Two-dimensional modelling of sedimentary basins using irregular polygons

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Abstract

We have presented a polygonal forward modelling of gravity data for representing continuous basement relief of sedimentary basins. The density contrast at the ground surface is assumed to be known, and it varies hyperbolically with depth. The interpretive model consists of a polygon with a fixed number of vertices, whose the two-dimensional Cartesian coordinates of each vertex are the main parameters of the model. We validated the method by simulating different types of sedimentary basins from other publications. The obtained results showed that the method offers a good degree-of-freedom in modelling sedimentary basins with very depositional structures.

Introduction

The estimation of basement relief is considered an important application of gravity methods due to a good indicative of sedimentation throughout the time (Barbosa et al., 1997). The negative density contrast between sediments and basement is an useful information to delineate the basement structure. Gravity models with non-uniform density contrast are useful in complex geologic scenarios, particularly in the analysis of gravity data through sedimentary basins, where density increases normally with depth (García-Abdeslem, 1996).

There is a vast number of researchers working with modelling of sedimentary basins from gravity data in the field of Geophysics (Silva et al., 2007; Chakravarthi and Sundararajan, 2007; Silva et al., 2010). In seventies, Murthy and Rao (1979) presented an extension of the line integral method of Hubbert (1948) to the case of density contrast varying with depth for two-dimensional gravity sources with arbitrary cross-section. The source is then approximated to a N-sided polygon and the gravity effect of each side is summed to yield the total gravity anomaly. Rao (1990) developed an equation for the 2-D gravity anomaly of an asymmetrical trapezoidal model in order to roughly represents a sedimentary basin. He applied the method in the interpretation of gravity anomalies over San Jacinto graben an the lower Godavari basin. Rao et al. (1994b) presented an expression for the 2-D gravity anomaly of a vertical prism using a hyperbolic density-depth function. To represent sedimentary basins, they treated the basins as an ensemble of several prisms juxtaposed. After that, the gravity anomalies of these prisms are separately calculated at every station and summed to get the total gravity anomaly of the basin. More recently, Chakravarthi et al. (2013) developed an automatic modelling technique in the space domain to analyse gravity anomalies of sedimentary basins with exponential density-depth function.

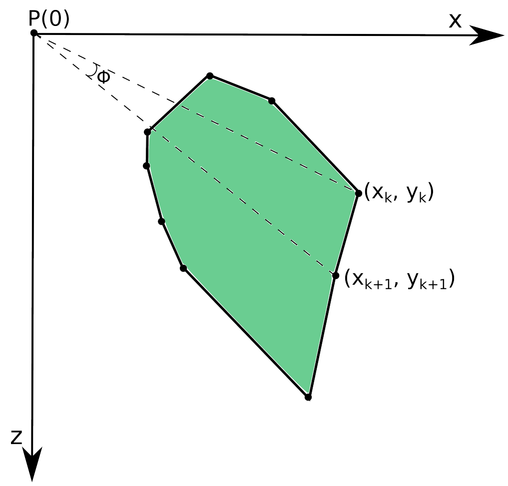

Figure 1: Polygonal model representation. $P(0)$ is one specific observation point in a profile, (x_k, y_k) and (x_{k+1}, y_{k+1}) are the coordinates of adjacent vertices of the polygon. The angle ϕ indicates the angle between adjacent vertices to be considered during the calculation of Equation 2.

The main concern of this work is to create two-dimensional models of sedimentary basins using irregular polygons. To achieve this goal, we implemented the equation in (Rao et al., 1994a), which computes the gravity effect produced by a 2-D polygon with irregular cross-section in different positions of a profile. In this work, we revisited others publications in order to reproduce some results and validate the implemented methodology.

Method

Let $\Delta_\rho(z)$ be the density contrast of a 2-D generic gravity source that can be computed by the following expression (Rao et al., 1994a):

$$\Delta\rho(z) = \frac{\Delta\rho_0\ \beta^2}{(\beta + z)^2}, \qquad (1)$$

where $\Delta\rho(z)$ is the density contrast, in g/cm^3, at any depth z, $\Delta\rho_0$ is the density contrast extrapolated to the ground surface, and β is the rate of density variation expressed in length units. As we can see in Equation 1, the density contrast depends strictly on depth and β values.

The gravity anomaly $\Delta g(0)$ at any point $P(0)$ on a profile of

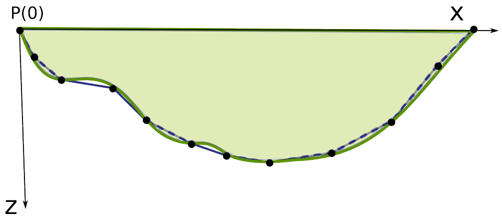

Figure 2: An example of how a sedimentary basin could be represented by an irregular polygon with 12 vertices. The green line is the true basement relief and black dots connected by black lines are the polygon outlines.

a 2-D source of irregular cross section is obtained by the integration of the gravitational effect of a line mass through out the cross section of the source (Rao et al., 1994a). Mathematically, we have:

$$\Delta g(0) = 2G \int \Delta\rho_z \frac{z ds}{x^2 + z^2}, \quad (2)$$

where $G = 6.67 \times 10^{-11}\ m^3/\ kg\ s^2$ is the universal gravity constant and $ds = dx \times dy$ is the differential element of a line mass. If the length parameters are measured in kilometers and density contrast in g/cm^3, the gravity anomalies are returned in milligals (mGal).

After some algebraic manipulation, the 2-D source can be represented by an ensemble of N vertices connected by edges that make the irregular polygon. By the superposition principle, we can represent the discrete version of Equation 2 by the following expression:

$$\Delta g(0) = \sum_{i=1}^{N} dg(i), \quad (3)$$

where $dg(i)$ is the gravity anomaly computed by the i$-th$ edge of the irregular polygon. Figure 1 explains the polygonal model representation.

Using the method presented so far, it is possible to model a different set of sedimentary basins by means of vertices connected by edges. In this work we are modelling three sets of sedimentary basins presented in the literature.

To build a polygonal model, one needs to follow three simple steps:

- Define a profile with the observation points;
- Create a file in which comprises the information about the polygon to be created (i.e., the 2-D Cartesian coordinates (x,z) of each vertex in clockwise direction and the number of vertices to be used);
- Define the density contrast $\Delta\rho_0$ and the value of β;

Figure 2 shows the use of a irregular polygon to create a sedimentary basin. The idea behind this method is that the edges comprising the outline of the polygon represent the an approximation for the basement relief (Rao, 1990; Rao et al., 1994b,a).

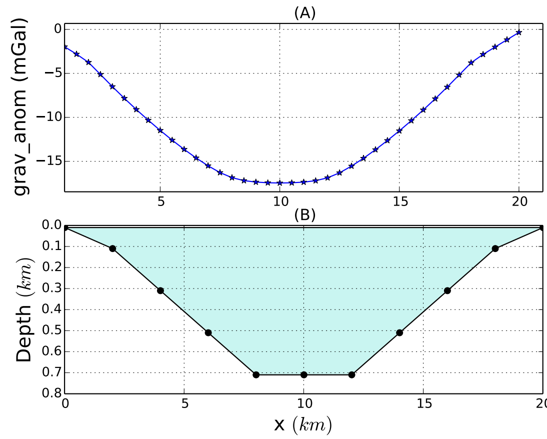

Figure 3: Example of a smooth basin, extracted from Silva et al. (2010). (A) The blue line is the gravity response produced by the eleven-node polygon at 41 observation points. (B) The smooth basin (light blue) made of 11 vertices (black dots) connected by edges (black lines). The density contrast at ground is $-0.88\ g/cm^3$. The bottom of the basin in this example is around $0.5\ km$.

Synthetic tests

We present three synthetic tests from literature to verify the applicability of our methodology to model 2-D sedimentary basins. In examples 1 and 2, we simulate a profile with 41 observation points at the surface ($z = 0$), while in the example 3 we set the synthetic profile with 87 points. For simplicity, all β values are the same for all tests equals to $\beta = 3.12$. We present plots of the density contrast versus the depth in order to observe the hyperbolic dependence of the density with depth.

The first example is extracted from Silva et al. (2010) (Figures 2-a and 2-b), which simulates a synthetic 2-D sedimentary basin with symmetrical shape. The second example is from Rao et al. (1994a) (Figure 3) where they simulated the shape of Los Angeles basin. The third and last example comes from the work of Carreira et al. (2016) (Figure 9) that compiled MT data to provide an interpretation of basement relief for Paranã basin, South Brazil.

Example 01: Smooth basin

Figure 3 (A) and (B) present the gravity anomaly and the modelled basement relief of Silva et al. (2010), respectively. In this case, the eleven-sided polygon is regular due to the separation of neighbouring vertices, which means that the edges connecting the adjacent vertices have approximately the same length. For running this test, we set the density contrast at ground surface as $\delta\rho_0 = -0.88\ g/cm^3$ and $\beta = 3.12$. The maximum depth of the basin is at $0.7\ km$.

This synthetic test simulates a typical smooth basin in which the gravity effect produced by deeper sediments is really week, which provides no relevant changes in the gravity anomaly curve at that depths. Figure 4 (a) shows the weak hyperbolic dependence of the density contrast with depth. This means the β value could be increased a little for a more hyperbolic framework.

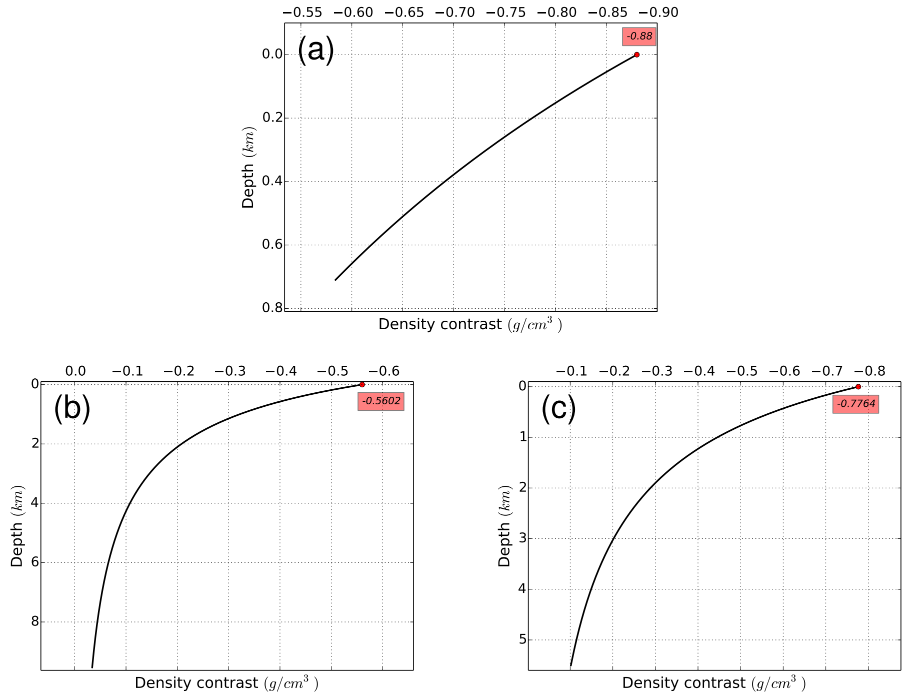

Figure 4: The hyperbolic dependence of density contrast with depth for examples 01 (a), 02 (b) and 03 (c). For all examples, β is 3.12. The value in light red box is the density contrast setted at the ground surface for each example.

Example 02: Los Angeles basin, California, US

Figure 5 presents the simulation of Los Angeles basin, in California, United States. The sediment is know to be differing with depth, which encouraged us to consider the hyperbolic density-function implementation. As we can see in Figure 4 (b), the hyperbolic shape of the density curve is more clarifying than in the previous example (i.e., Figure 4 (a)). We obtain similar results by using $N = 13$ vertices, density contrast of -0.5602 g/cm^3.

Example 03: Paraná basin, Brazil

The last example comes from the work of Carreira et al. (2016), in which they modelled Paraná basin in Brazil by means of MT data and geological contribution. For this test, we built a polygon with 42 vertices, a density contrast at ground of -0.7764 g/cm^3 and we simulated a synthetic profile with 87 observations. We also present the density contrast plot with depth in Figure 4 (c).

As we can see in Figure 6, the spikes in some parts of the polygon are related to big edges. This might be solved by adding more vertices to the polygon. The problem of doing so in this example is the lack of resolution in the gravity anomaly curve due to the large profile spacing, which indicates the we should have more observation points or a polygon with lesser number of vertices. These are definitively the main concerns of this method.

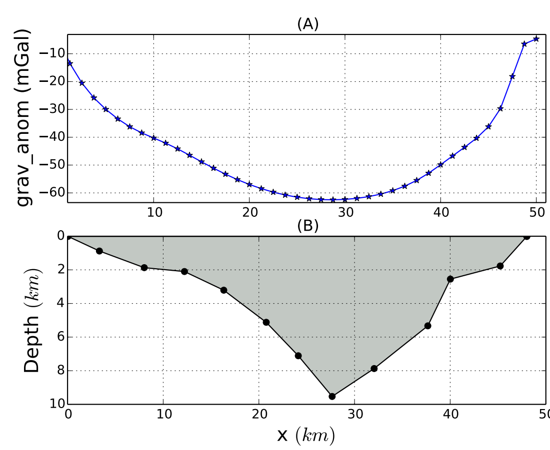

Figure 5: Example of Los Angeles basin from Rao et al. (1994a). (A) The blue line is the gravity response produced by the an thirteen-node polygon at 41 observation points. (B) The Los Angeles basin (light gray) made of 13 vertices (black dots) connected by edges (black lines). The density contrast at ground is -0.5602 g/cm^3 and β is 3.12. The basement relief in this example is around 10 km depth.

Conclusions

We hope that through this work we have demonstrated the great possibility that polygons can bring to geophysical modelling of sedimentary basins by means of gravity

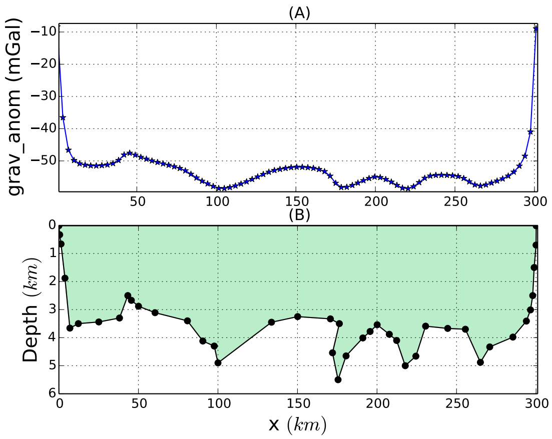

Figure 6: Example of Paraná basin (extracted from Carreira et al. (2016)). (A) The blue line is the gravity response produced by the a polygon with 42 vertices at 87 observation points. (B) The Paraná basin (light green with black outline) connected by edges. The density contrast at ground is $-0.7764\ g/cm^3$ and β is 3.12. The bottom of basement relief in this example is around $5.5\ km$ depth.

data. The mesh-free framework of the presented modelling strategy brings additional advantages to the representation of basement reliefs. We revised some publications to generate some knowledge models. The good advantages of the presented method are i) the simple implementation (the source code is in (Rao et al., 1994a)) and ii) the good degree-of-freedom that the polygon offers in terms of modelling sources beneath the surface. A challenging aspect of this method is controlling the number of vertices and the observations to avoid lack of resolution, which means that you are not suppose to freely increase the side of the polygon. Care must be taken during the definition of the number of vertices of the polygon in comparison with the number of data points to avoid lack of data resolution. A good possibility for extending this work might be an non-linear inversion method of gravity data to recover the basement relief by moving the vertices of the polygon around in order to fit the observed gravity data with the data produced by the resulting polygon.

Acknowledgments

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