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Reconstructing a 3D basement relief through gravity profiles inversion

Daniele Pantoja Monteiro (UNIVERSIDADE FEDERAL DO PAMPA), Darcicléa Ferreira Santos (UNIVERSIDADE FEDERAL DO PARÁ), João Batista Corrêa da Silva (UNIVERSIDADE FEDERAL DO PARÁ)

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Abstract

We present the reconstruction of the basement topography of sedimentary basins through the inversion of a set of 2D gravity inversions. The proposed procedure consists of: (i) using gravity data from selected profiles over a simulated basin; and (ii) applying inversion methodologies that employ 2D prisms to the selected profiles. Using synthetic data, we compare the simulated basement relief along selected profiles with the relief obtained from a full 3D inversion along the same profiles. The results demonstrate that a satisfactory estimate of the 3D geometry of a sedimentary basin can be achieved through the inversion of a sequence of profiles, that is, through a tomographic reconstruction of the basement relief, which reduces the overall processing cost by at least one order of magnitude.

Introduction

Initially, potential field methods in petroleum and mineral exploration often employed 2D datasets (e.g., Nettleton, 1941; Geyer, 1951). Interpretations were mostly limited to the qualitative correlation of geophysical anomalies with known geological structures or to quantitative interpretations using geometrically simple models, due to computational limitations.

In the mid-1970s, this situation began to change significantly with the introduction of a new interpretative model consisting of a mesh of prisms that discretizes the subsurface region containing the anomalous sources. In this approach, the parameters to be estimated are the physical properties of each prism; thus, the final interpretation yields the spatial distribution of the estimated physical property. A variant of this interpretative model consists of prisms with constant and known physical properties and with their tops at the Earth's surface. In this case, the parameters to be estimated are the thicknesses of the prisms.

Due to limited computational capabilities, the number of elements in interpretative models during the 1970s and 1980s was approximately one hundred, which restricted the practical applicability of interpretation methods. In the 1990s, thanks to the advent of new computational facilities, the number of elements increased substantially to around one thousand, making it possible to obtain more realistic interpretations (e.g., Barbosa et al., 1999). Furthermore, during the same decade, inversion using this type of interpretative model was extended to three dimensions (e.g., Li and Oldenburg, 1998), enabled by a significant increase in processing speed and computer memory capacity.

The very existence of current 3D inversion methods implies that sources cannot be satisfactorily approximated by a 2D distribution of physical properties. Consequently, there is a widespread assumption that 3D inversion is always superior to 2D inversion. The objective of this work is to demonstrate that sedimentary basins belong to an important class of 3D gravity sources whose geometry can be satisfactorily recovered through a set of 2D gravity inversions. This is possible because the basement relief of most sedimentary basins exhibits horizontal extensions that are significantly greater than their vertical depths. Using synthetic data, we compare the simulated basement relief along selected profiles with the relief obtained from 2D gravity data inversions along the same profiles. The results show that a satisfactory estimate of the 3D geometry of a sedimentary basin can be obtained through the inversion of a sequence of profiles, that is, via a tomographic reconstruction of the basement relief, which reduces the total computational cost by at least one order of magnitude.

Methodology

For the 2D inversion, we considered an interpretative model composed of a set of *M* juxtaposed vertical 2D prisms, assuming a density contrast that increases in absolute value with depth according to the parabolic law $\Delta\rho(z) = \frac{\Delta\rho_0{}^3}{(\Delta\rho_0 - \alpha z)^2}$ (Visweswara Rao et al., 1994), where $\Delta\rho_0$ and α represent the surface density contrast and the associated vertical decay rate, respectively. The parameters to be estimated from the gravity data are the thicknesses, p_j, of the prisms in the interpretative model, which are related to the gravity anomaly, g_i, at an arbitrary point r_i (x_i, z_i), through the nonlinear relation

$$g_i = \Delta\rho \sum_{j=1}^{M} F(p_j, r_i)\,,\ i\ =\ 1, 2, \ldots, N, \tag{1}$$

where $F(p_j, r_i)$ relates the *i*-th gravity observation (defined by the position vector r_i) to the thickness p_j of the *j*-th prism (Visweswara Rao et al., 1994).

A stable estimate of $\mathbf{p}$ is obtained by employing the 2D version of the extended Bott's method (Silva et al., 2014), stabilized through the first-order Tikhonov regularization functional (Tikhonov and Arsenin, 1977). The *N* thickness estimates are obtained by applying the initial estimate to $\hat{\mathbf{p}}^k$ the update

$$\hat{\mathbf{p}}^{k+1} =\ \hat{\mathbf{p}}^k + \Delta\hat{\mathbf{p}}^k, \tag{2}$$

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

$$\Delta\hat{\mathbf{p}}^k = [b^k\mathbf{I} + \mu\, \mathbf{R}^T\mathbf{R}]^{-1}[\mathbf{I}\Delta\mathbf{g}^k - \mu\, \mathbf{R}^T\mathbf{R}\mathbf{p}^k], \tag{3}$$

where $\mathbf{R}$ is the discrete first-derivative matrix, $\Delta\mathbf{g}^k$ is the gravity residual vector defined by the difference between the vectors $\mathbf{g}^0$ and $\mathbf{g}$ evaluated at $\hat{\mathbf{p}}^k$, and $\mathbf{I}$ is the identity matrix. The scalar μ is the regularization parameter controlled by the interpreter to produce smooth estimates, and b^k is a positive scalar updated at each *k*-th iteration, as defined by Silva et al. (2014).

Subsequently, we performed a full 3D inversion of the gravity data using the 3D extended Bott's method stabilized through the first-order Tikhonov functional (Monteiro, 2023). Finally, we compared the 2D inversions with the profiles extracted from the full 3D inversion.

Results

We computed the gravity anomaly on a 103 × 53 grid with a spacing of 2 km along both the *x* and *y* directions, simulating the real geological scenario (Figure 1a). We assigned $\Delta\rho_0$ = -0.45 g/cm³ and α = 0.18 g/cm³/km. Five profiles parallel to the *y* direction (AA'–EE') were selected for inversion using the procedure described in the previous section. The results demonstrate satisfactory agreement between the 2D profiles and those extracted from the full 3D inversion (Figures 1b–f). The average RMS difference between the inverted 2D profiles and the corresponding profiles from the 3D interpretation corresponds to 0.07 of the basin's maximum estimated depth. Finally, it is noted that all profiles in Figure 1 exhibit a vertical exaggeration of approximately 1:2.25. Without vertical exaggeration, the 2D and 3D profiles would be practically indistinguishable.

The efficiency of the proposed approach is evaluated through tests with synthetic data, comparing the processing time required for a standard 3D inversion with that needed for a sequence of 2D inversions. To this end, we monitored the elapsed times necessary to perform the inversion of synthetic data generated by a simulated rectangular basin discretized into an NX × NY set of prisms with identical horizontal dimensions, in two different ways: (i) a single standard 3D inversion involving all NX × NY data points, and (ii) NX two-dimensional inversions, each involving NY prisms. The results are presented in Figure 2, which shows processing times as a function of the number of parameters required for the standard 3D inversion (dashed line) and for the proposed 2D reconstruction (solid line). The results demonstrate that the standard 3D inversion produces an exponential increase in processing time with the number of parameters, whereas the proposed 2D reconstruction exhibits an essentially linear increase. For 5500 parameters, for example, the 2D reconstruction is approximately 44 times faster than the standard 3D inversion.

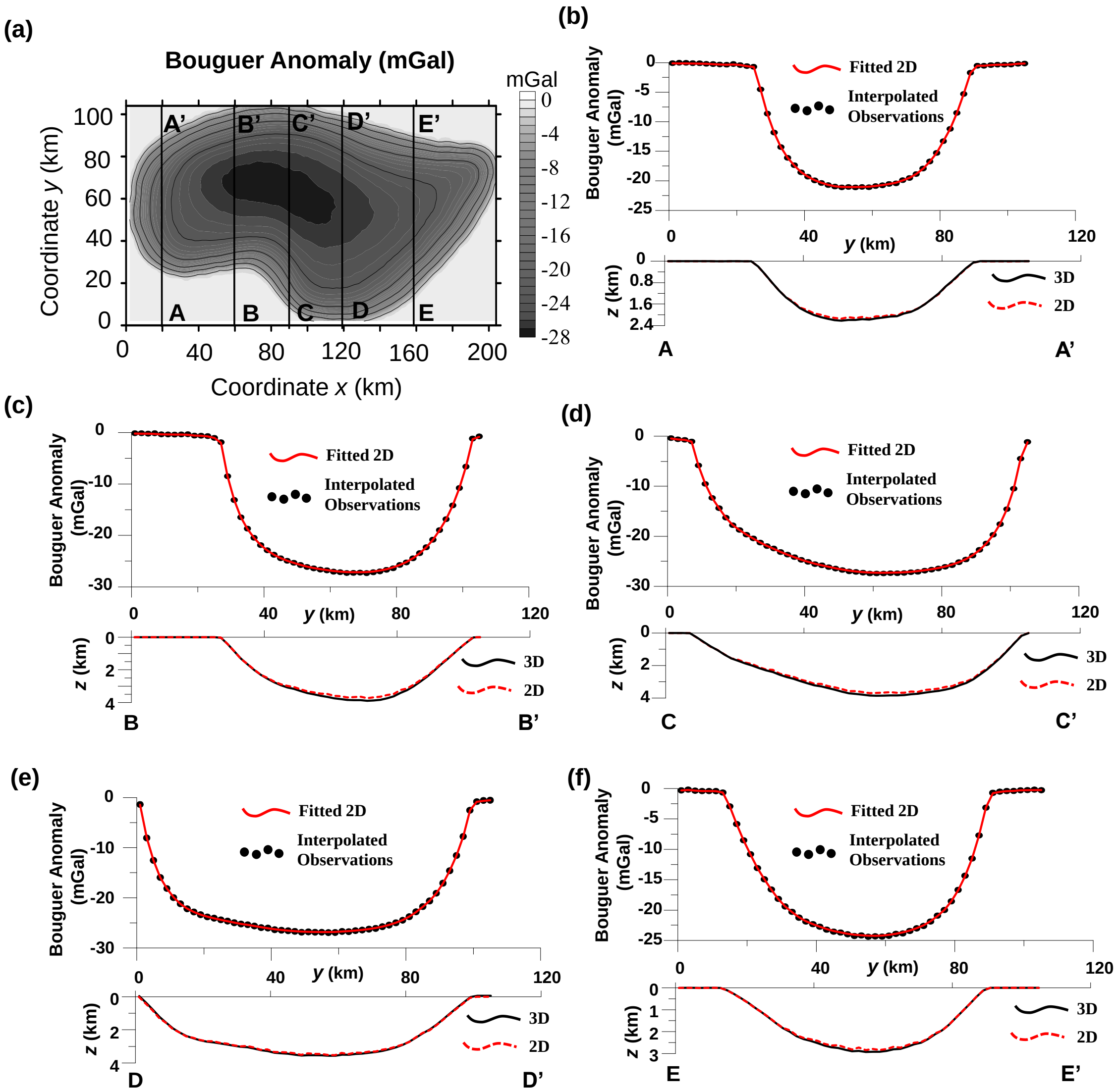

Figure 1 – (a) Gravity anomaly (contour lines) showing the location of the five profiles extracted along the y-axis. The profiles compare the estimated basement relief obtained through 2D profile inversion, represented by dashed lines, with the profiles extracted from a full 3D gravity inversion at the respective locations, shown as solid lines. All profiles exhibit a vertical exaggeration of 1:2.25. (b) Profile AA'. (c) Profile BB'. (d) Profile CC'. (e) Profile DD'. (f) Profile EE'.

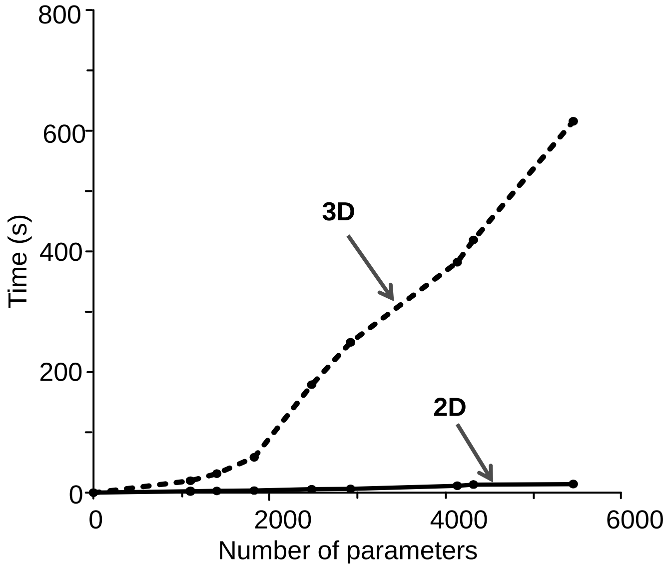

Figure 2 – Comparison of processing time as a function of the number of parameters to be estimated for the standard 3D inversion and the proposed 2D reconstruction, with the aim of producing comparable depth estimates in both cases.

Conclusion

We demonstrate that the three-dimensional basement topography of sedimentary basins can be estimated through a sequence of two-dimensional gravity inversions. Using synthetic data, we compared the relief solutions obtained from the 2D inversions with the simulated basement topography along selected profiles. The results evidenced satisfactory reconstructions of the basement morphology. Efficiency tests indicate that by applying a sequence of gravity profile inversions, it is possible to recover the 3D basement geometry while reducing the total processing time by at least one order of magnitude.

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