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Modeling Gravity Anomalies in Subduction Zones and Their Response in Gravity Gradient Tensor

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Abstract: Subduction zones are complex tectonic regions that often exhibit significant gravity anomalies. This study aims to model gravity anomalies in subduction zones and evaluate their responses in the form of gravity gradient tensors (GGT). Modeling is carried out using a Matlab-based numerical approach, by dividing the subduction zone into small cubic elements, each of which has a certain density contrast to the surrounding medium. From the model configuration, the gravity field response is calculated in three dimensions. Furthermore, the obtained gravity field is spatially reduced to obtain nine components of the gravity gradient tensor, each of which reflects the spatial variation of the gravity field in a certain direction. The results show that the pattern of GTG components is very sensitive to the geometry and density variations in the subduction zone, thus providing additional information that is more detailed than conventional gravity anomalies. This approach is expected to be a tool in interpreting subsurface structures, especially in complex tectonic regions such as subduction zones

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INTRODUCTION

The Quran in Surah Al-Ghashiyah [88]: 17–20 and Surah An-Naba' [78]: 6–7 tells us to think about how mountains become stabilizers and informs us that mountains move just as clouds move. All these verses were a confusing mystery a few centuries ago, but now scientists have proven their truth. Hot spots, the movement of tectonic plates and subduction zones have explained to us the truth of these verses. Subduction zones are one of the most tectonically active regions on the Earth's surface, where the process of oceanic plates subducting beneath continental plates or other oceanic plates occurs (Blakely, 1995). This process produces very complex subsurface structural variations and high density contrasts, which can be identified through gravity field measurements (Götze & Lahmeyer, 1988). Gravity methods have long been used in geophysical studies to map geological structures, due to their passive nature and ability to record subsurface density variations over a wide range (Nabighian et al., 2005).

However, conventional gravity anomaly interpretations often have resolution limitations, especially in revealing spatial details and lateral density contrasts in geologically complex areas such as subduction zones (Zhang & Li, 2016). To overcome these limitations, approaches based on Gravity Gradient Tensors (GTGs) are increasingly being applied in cutting-edge geophysical studies. TGG is a spatial derivative of the gravity field, and consists of nine tensor components, each representing changes in direction and magnitude of the gradient along the three principal axes (Pedersen & Rasmussen, 1990). These components have been shown to be more sensitive to lateral changes in density compared to conventional gravity anomaly methods (Li & Oldenburg, 1996). In this context, this study aims to model the distribution of gravity anomalies in subduction zones using a Matlab-based numerical approach. The subduction zone is modeled as an arrangement of homogeneous small cubic elements with varying densities, in accordance with the forward modeling approach commonly used in geophysics (Parker, 1972). Based on this model, the gravity field is calculated in three dimensions, and then derived numerically to produce nine gravity gradient tensor components. With this approach, it is expected to obtain a more detailed understanding of the subsurface structure and identify geological features that are not detected by conventional methods.

Gravity methods in geophysics are used to investigate the density distribution beneath the earth's surface by measuring variations in gravitational acceleration due to differences in rock mass (Blakely, 1995). Gravity anomalies arise as a result of the density contrast between the subsurface structure and the surrounding medium, and can be classified into Bouguer anomalies, free-air anomalies, and others depending on the corrections applied (Telford et al., 1990). Forward modeling aims to calculate the gravity response of a subsurface model whose density distribution has been determined (Götze & Lahmeyer, 1988). One common approach is to divide the subsurface volume into small homogeneous cube or block elements, then calculate the gravity contribution from each element (Parker, 1972). This approach allows modeling complex geological structures such as subduction zones, which have irregular geometry and significant density contrasts (Li & Oldenburg, 1996).

The basic equation used in calculating the gravitational force of a mass element is Newton's law of gravity, where the gravitational acceleration g at the observation point due to a volume element dV with density ρ is given by:

$$g = G \int_V [\rho(r') (r - r')] / |r - r'|^3 \, dV'$$

where G is the universal gravitational constant, r is the position of the observation point, and r' is the position of the mass source element (Blakely, 1995). To improve the resolution and sensitivity to lateral variations in density, the Gravity Gradient Tensor (GTG) approach is used, which is the first derivative of the gravitational field with respect to three Cartesian axes (Pedersen & Rasmussen, 1990). This tensor consists of nine components $T_{ij} = \partial g_i / \partial x_j$, which provide information about changes in the gravitational field locally (Zhang & Li, 2016). TGG components are very sensitive to the boundaries or edges of density anomalies, making them useful for detecting geological features such as faults, layer boundaries, or subduction planes (Li et al., 2010).

TGG analysis also has the added advantage of detecting small structures and sharp lateral changes, since it is a derivative of the gravity field and therefore responds more strongly to spatial changes (Beiki & Pedersen, 2010). Therefore, the integration of gravity modeling and TGG calculations allows for more detailed subsurface interpretations, especially in complex regions such as subduction zones. 3 Basic Theory of Gravity Gradient Tensor. Gravity Gradient Tensor (GTG) is the first derivative of the components of the gravitational field with respect to the spatial coordinate directions, and provides more detailed information about local changes in the gravitational field (Pedersen & Rasmussen, 1990). Mathematically, the GTG is defined as a second-order tensor with nine components $T_{ij} = \partial g_i / \partial x_j$, where g_i is the component of the gravitational field in direction i, and x_j is the coordinate direction j (Beiki & Pedersen, 2010).

The GTG components consist of three diagonal components (T_{xx}, T_{yy}, T_{zz}) and six non-diagonal components (T_{xy}, T_{xz}, T_{yx}, T_{yz}, T_{zx}, T_{zy}) (Zhang & Li, 2016). Since the gravity field is conservative, this tensor is symmetric, so that $T_{ij} = T_{ji}$, and the number of independent elements is only six (Pedersen & Rasmussen, 1990). One of the advantages of TGG compared to conventional gravity field measurements is its high sensitivity to lateral changes in density, especially near the edges or boundaries of geological structures such as faults, intrusions, or subduction zones (Li et al., 2010). TGG is able to strengthen the response of sharp features in the density distribution, because the differentiation operation enhances the signal from high gradients (Beiki & Pedersen, 2010).

In addition, information from TGG can also be used to form derived attributes such as total horizontal derivative, analytical signal, or invariant tensor, which further clarify the position and orientation of the anomaly source (Zhdanov, 2002). In qualitative and quantitative interpretations, TGG analysis has been shown to improve spatial resolution in mineral and hydrocarbon exploration, as well as in regional tectonic studies (Nabighian et al., 2005). TGG is usually obtained from direct measurements using gravity gradiometers, such as on the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) satellite mission, or calculated numerically from forward-modeling gravity field models (Li & Oldenburg, 1996). In the context of this study, the TGG component is calculated from the results of three-dimensional gravity field simulations using homogeneous cubic element-based modeling with a certain density

METHOD

Subsurface Model Design

The subduction zone in this study is numerically modeled as a three-dimensional volume consisting of small homogeneous cube-shaped elements. Each element has a flexible dimension and density, allowing the representation of complex subsurface structures. The model is built with the assumption that geological layers have density contrasts to the surrounding medium, which affects the distribution of the gravity field. The density distribution in the model reflects the typical characteristics of subduction zones, such as the presence of a subducting oceanic plate, an accretionary prism, and an upper mantle zone. The density parameters are adjusted based on common geophysical literature values, such as 2700 kg/m³ for continental crust, 3300 kg/m³ for the upper mantle, and around 2900 kg/m³ for oceanic crust.

Gravity Field Calculation

The gravity field calculation is carried out using a forward modeling approach. Each homogeneous cube element is calculated for its contribution to the gravity field at the observation point using the formulation of Newton's law of gravity. The total gravitational field at a point is the sum of all contributions from the elements in the model:

$$g = G \Sigma (\rho_i \int_{V_i} [(r - r') / |r - r'|^3] dV')$$

where G is the universal gravitational constant, ρ_i is the density of the i-th element, V_i is the volume of the i-th element, and r, r' are the position vectors of the observation point and the source. This calculation is implemented using a Matlab-based program, which is specifically developed to calculate the gravitational response of three-dimensional models with high computational efficiency.

Calculation of Gravity Gradient Tensor

After obtaining the distribution of the gravitational field at each observation point, the calculation of the Gravity Gradient Tensor (GGT) components is carried out. The GGT components are calculated numerically using a finite difference scheme, which serves as an approximation of the partial derivatives of the gravity field. This numerical method involves evaluating the difference in gravity values between adjacent observation points to estimate spatial variations. Each component of the tensor represents a second-order derivative of the gravitational potential in different directions. These components are crucial for enhancing the resolution and sensitivity of gravity-based subsurface investigations. By analyzing the GGT, geophysicists can detect subtle density contrasts and structural boundaries beneath the Earth's surface. Thus, the GGT offers a more detailed and localized interpretation of subsurface mass distribution compared to traditional gravity data alone.

$$T\_ij = [g\_i(x\_j + \Delta x) - g\_i(x\_j - \Delta x)] / (2\Delta x)$$

This step is performed for each direction i = x, y, z and j = x, y, z, resulting in nine components T_xx, T_xy, ..., T_zz. The calculations are performed on the same three-dimensional grid as the modeling grid, with predetermined grid spacings Δx, Δy, and Δz.

Visualization and Analysis

The modeling results are then visualized in the form of distribution maps of gravity field components and gravity gradient tensors at various slices (horizontal and vertical). The analysis is performed by comparing the gradient and gravity field patterns with the geometry and density contrast in the model. The TGG components that are most sensitive to lateral changes, such as T_xz, T_yz, and T_zz, are analyzed specifically to detect sharp features such as subduction planes and layer boundaries.

RESULT AND DISCUSSION

The results of gravity field modeling and its derivatives in the form of Gravity Gradient Tensor (GGT) components are presented in the figure below. Each panel represents a different component of the tensor, including both diagonal components (T_xx, T_yy, T_zz) and off-diagonal components (T_xy, T_xz, T_yz, etc.). The model simulates a subduction-like structure composed of elongated high-density blocks embedded within a uniform background. The conventional gravity field displays a smooth and broad anomaly centered over the source body, but lacks the resolution to clearly define the vertical edges of the anomalous zone. In contrast, the GGT components exhibit high sensitivity to the vertical boundaries of the density contrast. This is evident from the strong, symmetric bipolar patterns seen in components such as T_xz and T_yz. These results demonstrate the added value of gravity gradient analysis in enhancing the detectability and resolution of subsurface geological structures.

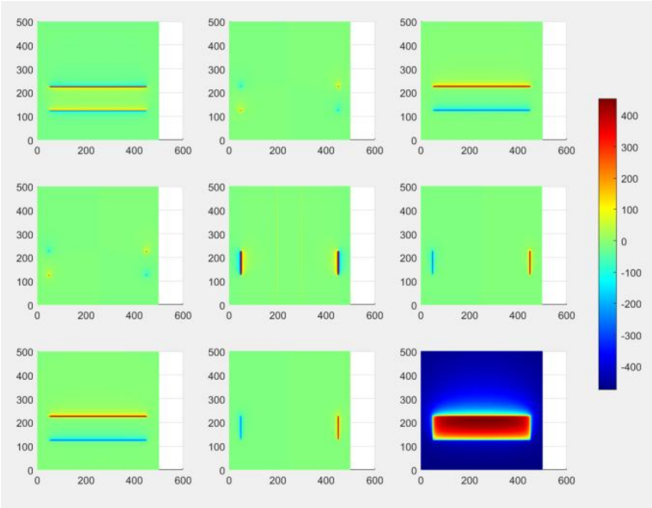

Figure 1. Gravity field and GGT component responses for a modeled subduction zone.

The T_zz component, which is the vertical derivative of the vertical gravity component, provides the most focused and intense response, indicating maximum contrast directly above the anomalous source. The tensor maps also show symmetric polarity changes, which are strongly related to the geometrical layout of the modeled subduction zone. These results confirm previous findings that GGT can better delineate subsurface features, particularly the sharp lateral and vertical density contrasts (Beiki & Pedersen, 2010; Zhang & Li, 2016). Therefore, the integration of GGT in forward modeling significantly enhances the resolution and interpretability of gravity-based subsurface investigations.

CONCLUSIONS

This study has successfully modeled gravity anomalies and Gravity Gradient Tensor (GGT) responses for a subduction zone structure using a Matlab-based forward modeling approach. The results demonstrate that:

1. GGT provides significantly higher spatial resolution than conventional gravity measurements.
2. GGT components are highly sensitive to both vertical and lateral boundaries of density anomalies, characteristic of subduction zone structures.
3. The distinct and strong responses of the GGT enable more accurate interpretation of subsurface geometry.

In conclusion, the use of GGT in gravity modeling offers a powerful tool for geophysical exploration, especially in tectonically complex regions. Future research may extend this method to inversion modeling and real field data applications.

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AUTHOR CONTRIBUTIONS

Author MZ designing the research, constructing model and construct the computer program and analyze the result. Author MZ and SS writing the manuscript of this reazearch.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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