Inversion of gravity gradiometry for a basin fault network in an oil application in Brazil, using 3D "worming"

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Summary

Brazil, via the efforts of the Oil, and Mineral exploration companies and the Government geological surveys, has a program of acquiring ever bigger, higher-resolution, potential field geophysical datasets. The use of airborne tensor gravity gradiometry (AGG), has increased dramatically. One such example presented here, is curtesy of Aurizonia Petroleum. 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 prove effective 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 to produce 3D contacts that can be interpreted, particularly the sub-set that indicates a primary fault network.

The new method allows the gathering of related worms to rapidly compute a consistent 3D fault network for parts of Brazil by linking the dominant deep features back to the surface. This is illustrated with measured gravity curvature gradients showing, an improved and more detailed use of the method at the prospect scale.

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 in which the structures are produced. Work on multi-scale edge detection ("worming") by Hornby *et al*. (1999) and Fedi and Florio (2001) has become increasingly popular because it is a starting point for rapid interpretation using potential field data. Both gravity and magnetic grids are used that are often freely available from Australian Government websites. The application of "worming" on Australian gravity at a regional scale was published by 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).

The original "worming' method has a large 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 and assist in 3D interpretation of geological structures, have a big role to play in the coming years. Gravity acquisition is cheaper and much quicker than an exploration program involving on-shore 3D seismic. In this context, during 2012 a large scale series of Full Tensor Gravity (FTG) surveys over the rift in Kenya has resulted in the rapid acquisition of high-quality and easily interpretable geophysical data in a complex setting. With the need to synchronise this with existing and planned 2D seismic lines, and then tie-in to wildcat drilling, a new and improved 3D worming method has been applied in order to rapidly delineate the horst/graben structures in the active rift zone. Both the regional scale and the rift setting of this work, have application in South America.

All of this is only possible after further developments, as listed below, that have recently been completed to the multi-scale edge detection technology. These developments consist of:

(a). support for gravity gradiometry using the measured gradients directly;

(b). creation of interface and foliation data implying 3D geolocated surfaces; and

(c). adaptation of Euler deconvolution techniques to both full FTG and a best-located method for scalar measures.

More than 70% of Brazil's basement geology is obscured by cover material so geophysical methods designed to assist mapping under cover are critical.

Methods

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

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. The upward continued observed data is best "rarified" by doubling the cell size progressively, allowing easier location and joins of worms. 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 worms, which may be displayed in plan view (2D) for each level of upward continuation.

In multi-scale 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.

The new work by Florio and Fedi (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

Murphy and Brewster (2007) show an early application of 2D worming to FTG data. This work uses the invariant properties of the tensor to derive a strike for any 2D bodies. Late in 2012, an extension was added to the Intrepid™ routines used here to allow the use of observed FTG survey data directly, in a gridded form. The upward continuation step is still required. This is novel, and follows from techniques reported in FitzGerald (2006). Whilst we have experimented with many of the possible gradient components, the current implementation still uses ZX and ZY, combined to form a total horizontal derivative, as classically used for scalar potentials. Measured curvature gradients generally contain up to 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, compared to scalar potential fields. It is recommended to use the directly-recorded FTG data in your geophysical calculations if you have access to such data. Note, no support for FALCON as yet. The reason for this follows from what is measured by the horizontal spinning disks in a Falcon system - the total horizontal curvature gradient. Maxima of this measure do not fall naturally over the contact edges, but rather represent a departure from a spherical body shape.

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 (after Hornby) 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 (2013) propose three 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,
- the zero vertical gradient, and
- the zero signal.

Mathematically, these three 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 structural index (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 important when attempting continental-scale studies.

Source Geometry/Depth Dilemma

As the continuation level rises, the homogeneity of the source body, as reflected in the SI, improves. For gravity, what appears to be a dyke when observed at close quarters will have a 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 observer's 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 linking continuation and homogeneity. A further innovation is to estimate a dip or foliation at several points for each distinct 3D cluster.

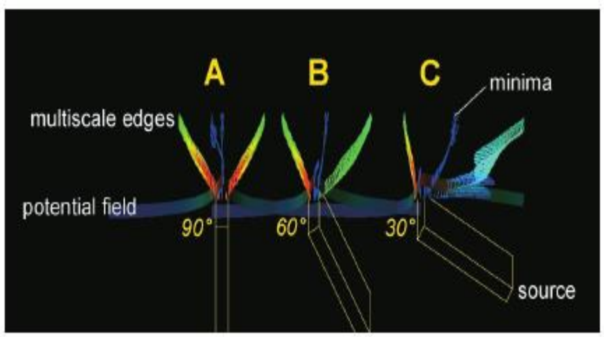

Figure 1. Original work on finding the dip of 2D structures. Synthetic dipping dykes (yellow) and the upward continued response, and multi-scale edges with increasing scale upwards (blue coloured points) A. Vertical dyke, B. Dyke dipping 60º to right C. Dyke dipping 30º to the right. After Holden *et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

Figure 1 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. Holden *et al*. (2000) undertook model studies, 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 that is not empirically derived, 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.

Modifications to the Intrepid™ WormE 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 assumed to be 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, a 3D ellipsoid of influence 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 modelling environment. Where there is other independent data such as 2D seismic, well data etc., the juxtaposition of all helps the interpretation and data validation.

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 has no manual interpretation bias in its linear feature delineations. 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

Vale, Petrobras & PetraEnergia have all been actively using this gravity gradiometry in Brazil in the last 2 years. This paper reports on these new extensions to the multi-scale edge technology applied to the Full Tensor Gravity Gradiometry survey collected by the Aurizonia Petroleum company several years ago. The setting is one of using gravity to find shallow buried gas bubbles in traps that follow ancient dunes. The survey is discussed by Murphy et al 2007.

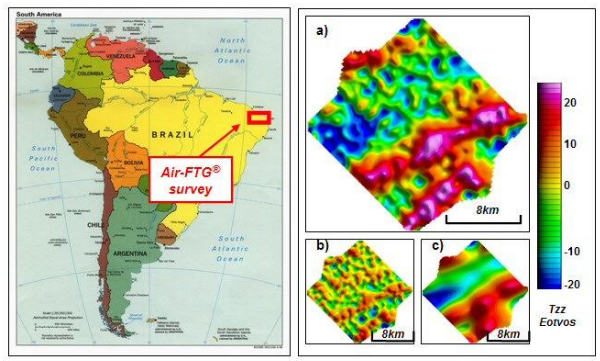

Figure 2. Location for survey. Inset shows the Terrain Corrected Tzz (a) and wavelength filtered images of Tzz for b) less than 6km and c) greater than 6km spatial wavelengths. (after Murphy *et al*., 2007).

In on-going work at Geoscience Australia, using classical 2D geology interpretation, a continental scale gravity dataset was 2D wormed and the prominent structures thought to derive from 30 km below the surface, ie mid-crust, used as the primary fabric. Following the same thoughts, the new algorithm also clusters up from the deeper structures, and ignores the near surface secondary and tertiary faults/contacts.

Practically, for this automatic fault mapping in 3D for Brazil, we have tuned the process to produce fewer than 20 features. Figure 3 shows both a plan view and a 3D projection of one of many tuning runs. We plan to continue to calibrate the method, using a well-known dominant surface features, shown projected back to the surface with the known location and extents. This part of the process 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. Feature numbers 18 & 19 are really the same fault, so the "Merge" facility has been used to combine the contacts and extend the limited extents to cover both features.

Unfinished Issues

The relationship between differing edge detection criteria and depths has been 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 method formulations yields an estimate of body dip. This has not yet been pursued. Ground truthing needs to confirm the indicated errors of around 15% from model studies for depths and SI.

Conclusions

Significant new technology, combined with better regional potential field datasets and vastly increased computing capacity, have led to a better understanding of the physics and to strive for an automated 3D fault network method.

Deeper crustal features are inferred from the upward continued gravity data but, when capturing these features, the desire to tie these back to known surface expressions proves to be a challenge. The implications of this work extend to helping those who wish to understand continental-scale tectonic processes to construct 3D and 4D models. There are also implications for the oil & minerals exploration program for Brazil, in that prospectivity improves around deeper structural features, as they migrate to the surface.

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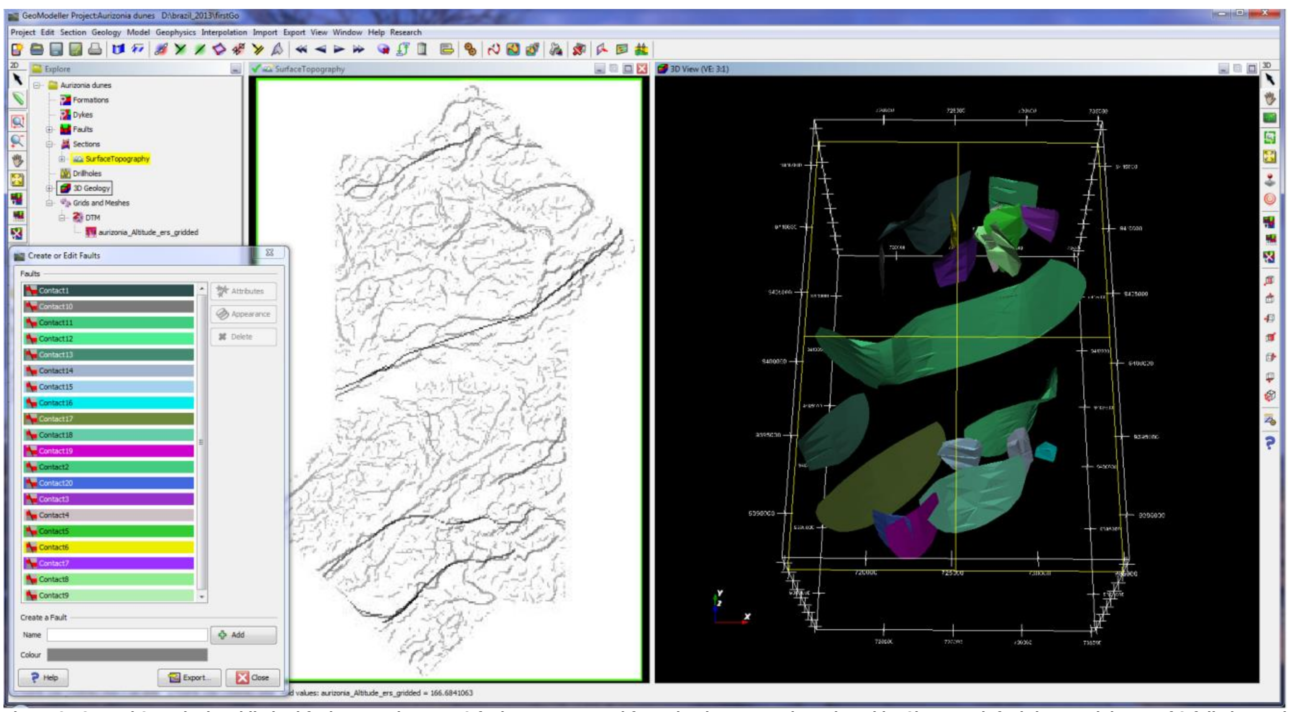

Figure 3. 2D and 3D calculated limited fault network. Just 19 faults are extracted from the data upward continued by 3km. Each fault has a minimum of 2 foliation estimates and 2 levels of interface points. The vertical exaggeration is set to 3. Some subsequent merging of faults further reduces the network complexity.