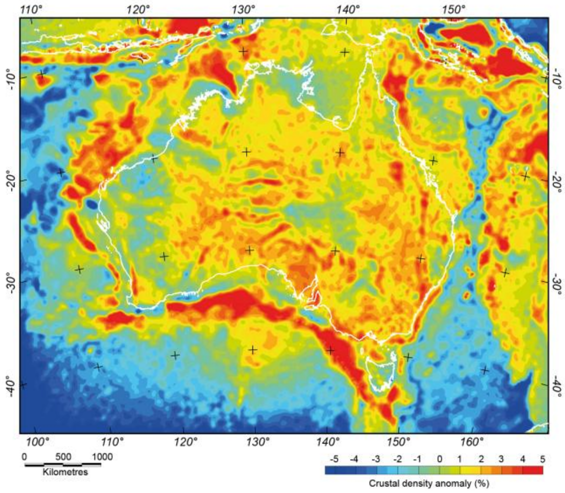

Figure 5: Crustal density anomaly (%) map, representing the vertically integrated percentage discrepancy in density from the initial model. See Aitken (2010).

Note that this image shows the most problematic area in terms of Moho geomerty - central and southern Australia - is characterised by thick, high density crust that is ill-suited to robust gravity modelling.

CONCLUSIONS

These examples demonstrate that "ensemble" inversion of gravity and magnetic data is easily applied, with a little effort, and provides several key benefits:

1- A truly representative model can be derived that is in the middle of the range of possibilities.
2- The relative importance of property and geometry changes can be tested.
3- An analytical uncertainty of the process can be derived.
4- This can help identify regions where the method is inappropriate or has low capability.

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REFERENCES

Aitken, A.R.A., 2010, Moho Geometry Gravity Inversion Experiment (Moggie): A Refined Model of the Australian Moho, and Its Tectonic and Isostatic Implications. Earth and Planetary Science Letters 297, 71-83.

Aitken, A.R.A., Joly, A., Dentith, M.C., Evans, S., Gallardo, L., Thiel, S., Smithies, R.H., and Tyler, I.M., 2013, Imaging Crustal Structure in the West Musgrave Province from

Magnetotelluric and Potential Field Data, GSWA Report. Geological Survey of Western Australia.
Aitken, A.R.A., Salmon, M.L., and Kennett, B.L.N., 2013, Australia's Moho: A Test of the Usefulness of Gravity Modelling for the Determination of Moho Depth. Tectonophysics.
Frogtech pty ltd, 2005, Oz Seebase™ Study 2005, Public Domain Report to Shell Development Australia by Frog Tech Pty Ltd.
Fullagar, P.K., Pears, G.A., and McMonnies, B., 2008, Constrained Inversion of Geologic Surfaces - Pushing the Boundaries. The Leading Edge (Tulsa, OK) 27, 98-105.
Guillen, A., Calcagno, P., Courrioux, G., Joly, A., and Ledru, P., 2008, Geological Modelling from Field Data and Geological Knowledge. Part Ii. Modelling Validation Using Gravity and Magnetic Data Inversion. Physics of the Earth and Planetary Interiors 171, 158-69.
Kennett, B.L.N., Salmon, M., Saygin, E., and Group, A.W., 2011, Ausmoho: The Variation of Moho Depth in Australia. Geophysical Journal International 187, 946-58.
Li, Y., and Oldenburg, D.W., 1998, 3-D Inversion of Gravity Data. Geophysics 63, 109-19.
———, 1996, 3-D Inversion of Magnetic Data. Geophysics 61, 394-408.
———, 2003, Fast Inversion of Large-Scale Magnetic Data Using Wavelet Transforms and a Logarithmic Barrier Method. Geophysical Journal International 152, 251-65.
Oldenburg, D.W., 1974, Inversion and Interpretation of Gravity Anomalies. Geophysics 39, 526-36.
Parker, R.L., 1972, The Rapid Calculation of Potential Anomalies. Geophys. J. R. Astron. Soc. 31, 447-55.