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Defining a deep fault network for Australia, using 3D "worming"

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Summary

Australia, via the efforts of the Government Geological surveys, has a program of releasing ever bigger, higher resolution, continental-scale datasets. The recently released isostatically corrected gravity data imagesmany deep and large-scale crustal features. This is a key dataset for understanding the primary structure of the deep crust across thousands of kilometres. Direct "inversion" of this dataset to a consistent 3D fault surfaces network explains more than 50% of the primary information.
The method of choice relies on multi-scale edge detection or "worming". This continues to enjoy increasing popularity in the regional mapping domain. Large-scale minerals and oil exploration mapping often make use of this technique. With the current shift to 3D geology modelling, issues arise to improve/generalise the worming technology and get 3D contacts that can be interpreted, particularly the sub-set that indicates a primary fault network.
Methods to rapidly compute a consistent 3Dfault network for the entire Australian continent, linking the dominant 20 km deep features back to the surface, are described. If measured gravity curvature gradients are available an even better, more detailed use of these methods at the prospect scale is now available.

Key words: Continental, worms, faults, 3D, gravity, tensor.

Introduction

The analysis of lineaments is of fundamental importance for understanding geological structures and the stress regimes inwhich they are produced. Work on multi-scale edge detection ("worming") by Hornby *et al*. (1999) and Fedi and Florio (2001) has become increasingly popular as a starting point for rapid interpretation using potential field data. Both gravity and magnetic grids are used, often those directly and freely available from Australian government websites. The first published work on Australian gravity at a regional scale was Hobbs *et al*. (2000). Several improvements have been made in the following years such that it is now routine to capture points, "worms", and linear features in a form suitable for overlay in GIS packages. These were reported in Milligan *et al*. (2003).

This technology has a big benefit for the wider geoscience community, in that it minimizes the need for an experienced geophysicist to be present whilst the independent information from potential field data is incorporated in an interpretation. With the benefit of seeing how these rapidly produced "lineament" maps have been used by geologists, and also with the greatly enhanced ability to handle big data, in 3D, up scaling of this technology has recently occurred.

There is also a resurgence of interest in the use of gravity and gravity gradient data, particularly airborne, as part of the rapid mapping package for a staged oil exploration program in a greenfields area. Non-seismic methods that can assist in defining a primary fault network, show good correspondence and assist in 3D interpretation of geological structures, have a big role to play in the coming years.It is cheaper and much quicker than an exploration program involving on-shore 3D seismic. In just this context, during 2012 a large scale series of FTG surveys over the rift in Kenya has resulted in a rapid acquisition of high quality and easily interpretable geophysics data in a complex setting. With the urge to synchronise this with existing and planned 2D seismic lines, and then tie-in to wildcat drilling, a new and improved 3D worming has been applied in the context of rapidly defining the horst/graben layouts in the active rift zone.

All of this is only possible after important extensions which have recently been completed:

(a). support for gravity gradiometry using the measured gradients directly.
(b). creation of interface and foliation data implying 3D surfaces that are geolocated.
(c). adaptation of Euler deconvolution techniques to both full tensor gravity gradiometry (FTG) and a best located method for scalar measures.

More than 70% of Australia has hidden basement geology so geophysical methods designed to assist mapping under cover are critical.

Methods and Results

The method relies on producing unbiased estimates of sharp lateralchanges in physical properties of rocks. The assumption is made that the position of the maxima in the horizontal gradient of gravity or magneticdata represents the edges of the source bodies. Such maxima can be detected and mapped as points, providing the interpreter with an unbiased estimate of their positions.

The process of mapping maxima as points can be extended to many different levels of upward continuation, thus providing sets of points that can be displayed in three dimensions, using the height of upward continuation as the z-dimension. There is a great deal of flexibility in tuning this technology. The upward continued observed data is best "rarified", by doubling the cell size progressively, allowing easier location and joins of worms. In multiscale edge analysis the assumption is made that lower levels of upward continuation map near-surface sources while higher levels of continuation map deeper sources. This assumption is generally true but must be treated with caution, due to the non-uniqueness of potential field solutions. Points mapping the maxima are further analyzed by converting them to poly-lines or "worms". Best-fitting straight lines are then computed for highly linear strings, which may be displayed in plan view (2D) for each level of upward continuation. The new work by Florio andFedi (2013) illuminates the subject by offering the observation that the further the observer is away from the source of the anomaly, the simpler the source geometry appears to be. The position of the source has not changed, and appears to be more homogeneous.

Full Tensor Gradiometry

Late in 2012, an extension to allow the use of observed Full Tensor Gravity gradiometry survey data directly, in a gridded form, by adapting the above sequence, was added. Measured curvature gradients generally contain upto 5 times the spatial frequency content, have better local consistency, and more precisely reflect the geometry of the buried geology once the terrain effects have been removed. So, it is always recommended to use the FTG data that was measured directly in your geophysical calculations if you are lucky enough to have access to such data. The upward continuation of FTG gridded survey data is required, and is also novel, and follows from techniques reported in FitzGerald (2006).

Depth Estimation

There have been several attempts at defining an efficient and sufficiently robust method of estimating a "true" depth of the edge points. The original guideline was to assume approximately half the continuation height as the depth. The obvious first step is to make use of the located contact points and just estimate using this set of points. Most potential field depth methods rely on the vertical derivative of the signal, so this calculation was added. Typically, depth methods work on a moving window over a grid and employ a least squares scheme to best fit locally the solutions., This is too computationally inefficient, and not targeted enough for the current circumstance. The established Euler/Werner deconvolution technology (FitzGerald *et al*., 2004) requires some extra curvature gradients to be realizable. Florio and Fedi propose 3 other criteria for finding the worms, based upon the desire to better locate the depth. These involve tracking the sign changes in components of the field over the sources

- the zero horizontal gradient,
- thezero vertical gradient,
- the zero signal.

Mathematically, these 3 distinct families of ridges do not lie directly over the source body edges, but elegantly indicate where the sources lie.

We have experimented with most of the above possibilities to date, while, also using the Hilbert transform and a moving window on located points down the worm. An overall best estimate for depth and SI at each continuation level is computed. Further experimentation with combined edge/depth methods is still indicated. Computational efficiency has also dominated thinking on this subject, and it remains very important when attempting continental scale studies.

The Source Geometry/Depth Dilemma

Also, as the continuation level rises, the homogeneity of the source body, as reflected in the Structural Index improves. For gravity, what appears to be a dyke when observed at close quarters will have a Structural Index (SI), as reported by Euler Deconvolution of near 1. The same body when viewed from afar, as in the case where the observed signal is upwards continued, now appears to be a fault or contact, with a SI of 0. There is no change of position of the source geometry, just the observers position has changed. In the algorithm developed here, the aim is to find those sources that can still be observed from a great distance, and in doing that, also have their geometries greatly simplified. There remains only one depth to the body hot-spot that we can use, while tracking along the worm. So to truly go to 3D, we need the dip of the body.

Meaningful 3D Surfaces

Using the edge points after resorting and clustering is a recent addition — finding and matching like with like from continuation level to continuation level. Properly registering these "worms" in the depth dimension is not enough to generate surfaces, especially in the light of the new insights. A further innovation is to estimate a dip or foliation at several points for each distinct 3D cluster. Figure 1 (Holden *et al*., 2000) demonstrates that this is not an easy task if you rely on the upward continued point locations. There is only an indirect link between the apparent slopes above the horizon and the actual dip. Model studies were undertaken, and an empirical guideline as to how to estimate the dip was given based upon the combination of the anomaly magnitude at each continuation level and the curvature of the maximum amplitude ridge, leading away from the body edges. Thus the need to provide an interpreted dip has plagued this technology. Initially it was thought that provided the additional depth to source is correctly located, the dip calculation would become a standard trigonometric step. This then allows one or more estimates of the dip of the 3D contact, starting from a central location. The modified tool started with this assumption. In the 3D clustering algorithm, joining shallower worms with the initial deep one, also benefits from looking at the angular relationships. Worms bifurcate towards the surface, relative to what you see at depth, so adding worm fragments at any one continuation level, to a 3D cluster involves thinning down the list of possible near candidates and or joining and finding the longest braches. The "dip" for this aspect is calculated using

- the nearest horizontal distance between candidate worms,
- a requirement that the 2 candidates are sub-parallel,
- and the vertical separation is half the continuation distance separation.

This is a vital step when considering what is needed to transform the "worms" into a limited 3D surface. The 3D geology surface interpolator is described in Lajaunie *et al.* (1997), and uses a 3D implicit function and co-kriging.

As this technique picks out spatially limited features, an influence 3D ellipsoid is also estimated for each feature. The result is a workflow that produces limited thin surfaces, that reproduce a fault and contacts network in a 3D modeling environment. Where there is other independent data such as 2D seismic, well data etc., the juxtaposition of all helps the interpretation and data validation.

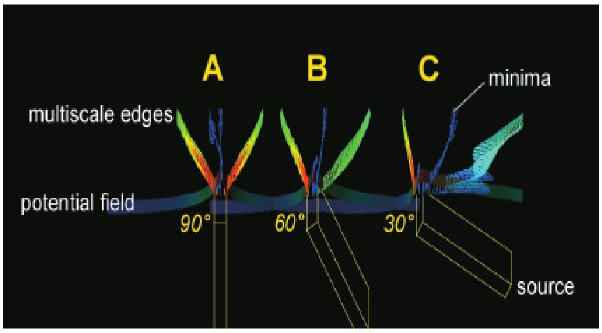

Figure 1. Original work on finding the dip of 2D structures. Synthetic dipping dykes (yellow) and the upward continued response, and multiscale edges with increasing scale upwards (blue coloured points) a. Vertical dyke, b. Dyke dipping 60º to right c. Dyke dipping 30º to the right. After Holden *et al.*, 2000.

Comments

It is difficult highlighting only features that come from significant depths with the ambiguity involved in gravity. By inspection and now convention, some large low value areas in the gravity grid are "basins". The worms found on the basin margins have depths to the top of the fault throw, not the bottom. For an interpretation of crustal elements, depths to basement are important and this is not covered in this technology.

Also, in traditional 2D worming, some major features picked out don't have an expression in just one major worm, the continuity is more subtle than that. Truncations are important for revealing other features. We emphasize that the current worm method to date is an unbiased delineation as a starting point for interpretation. We are aiming to push the technique firmly into the quantitative, rather than qualitative category.

Taken together, this set of innovations rivals some of the ever popular unconstrained inversion schemes for potential field data. Rather than use a mathematical regularization term to influence the geometry of the densities at depth, the new method, based upon geophysical principles, seeks to define, using continuous surfaces, the major density property boundaries. The existing classic inversion schemes use a "checkerboard" approach, and find it hard to define sharp boundaries.

Results

This paper reports on these new extensions applied to the recently published, isostatically corrected, high resolution, Australian gravity grid, see Figure 2.

This large-scale gravity dataset, with a high density of near surface features, contains far too many gradients interpreted as faults, so a thinning strategy is required to find the significant deep crustal faults.

In on going work at Geoscience Australia, using classical 2D geology interpretation, this same dataset was 2D wormed and the prominent structures thought to derive from 20 kms below the surface, ie mid-crust, used as the primary fabric. Following the same thoughts, the new algorithm also clusters up from 20km or deeper structures, and ignores the near surface secondary and tertiary faults/contacts.

Practically, in this first attempt at 3D automatic fault mapping in 3D for Australia, we have tuned the process to produce less than 150 features. Figure 3 shows both a plan view and a 3D projection of one of many tuning runs. Many combinations of continuation levels, cell size, when to rarify, linearity of features etc. are in play.Another technical challenge is to get well known dominant surface features, such as the Darling Fault, shown projected back to the surface with the known location and extents. This part of the puzzle, relies on controlling the interpolation of the surfaces in 3D, from the simplified geometry and average foliation. Critical to this is matching the deepest worm all the way to the surface, and not losing it on the way. In the work shown, just 4 levels of continuation were used 3,7,15 and 26 km and already the surface detail cannot be present, as there was no surface worm to join to.

Unfinished Issues

The relationship between differing edge detection criteria and depths has just opened up for a lot more investigation. The equally difficult issue of estimating the foliation or dip, of the bodies also deserves more investigation. One of the extended Euler methods has also attempted an estimate of body dip, and this has not yet been pursued.

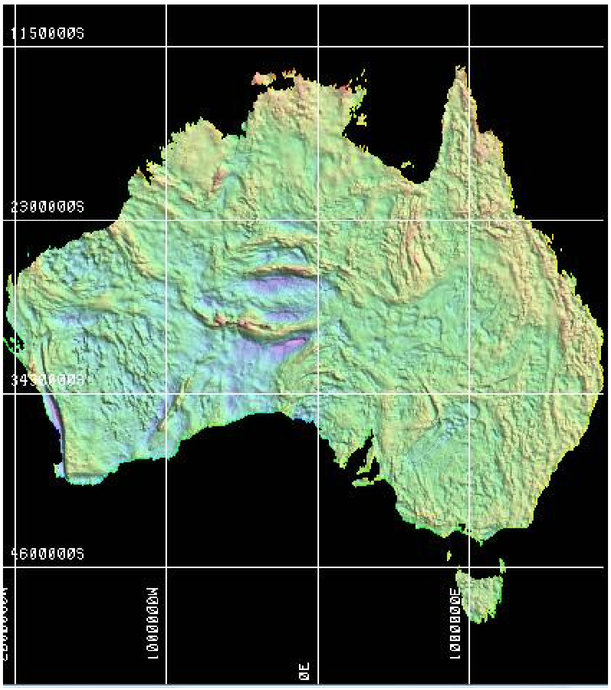

Figure 2. Isostatically corrected gravity grid for Australia. Cell size 800m, projection Lambert Conic Conformal. Note many primary lineaments, mostly deeply rooted in the mid to lower crust. Also note the major topographic highs are properly equalised.

Conclusions

Significant new technology married to better regional potential field datasets and vastly increased computing capacity, have lead to the desire to understand the physics and strive for an automated 3D fault network method. The current work adds real extra value by getting accurate depth information and also the attitude of interfaces.

Deeper crustal features are inferred from the upward continued gravity data, and when capturing these features, the desire to tie these back to known surface expressions proves to be a challenge. Getting a better handle on the complex issues at play has already progressed, and promises much more. The implications of this work extend to helping those who wish to understand continental scale tectonic processes, construct 3D and 4D models. There are also implications for the UNCOVER minerals exploration program for Australia, in that prospectivity improves around deeper structural features, as they come to the surface. The challenge of joining Euler Deconvolution technology with multi-scale detection methods has broadened to include 3D surface outputs.

Acknowledgments

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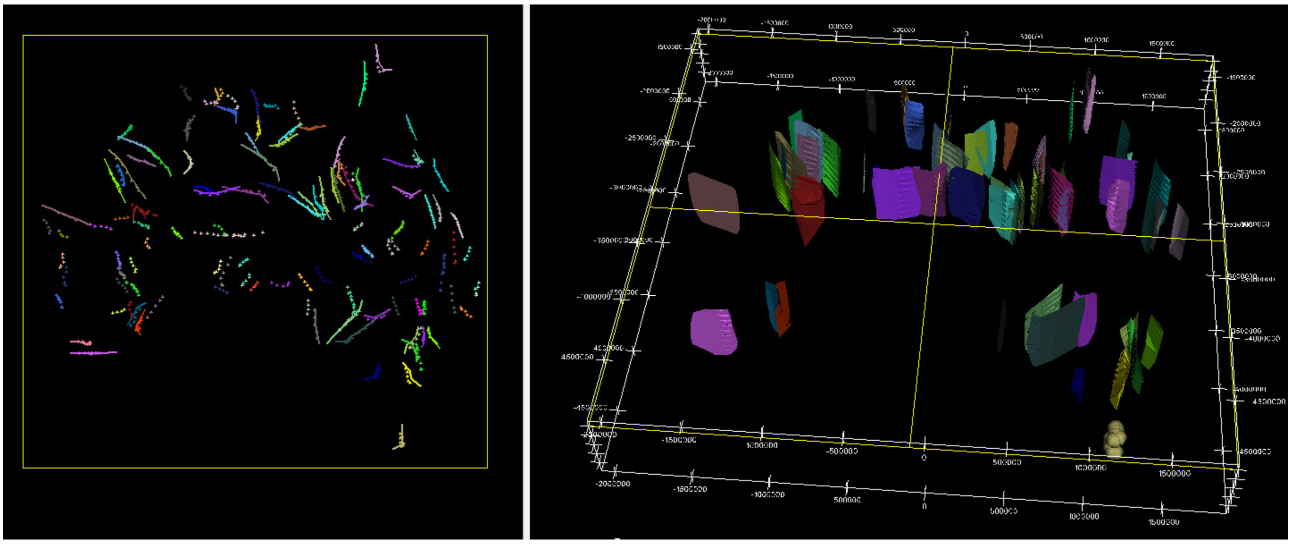

Figure 3. 2D and 3D calculated limited fault network. Just 114 faults are extracted from the data upward continued by 30km. Not all the 3D faults are shown. Each fault has a minimum of 2 foliation estimates, and 2 levels of interface points. The vertical exaggeration is set to 10.

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