Hybrid Euler magnetic basement depth estimation: Integration into 3D Geological Models

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SUMMARY

We propose an improved magnetic basement depth estimator using a hybrid of two Extended Euler methods. We test the method on the realistic Bishop model. In a significant advance on previous practice, we estimate basement depths independent of any structural index assumptions. We derive structural indices separately. The derived depths follow the general depth trends of the model with some discrepancies that are beyond the capabilities of magnetic depth estimation methods. The results are incorporated into a 3D GeoModeller project for the Curnamona Province in South Australia along with new seismic data. Scalar, Vector and Tensor Potential Field Data Sets are assessed for applicability.

Key words: Euler, basement depths, 3D Geology, magnetics, full tensor gradients, Curnamona.

INTRODUCTION

Depth to magnetic basement estimation is a time-honoured requirement of minerals exploration. Most methods have explicit or implicit assumptions about the geometry of magnetic sources, and are therefore to some degree model-dependent. Recent extensions to the Euler magnetic depth estimation method eliminate the most obvious model assumption (the Structural Index, or SI). They estimate source depth independent of any assumed SI. The calculation of high order derivatives is also avoided, and the method is therefore not prey to noise problems. Recent extensions to potential field data processing are also reviewed.

A realistic test of the technique is possible using the Bishop model proposed by Fairhead et al (2004). This was reported upon by Reid et al (2005). The current study reports on using the magnetic basement depth surface as part of the input constraints to building 3D geological models in South Australia.

METHOD AND RESULTS

Scalar Data Sets

Most of the technical literature on Euler concerns magnetic scalar data sets. The extended Euler method implements an extra differential equation, which imposes rotational invariance on the original single Euler equation. This equation effectively is a scaling law (Mushayandebvu et al., 2001, 2004). Hilbert transformation of the equations (Nabighian & Hansen 2001) makes available a variety of forms.

The “two equation Hilbert” form permits simultaneous solution for depth and SI. In the remainder of this paper, we call this the Hilbert method.

The prevailing view about Potential field geophysics is that there are ambiguities inherent in all depth estimation and modeling techniques. If we can now solve for body type and depth, what assumptions are still in play that cause ambiguities? The solver assumes that a simple and single source is responsible for the local anomaly. This is clearly very rarely true for real geology. We therefore see a full statistical range of predicted SI values rather than the discrete integer values you might expect from theory

The “No SI” form combines the standard and Hilbert equations to eliminate SI. This permits direct solution for depth with reduced uncertainty and with no need to assume any fixed SI—a significant benefit. We find in practice that the “No SI” method can generate small but misleading lateral offsets. This is due to the non-homogeneity of the geological contact when the “classical” equation is applied. A Hilbert transform of your data is in effect a differentiation and so this non-homogeneity is removed. We therefore propose a hybrid Euler method which combines the best of both. The steps are as follows:

- For each moving window position:
  - Apply the Hilbert method to estimate source X, Y and Z location and SI.
  - Apply the No SI method to estimate source Z.
- Eliminate poor solutions using an appropriate selector.
- Map the good solutions and, if appropriate, grid the depth to basement surface.

Solution selection & Errors

All conventional Euler techniques known to us produce sprays of spurious solutions, typically from the anomaly flanks. They are likely to mislead the unwary. This is also true of the Extended Hilbert and No SI techniques but to a considerably lesser degree. Also, the solution for a contact is known to be non-homogeneous and only the true Hilbert solver correctly estimates the X & Y edge co-ordinates for this case. Another manifestation of errors is the coupling of depth and SI by the physics, so this method yields them with higher variances (and therefore uncertainties) than is desirable.

A number of selectors, discriminators and clustering methods have been proposed but we do not seek to review them here. After considerable testing, we have chosen to use depth uncertainty (σ_E) normalized by the square root of estimated depth (E). That is, $\sigma_E / \sqrt{E}$. This appears to discriminate against both shallow and deep spurious solutions about equally.

Euler Calibration Test

We have applied the above approach to the Bishop model (Reid, 2005). This uses a real faulted topographic surface from the Bishop area, California. The surface is expanded and buried and used as a top basement surface. It is shown in Figure 1.

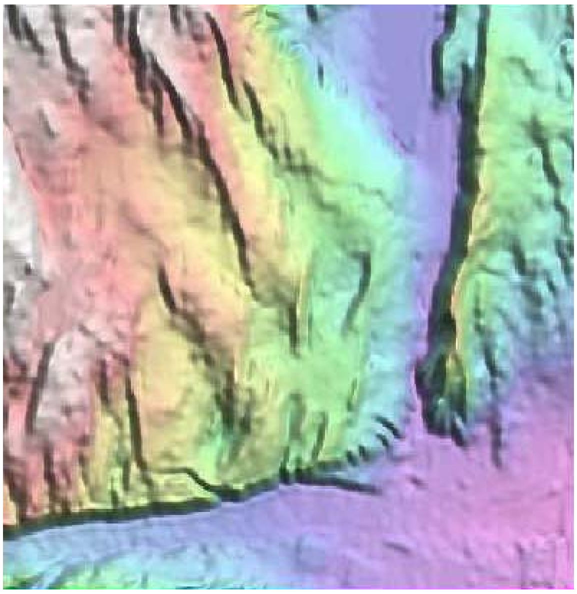

Figure 1. The Bishop Basement depth model. It is 315 x 325 km. Depth varies from 430 m (NW) to 9162 m (SE).

The Bishop model also uses varying basement susceptibility. It is shown in Figure 2.

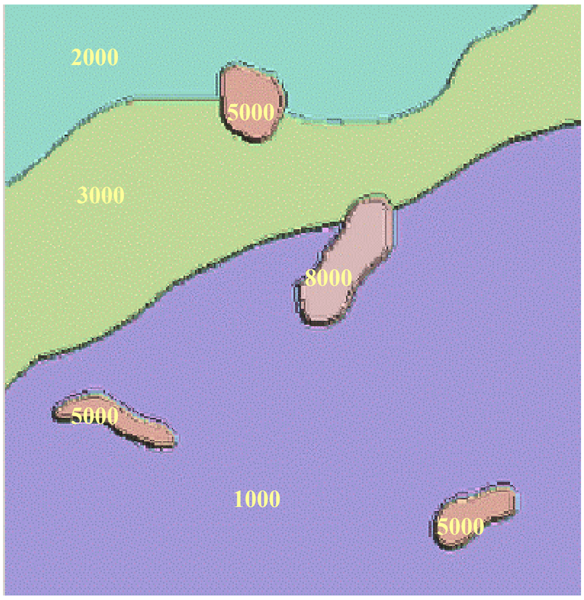

Figure 2. Bishop model basement susceptibilities in micro-cgs. All interfaces are vertical.

The pole-reduced magnetic field was calculated from the above model. It is shown in Figure 3.

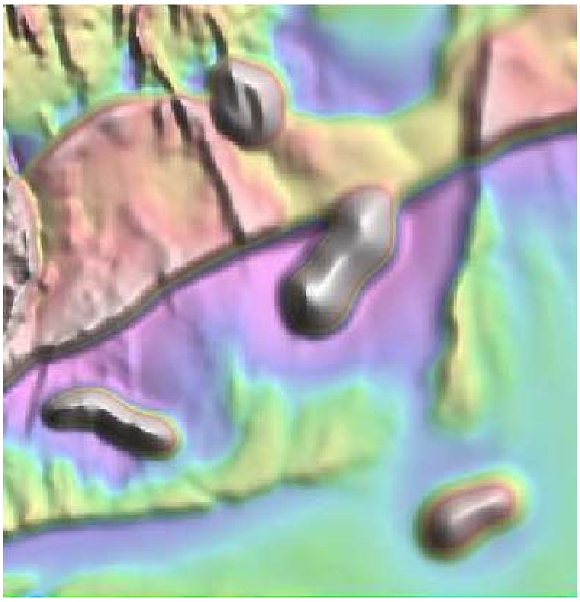

Figure 3. Pole reduced magnetic anomaly. Range 850 nT

The basement depth estimated using the No SI technique for Z and the Hilbert technique for X and Y are shown in figure 4. The solutions have been culled to retain only reliable depth estimates. In the process some structural detail has also been eliminated.

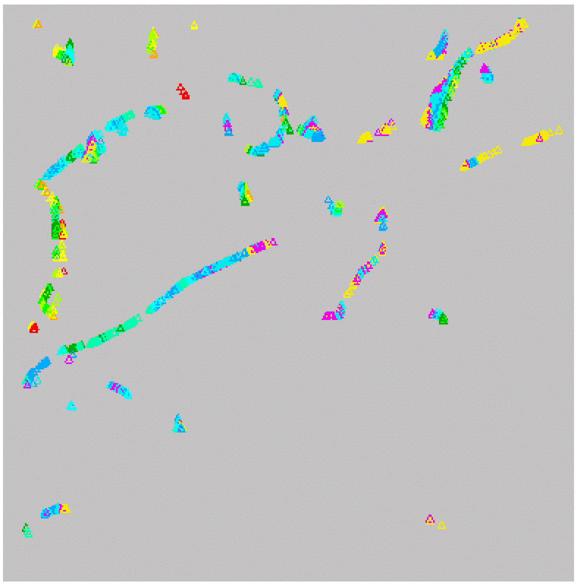

Figure 4. Basement depth estimated using the extended Euler "No SI" technique. Depth range is 560m to 6900 m

The SI estimated using the Hilbert technique is shown in figure 5. Values range from 0 to 3.

The estimated depth was gridded (and low-pass filtered using a 50 km low pass filter) to produce an approximate depth to basement map. It is shown in figure 6. It shows no detail, and could not do so, given the sparse nature of the depth estimates. It does show the general basement trend.

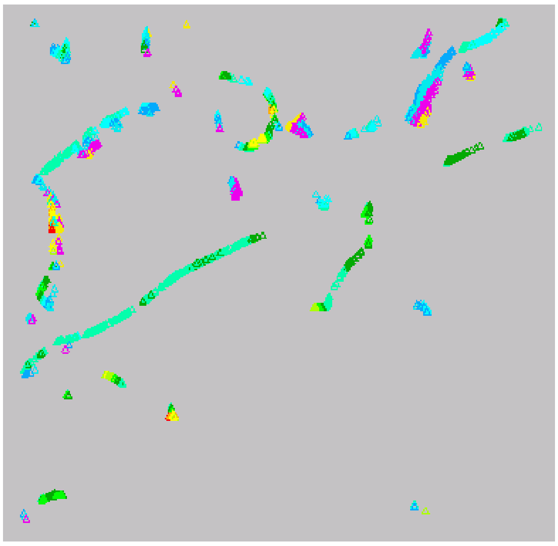

Figure 5: Structural index values estimated using the Hilbert method. They range from 0 to 3. The clear linear features are between 0.5 and 1.0

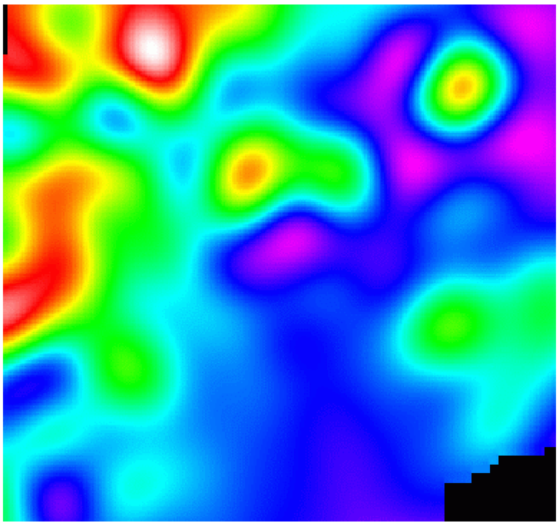

Figure 6. Depth to basement gridded from No SI Euler depth estimates. A 50 km low-pass filter has been applied. Depths range from 1000 m to 10 200 m

Discussion

The magnetic depth estimates are sparse. It is only possible to obtain a depth estimate from magnetic data where there is some lateral discontinuity in magnetization, either because of susceptibility variations or because of top-basement faulting. Where there is no such discontinuity, no depth estimation is possible. This problem is common to all magnetic depth estimators, although many wish it were otherwise.

The estimated basement depths (figure 4) along the western edge show some values much deeper than the model depths. They arise because there is a smooth channel in the basement depth model which gives rise to a smooth low anomaly. The Euler depth estimator requires a sharp edge and is unable to cope with such smoothly varying topologies. It assigns a misleadingly deep basement to the feature. The same problem will occur with many other depth estimation methods. Virtually all of them assume sharp edges. This is an innate flaw in magnetic depth estimation.

Vector and Tensor Data Sets

A revolution in data acquisition together with more competition between contractors is leading to new generation potential field data sets. Full tensor gravity gradiometry (FTG), partial tensor gravity gradiometry (FALCON), 3 component gravity, vector change of magnetic field and, most recently, full tensor magnetic gradiometry are all viable alternative survey data sets. To date, scalar methods are commonly still used to prepare grids of, in particular Tzz component data. Also commonly, these grids maybe band-passed by the contractors in the belief that this reveals the anomalies clients want to see. It is causing quite a bit of confusion with both geologists and geophysicists who are attempting to interpret the data in the context of other independent data sets and the known geology. Exploration geophysics is about creating anomaly grids, but these should also have a defendable quantitative meaning and history. It should be a goal to be able to consistently tie new generation vector and tensor data into previous generation efforts, showing the link and improvements. Software to properly maintain the signal integrity during levelling and gridding is now available (FitzGerald 2006). In particular, the proper use of higher order gradients to interpolate the field leads to much more coherent estimates in the grids. These interpolation errors have not been recognised as significant. All sorts of difficulties and inconsistencies have been raised by various authors when using real tensor data as opposed to theoretical models. We believe quite a few of the difficulties can be attributed to inappropriate data & gridding methods. Among the more notable examples:

- While (2006) when looking at co-variance in FAST Fourier Transform Space
- Lane (2004) when rating the band limited nature of FALCON data to ground gravity

The new spherical interpolation algorithm that honours higher order gradients during interpolation overcomes most of these issues and should be used wherever the full tensor data is available. For standard gridding, where the cell size is set to approximately ¼ the line spacing, the average interpolation error in estimating Tzz can be greater than 5 Eotvos. The implication here is that for anything less than the full tensor, expect ever increasing errors as you try to extract more detailed grids from your profiles.

Euler De-correlation and Tensors

For Euler to work on finding deeper source rocks, longer wavelength features must still be present in your tensor data grids. You cannot use data grids where all “biases” have been removed. This is in effect a band-pass filtering operation designed to show the terrain and regolith features to full advantage. Assuming you have prepared a full tensor grid by the recommended process, the aim is to use this data in the same two ways that we use Scalar potential field data while building and testing 3D Geological Model. Namely

(a) Use Euler Deconvolution to help identify and constrain in 3D space the main buried edges and contacts that have a potential field signal.
(b) Use the full tensor/vector data sets in inversion to test the likelihood of your model being able to explain the independent geophysical observations.

The tensor Euler scheme adopted is that of Zhang (2000). All elements of a Full tensor grid can be utilised in 3 equations. Other requirements are for one or more grids of the field X, Y & Z components. Often, for gravity you may have an observed vertical component grid (Free Air or Bouguer). This can be used if it is upward continued to the same height at the survey. Alternatively, an integration of the tensor grid, to estimate this quantity, is possible.

Case Study: Curnamona Province 3D Geology

The Curnamona province in South Australia contains the Broken Hill ore body and several other Cu-Au prospects. There is limited outcrop so the geologist must call on all available geoscience data to aid in interpretation & mapping. A multi-data source approach to compiling a new solid geology model for this study is also reported in Burtt et. al. (2005). Some major structural trend data is available as well as drilling, some seismic lines and outcrop maps. The solid geology map (figure 7) was also used as a starting point in the 3D model.

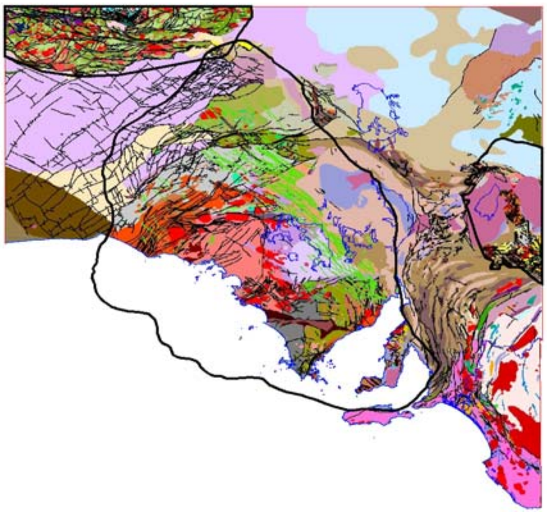
Solid geology interpretation
Geology maps

Figure 7: Curnamona Setting

For the purposes of this study, depth to basement is taken to be the shallowest crystalline rocks affected by a pervasive orogenic event. These are Palaeo- to Mesoproterozoic in age.
The Euler method is an important means of constraining the basement for this model when used in conjunction with limited seismic & drill hole data. We found that is was difficult to determine depth to basement in some areas as the depth to magnetic basement was different or not offered by the technique. This is characteristic of the method as we have just shown. Also the depth to true basement is not necessarily magnetic so two grids were used, with a blending process (figure 8 & 9).

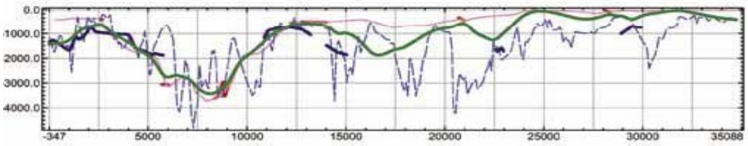

Figure 8: Profile comparison of Euler Depth to magnetic source solutions with combined Euler solutions-drillhole-seismic depth grid and drillhole-seismic depth to basement grid (Burtt 2005)

— Combined Euler solution-drillhole-seismic depth

— Clustered Euler depth to magnetic source solutions

– – Euler depth to magnetic source solutions

— Drillhole-seismic DTB profile

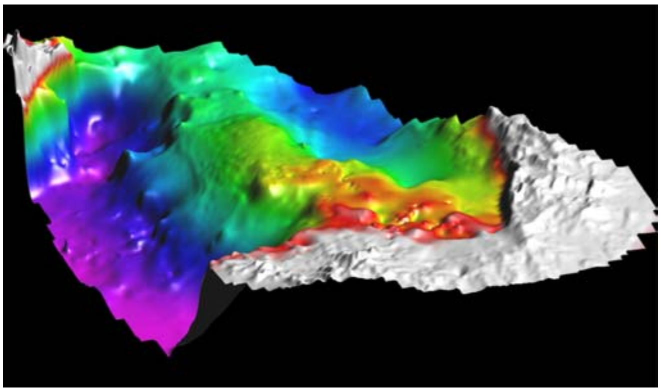

Figure 9: Depth to basement used in Curnamona study

Whilst there is no clear unconformity between the Broken Hill and Olary Domains, it is one possible solution to explain the difference in the amount of Broken Hill Group rocks between Broken Hill and Olary Domains. As 3D Geomodeller can create unconformities in the form of erosional surfaces, it is the simplest solution to having Broken Hill Group only on the Broken Hill side of the Mundi Mundi Fault (figure 10). This is a generalisation because there are known sequences of Broken Hill Group in the Olary Domain.
The alternative scenarios that could be thought of to explain the scarcity of the Broken Hill group in the Olary Domain include structural removal, extension or non-deposition.

The province has complex geology & is multiply deformed. The formations observed in the province are:

- Palaeo- to Mesoproterozoic
- Metasediments
- Metavolcanics
- Igneous intrusives
- Outcrop limited to Broken Hill and Olary Domains, Mt. Painter/Babbage
- Neoproterozoic, Cambrian, Mesozoic and Cainozoic cover
- Pb-Zn-Ag
- Cu-Au

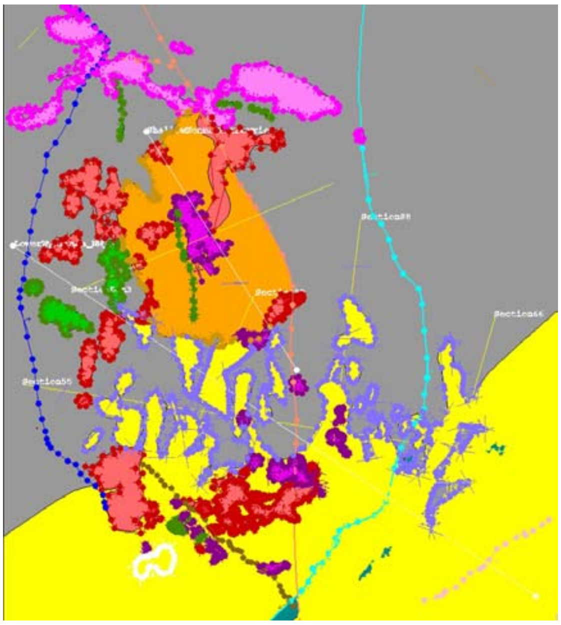

Figure 10: 3DGeomodeller plan view. Note Mundi Mundi Fault shown in light blue.

3D GeoModeller Results

The province has a clear unconformity between East & West domains in that the Broken Hill group only occurs in the Eastern side. Also, all granites have been restricted to the top 10km of the crust. The modelling has helped resolve the upper crust, even before testing using gravity inversion. This is a clear advantage gained by using a geological editor to pose and then test a proposition in conjunction with all known facts. It relieves the geologists of the tedium of constructing by hand all elements in 3D. In 2005, important new extra data in the form of the seismic survey was acquired and this has been used to create a 2nd generation updated model to further constrain the lower crust. This later work has confirmed the original assumption that the granites are confined to the top 10km of the crust.

ACKNOWLEDGEMENT

The 3D Model of Curnamona Province was constructed with the help of the Geological staff at PIRSA. In particular, the SA solid geology map is the culmination of 2 years work by Wayne Cowley.

CONCLUSIONS

A hybrid extended Euler method has been used to estimate depth to basement over the realistic Bishop model & also as one of the elements in a multi-data technique for the Curnamona Province. No structural index was assumed. The depths are in reasonable agreement with the model method, given the inherent difficulty of the process. Additionally, source structural indices have been separately estimated, giving scope for further interpretation of the nature of each source. This demonstrates that the recent theoretical advances may be applied to realistic models and can yield useful results.

The independent estimation of depth and structural index represents a useful extension of the Euler method. Tensor gravity gradiometry data can also be fed into an Euler process, but care must be made with the preparation of the geophysical data. GeoModeller proved a very successful technique for proposing a geological interpretation to the observed Olary/Broken Hill Group occurrences. It also tested an exploration of the extent of the granites.

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