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3D Basement Relief Delineation of the Riacho do Rosário Sub-basin

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Abstract

We present the delineation of the basement relief of the Riacho do Rosário Sub-basin using the extension of the Bott method, stabilized by the first-order Tikhonov regularization functional. The sedimentary pack is approximated by a set of 3D rectangular prisms with a constant density contrast with depth. The prisms' thicknesses represent the depths of the top of the basement and are the parameters to be estimated from the gravity data. The results were satisfactory, producing an estimate of the maximum basement depth of 302 m, consistent with the available geological information of the study area.

Introduction

The Paleozoic and Mesozoic basins are distributed throughout the Northeast Region of Brazil. Their origin and evolution are associated with tectonic events that led to the Gondwana rifting and the opening of the South Atlantic. Among these basins, the Riacho do Rosário Sub-basin stands out, forming part of the set of sub-basins that constitute the Lavras da Mangabeira sedimentary basin. This sub-basin covers an area of 24.8 km² (Granjeiro et al., 2008). Its sedimentary infill consists mainly of fluvial plain and shallow lake deposits, which may represent, in the region, a hydrogeological domain with potential for the occurrence of groundwater (Ministry of Mines and Energy, 2008).

Despite its hydrogeological relevance, the Riacho do Rosário Sub-basin requires geological and geophysical studies to better understand its structural and tectonic evolution. The main available studies consist of reports from the Geological Survey of Brazil (CPRM), as well as some geological and geochemical studies (Marzoli et al., 1999; Ernesto et al., 2003; Granjeiro et al., 2008; Batista, 2015), and a limited number of works incorporating geophysical data (Branco et al., 2006; Castro et al., 2006). This limitation results in a low density of information regarding the stratigraphy, evolution, and ages of the geological units.

The technique of gravity data inversion has been successfully employed in mapping the structural framework of sedimentary basins. The present study aims to contribute to the geological understanding of the Riacho do Rosário Sub-basin through the inversion of gravity data, in order to estimate the topography of the crystalline basement. We present the 3D basement relief delineation of the Riacho do Rosário Sub-basin using the extended Bott's method, stabilized by a first-order Tikhonov regularization functional (Monteiro, 2023). This method employs approximations of the gradient vector and the Hessian matrix, which significantly reduce processing time. Unlike the approach adopted by Monteiro (2023), we use an interpretative model composed of a set of horizontally juxtaposed 3D prisms with constant density contrast with depth. The prism thicknesses represent the depths to the top of the basement and are the parameters to be estimated from the gravity data. The results obtained were satisfactory, producing a maximum depth estimate of 302 m, consistent with the available geological information.

Geological Setting of the Riacho do Rosário Sub-basin

The Riacho do Rosário Sub-basin is part of the group of sub-basins that make up the Lavras da Mangabeira sedimentary basin, located in the southwestern portion of the state of Ceará, Brazil (Figure 1). This group of sub-basins is situated within a structural flexure zone in the northern portion of the Borborema Province, bounded to the south by the Patos Shear Zone and to the west by the Jaguaribe/Tatajuba Shear Zones.

The geometric structural framework of the Riacho do Rosário Sub-basin exhibits a half-graben geometry, with sedimentary strata resting unconformably on the Precambrian basement. The sedimentary fill comprises the Serrote do Limoeiro lithostratigraphic unit, with an estimated thickness ranging from approximately 300 to 320 meters (CPRM). The crystalline basement is composed of metamorphic rocks of the Borborema Province.

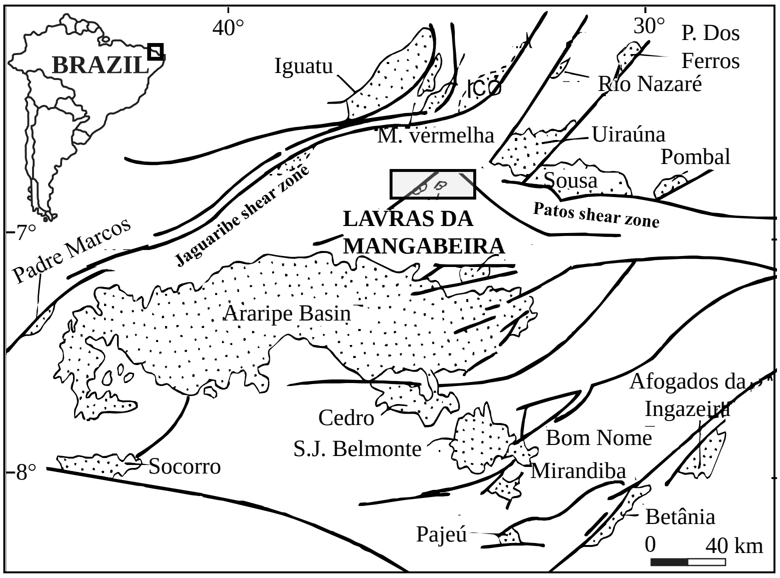

Figure 1: Intra-cratonic basins of Northeast Brazil, highlighting the location of the Lavras da Mangabeira Basin (modified from de Souza Carvalho, 2000).

Methodology

Let $\mathbf{g}^0$ be the *N*-dimensional vector containing a set of gravity observations due to a sedimentary basin. Consider that: (1) the basin has a smoothly varying basement topography, (2) the sedimentary section can be approximated by an interpretative model composed of a set of *N* rectangular 3D prisms, horizontally juxtaposed along the x and y axes, and (3) the density contrast of the sediments relative to the basement is constant with depth (Murthy and Swamy, 1996).

The thicknesses of the prisms locally define the depth to the top of the basement and are the parameters to be estimated. The theoretical gravity observation, g_i, calculated at the *i*-th observation point, is related to the thickness of the *j*-th 3D prism through the relation

$$\mathbf{g} \equiv g_i = \sum_{j=1}^{N} F_{\boldsymbol{P}}\,(p_j, \Delta\rho), \;\; i = 1, \ldots, N, \tag{1}$$

where the nonlinear function $F_{\boldsymbol{P}}\,(p_j, \Delta\rho)$ is defined by Murthy and Swamy (1996).

We obtained the solution $\hat{\mathbf{p}}^k$using the method proposed by Monteiro (2023). This method employs the extended Bott's method (Silva et al., 2014), stabilized by a first-order Tikhonov regularization functional (Tikhonov and Arsenin, 1977). The *N* estimates of the thicknesses $\hat{\mathbf{p}}^k$are obtained by applying the initial estimate $\hat{\mathbf{p}}^k$ to the update

$$\hat{\mathbf{p}}^{k+1} = \hat{\mathbf{p}}^k + \Delta\hat{\mathbf{p}}^k, \tag{3}$$

whose correction vector $\Delta\hat{\mathbf{p}}^k$ at the *k*-th iteration is

$$\Delta\hat{\mathbf{p}}^k = (\mathbf{H}^k)^{-1}\mathbf{J}^k. \tag{4}$$

The generalized Hessian matrix and the generalized gradient vector are given, respectively, by

$$\mathbf{H}^k = b^k\,\mathbf{I} + \mu\,\mathbf{R}^T\mathbf{R}, \tag{5}$$

$$\mathbf{J}^k = (\mathbf{g}^0 - \mathbf{g}) - \mu\mathbf{R}^T\mathbf{R}\hat{\mathbf{p}}^k, \tag{6}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{R}$ is a finite-difference matrix. The scalar μ is the regularization parameter, and b^k is a positive scalar updated at each k-th iteration, as described by Silva et al. (2014). The correction vector $\Delta\hat{\mathbf{p}}^k$ is obtained by solving the linear system using the iterative Least Squares Regression (LSQR) method (Paige and Saunders, 1982).

Results

Figure 2a shows a set of 1,271 digitized gravity data points from the Riacho do Rosário Sub-basin. According to Castro et al. (2006), the Bouguer anomalies were generated exclusively by a density contrast of – 0.27 g/cm³. We applied the proposed method to the gravity data using an interpretative model composed of 41 × 31 prisms juxtaposed along the *x*- and *y*-axes, respectively. All prisms have horizontal dimensions of 0.3 km and a constant density contrast of – 0.27 g/cm³.

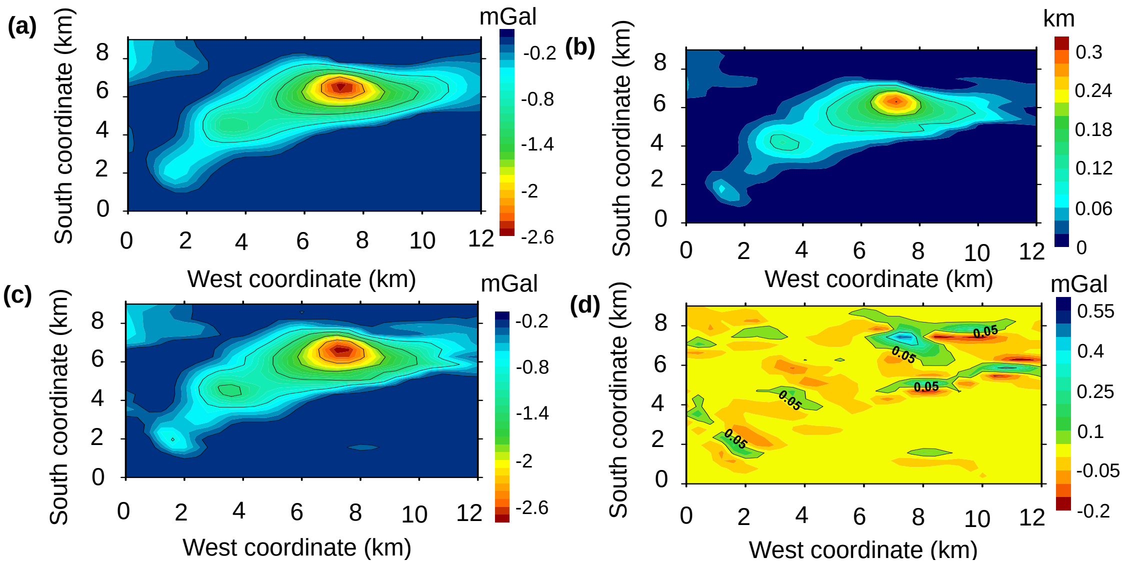

Figure 2: Riacho do Rosário Sub-basin. (a) Gravity anomaly. (b) Estimated basement relief. (c) Fitted gravity anomaly. (d) Difference between the observed anomaly (a) and the fitted anomaly (c).

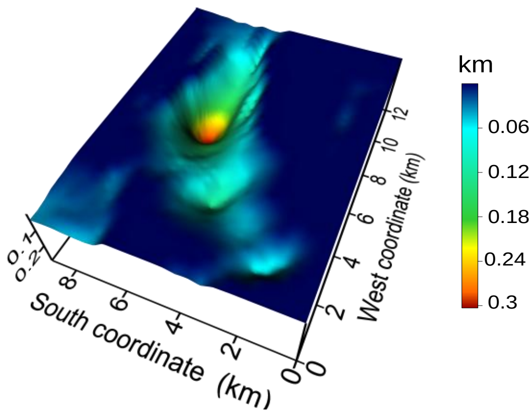

Figure 3: Estimated basement relief of the Riacho do Rosário Sub-basin.

We generated the estimated basement relief (Figure 2b) using the free variables b = 8.4, r_1 = 0.6 e r_2 = 0.1 e μ = 0.3. The estimated basement relief reaches a maximum depth of approximately 302 m, which is consistent with the available geological information (Ministério de Minas e Energia, 2008). Its main axis trends N50°E, curving towards E–W in its eastern portion. In Figure 2b, a secondary depocenter is observed in the southwestern portion, with an approximate depth of 126 m. The corresponding theoretical gravity anomaly (Figure 2c) yielded an RMS misfit of 0.055 mGal. The absolute difference between the observed gravity data (Figure 2a) and the fitted data (Figure 2c) ranges from – 0.2 mGal to 0.55 mGal (Figure 2d). Figure 3 shows a perspective view of the estimated basement relief depths of the Riacho do Rosário Sub-basin.

Conclusion

We present the delineation of the basement relief of the Riacho do Rosário Sub-basin through the interpretation of gravity data. The estimated relief of the Riacho do Rosário Sub-basin demonstrated satisfactory results, in agreement with available geological information. We estimate that the maximum depth of the basement is approximately 302 m, in the eastern portion. Additionally, we observed a secondary depocenter in the southwest portion, with a depth of approximately 126 m.

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