



Full Tensor Gravity Gradiometry Sensitivity Analysis for Delineating Lateral Reservoir Boundaries and Subtle Density Contrasts

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ABSTRACT - The gravity method is frequently used for regional basin mapping. However, this method has limitations in resolving rock layers at shallow targets or detecting subtle density contrasts between rock formations in oil and gas exploration. This study investigates the capability of Full Tensor Gravity (FTG) gradiometry to overcome these challenges in sedimentary basin delineation and shallow reservoir characterization. Forward numerical modeling was conducted using the SimPEG Python package to simulate a sedimentary basin containing a reservoir with varying thicknesses (100–500 meters) and rock density contrasts under different saturation conditions. Quantitative analysis demonstrates the superior sensitivity of FTG compared to conventional methods. For a 500-meter-thick gas-saturated reservoir, the horizontal FTG components (G_{xx} , G_{yy}) showed an anomaly magnitude change of 66.7%, and the vertical gradient (G_{zz}) exhibited an increase of 62.5%. These values are higher than the change in the conventional gravity anomaly (G_z), which only reached 52.0%. Furthermore, horizontal gradients effectively delineate the reservoir's lateral boundaries, while the vertical component provides a clearer representation of the overall basin structural geometry. This study confirms that FTG analysis yields a quantitatively improved subsurface model, thereby reducing the ambiguity associated with conventional gravity methods in delineating shallow prospects.

Keywords: density contrast, full tensor gravity, gravity modeling, reservoir characterization, SimPEG

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1. Introduction

Earth's surface exploration relies heavily on various geophysical technologies to map subsurface structures precisely, accurately, and efficiently. In the oil and gas industry, companies routinely employ a variety of geophysical methods—such as gravity, magnetic, and seismic surveys—tailored to specific exploration needs (Anderson et al., 2015; Haldar 2018). Among these methods, conventional gravity is a well-established and widely used tool for regional basin mapping. This method provides a fundamental understanding of the structural architecture of sedimentary basins over large areas (Blakely 1996; Hinze et al., 2013) and helps identify shallow structural features below the surface (Kebede & Mammo 2021).

However, critical limitations arise when exploration targets shallow structures or reservoirs characterized by low density contrast. While conventional gravity methods are expected to map these targets, in reality, they often struggle to distinguish anomalous responses from adjacent rock layers with relatively similar density values. Previous efforts to address this weakness led to the development of full tensor gravity (FTG) gradiometry, which theoretically offers higher-frequency data and superior spatial resolution. (Murphy 2004) However, significant practical gaps remain: FTG data acquisition is significantly more expensive than conventional gravity surveying. Furthermore, its effectiveness is sometimes debated, as some researchers argue that FTG results can be conceptually approximated simply by mathematically differentiating conventional gravity data. This debate raises ambiguity regarding the efficiency and necessity of applying FTG in shallow prospect evaluation (Kebede et al., 2022), even though initial prospect-scale modeling demonstrated FTG's significant potential for defining rock body boundaries (Grandis & Dahrin 2014).

To address this ambiguity and test the hypothesis that FTG can clearly resolve small density contrasts, this study applies a quantitative forward numerical modeling approach. Utilizing the SimPEG framework, synthetic FTG components are generated from a simulated sedimentary basin model. This modeling strategy enables the systematic isolation of geological variables by maintaining constant basin geometry and volume while varying only the thickness and density contrast of the fluid-saturated reservoir. This controlled environment eliminates interference from complex structural noise, providing a direct and mathematically robust comparison between the conventional gravity response and FTG components. The specific expected output of this study is a definitive quantitative evaluation demonstrating the sensitivity differences between the conventional gravity method, its vertical derivative, and the FTG components. By establishing measurable performance metrics on this synthetic model, the study findings will serve as a practical evaluation framework for processing and interpreting real-world field data. For example, A thorough comprehension of the structural framework of gas reservoirs is essential not only for traditional hydrocarbon exploration but also for prospective uses like long-term CO_2 sequestration (Iskandar et al., 2026) Ultimately, this study aims to provide a clear framework for stakeholders to reduce ambiguity in subsurface interpretation and improve the accuracy of delineating potential shallow reservoir geometries.

2. Methodology

2.1 Problem-Solving approach and assumptions

To overcome the resolution limitations of conventional gravity data in defining shallow reservoir boundaries, this study utilizes a forward numerical modeling approach, which has proven essential for generating high-resolution models (Montesinos-Flores et al., 2023). This approach allows for the isolation of subsurface variables. The baseline model consists of a simple sediment trap without complex structural settlements and is based on a regional basin exploration framework from eastern Indonesia (Argakoesoemah & Hughes 2017). Model Density parameters are assigned using regional geological references and standard rock/mineral density tables (Telford 1990; Harsono 1997; Glover 2007). The model is assumed to have a dense (ϕ) matrix characterized by low porosity (<5%) for the dominant sedimentary rocks, whereas the reservoir is assigned a porosity of 20%.

2.2 FTG simulation calculation

The gravity response and gradiometry components of full tensor gravity (FTG) modeling were executed in the spatial domain using the open-source Python framework, SimPEG (Cockett et al., 2015; Heagy et al., 2024). Unlike frequency domain (FFT) methods, SimPEG uses a volume integral approach to calculate the gravitational anomaly of a set of 3D rectangular prisms. The gravitational potential (V) of a 3D block cell is calculated using Newton's Law of Gravitation. The FTG tensor component ($G_{xx}, G_{yy}, G_{zz}, G_{xy}, G_{xz}, G_{yz}$ s) are analytically extracted as the second-order spatial derivatives of the gravitational potential, which is mathematically based on the formulation of Nagy et al. (2000), Equation 1

$$G_{ij} = \gamma \iiint \Delta\rho \frac{\partial^2}{\partial i \partial j} \left(\frac{1}{r} \right) dx' dy' dz' \quad (1)$$

where γ , $\Delta\rho$, and r are the gravitational constant, the density contrast, and the distance between the observation point and the center of mass, and $i, j \in \{x, y, z\}$, respectively. To calculate the specific density contrast ($\Delta\rho$) in the reservoir zone, the bulk density (ρ_{bulk}) of both the fluid-saturated rock and the surrounding bedrock are calculated using the following petrophysical Equation 2

$$\rho_{bulk} = (1 - \phi)\rho_{ma} + (\phi\rho_{fluid}) \quad (2)$$

The reservoir density contrast basin ($\Delta\rho_{res-bas}$) and with respect to the bedrock background ($\Delta\rho_{res-back}$) is calculated as Equation 3 and Equation 4

$$\Delta\rho_{res-bas} = \rho_{res} - \rho_{bas} \quad (3)$$

$$\Delta\rho_{res-back} = \rho_{res} - \rho_{back} \quad (4)$$

2.3 Application scenarios and analytical tools

Modeling experiments were conducted using a basin geometry model with a depth and a reservoir geometry with a thickness of 1.5 km, a top area of 1.8×1.8 km, and a base area that narrows to 0.8×0.8 km. The forward modeling scenario focused on observing anomalous responses due to variations in reservoir thickness (100 m to 500 m) and fluid saturation conditions (empty, freshwater, oil, and methane). The FTG responses generated from the Python-based simulation were subsequently exported and integrated into Geosoft Oasis Montaj software (provided by PT PHE) for grid calculation analysis, advanced filtering, and qualitative comparison with actual field data responses.

Table 1.
Basin Model Geometry and Petrophysical Parameters.

Parameter category	Properties	Value / Description
Basin Geometry	Depth to Top Basin	1.5 km
	Basin thickness	1.5 km
	Top basin size	1.8 x 1.8 km
	Bottom basin size	0.8 x 0.8 km
	Target reservoir thickness	100 m –500 m
	Dominant sediment (sandstone)	2.60 gr/cc ($\phi < 5\%$)
Petrophysical (Density)	Basement rock (dolomite)	2.70 gr/cc
	Fresh water saturated	2.44 gr/cc
	Oil saturated	2.425 gr/cc
	Gas (Methane) Saturated	2.36 r/cc

3. Result and Discussion

3.1 Synthetic basin and reservoir model

The initial stage of the computational analysis focused on reconstructing the geometry of a three-dimensional (3D) synthetic model representing a sedimentary basin and its associated reservoir zones. This model creation is crucial for understanding the distribution of subsurface physical properties prior to the computation of gravity anomalies and gradiometry tensor components. Based on predetermined parameters, the sedimentary basin is modeled as an inverted trapezoidal prism extending from the surface to a maximum depth of 1.5 km. The basin's geometry was defined by upper lateral dimensions of 1.8 x 1.8 km, which gradually narrowed to 0.8 x 0.8 km at the basin base, discretized using a minimum cell size of 100 m.

This modeling scenario assumes an idealized sediment-trap system without the influence of complex faulting or folding structures, thereby allowing the physical response of the model to be isolated and evaluated more rigorously. A cross-section of the synthetic model variation along the $Y = 0$ plane is shown in (Figure 1). The distribution of rock and fluid saturation density values was injected into each cell block (right rectangular prism) of the mesh based on petrophysical calculations based on field geological parameters.

The basement is represented by dolomite lithology with a density of 2.70 g/cc, which acts as the background density. The sedimentary basin is filled with sandstone material with a matrix density of 2.60 g/cc in an unfilled basin. To evaluate the resolution limits of full tensor gravity (FTG) resolution sensitivity, a shallow reservoir zone was simulated within a basin with a porosity of 20% and a pure methane gas saturation level of 100%.

According to Equation 2, the presence of this gas saturation significantly reduces the bulk density of the reservoir rock to 2.36 gr/cc, resulting in a local density contrast ($\Delta\rho$) of -0.24 gr/cc relative to the surrounding basin rocks. The sensitivity analysis was then carried out comparatively by gradually changing the vertical thickness of the gas-saturated reservoir rock, starting from a thin thickness of 100 m, a medium thickness of 300 m, to a thick compartment of 500 m, as illustrated in (Figure 1b-d).

3.2 Qualitative anomaly response: conventional gravity vs. FTG

A qualitative analysis was conducted to visually compare the delineation capabilities of conventional gravity and full tensor gravity (FTG) methods. The initial evaluation focused on the conventional vertical gravity anomaly (G_z) response in an unfilled basin compared to a basin containing a gas-saturated reservoir (Figure 2).

The modeling results show that the G_z anomaly is characterized by a broad, low-frequency contour pattern that tends to be circular. Although the presence of a low-density gas reservoir (2.36 g/cc) reduces the anomaly value at the basin center to approximately -1.5 mGal, the change in contour pattern is minimal. As a result, the macroscopic geometry of the basin appears to dominate the response, while the lateral boundaries of the reservoir remain poorly resolved and cannot be clearly delineated.

This limitation of the conventional gravity (G_z) method is successfully overcome by the FTG tensor component, which demonstrates significantly higher visual sensitivity (Figure 3). The separation of the vertical and horizontal gravity gradient components provides specific structural information. In the vertical gradient, the G_{zz} component displays a centralized anomaly that emphasizes the location of mass deficit accumulation, while G_{xz} and G_{yz} begin to exhibit a bi-polar pattern indicating a density transition.

The superior capability of FTG for boundary delineation is strongly confirmed by its horizontal gradient components (G_{xx} and G_{yy}). Unlike the fuzzy G_z , the G_{xx} and G_{yy} components (Figure 3d-e) exhibit narrowing contours that spatially align closely with the physical boundaries of the reservoir compartment. The high spatial frequency of these horizontal components effectively defines the geometry of the edges of the target zone, qualitatively demonstrating that FTG gradiometry is far superior to conventional gravity in mapping the boundaries of low-density reservoirs.

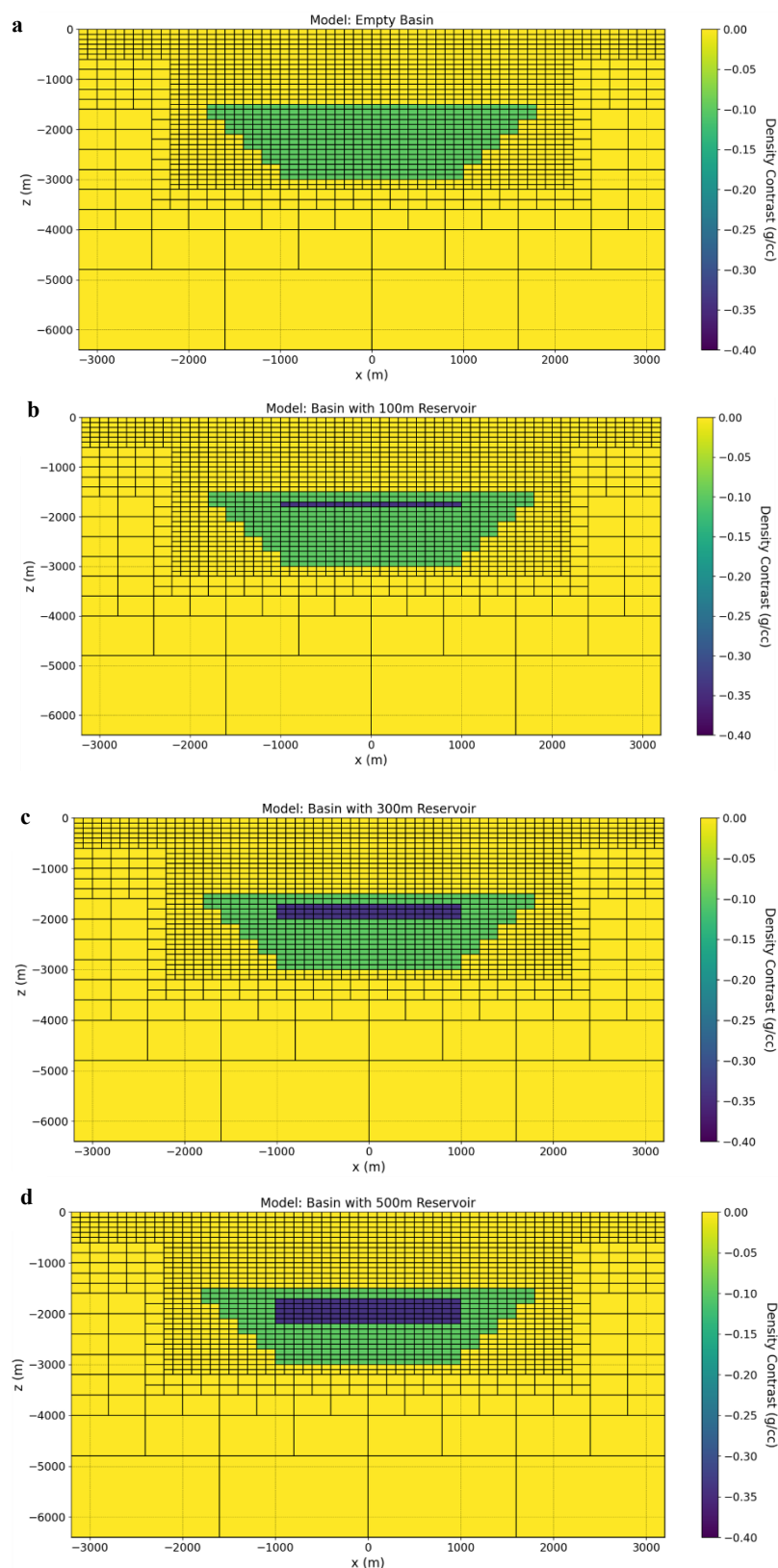


Figure 1.

Cross-section of the Y=0 coordinate path of a synthetic sedimentary basin model (yellow indicates bedrock, grid pattern indicates sedimentary material). This model shows a variety of geometric trap conditions of the basin including: (a) Empty sedimentary basin with a density of 2.60 gr/cc without the presence of hydrocarbons; (b) Injection of a methane-saturated reservoir (density of 2.36 gr/cc) with a vertical thickness of 100 m; (c) Gas-saturated reservoir with a thickness of 300 m; and (d) Gas-saturated reservoir with a maximum thickness of 500 m.

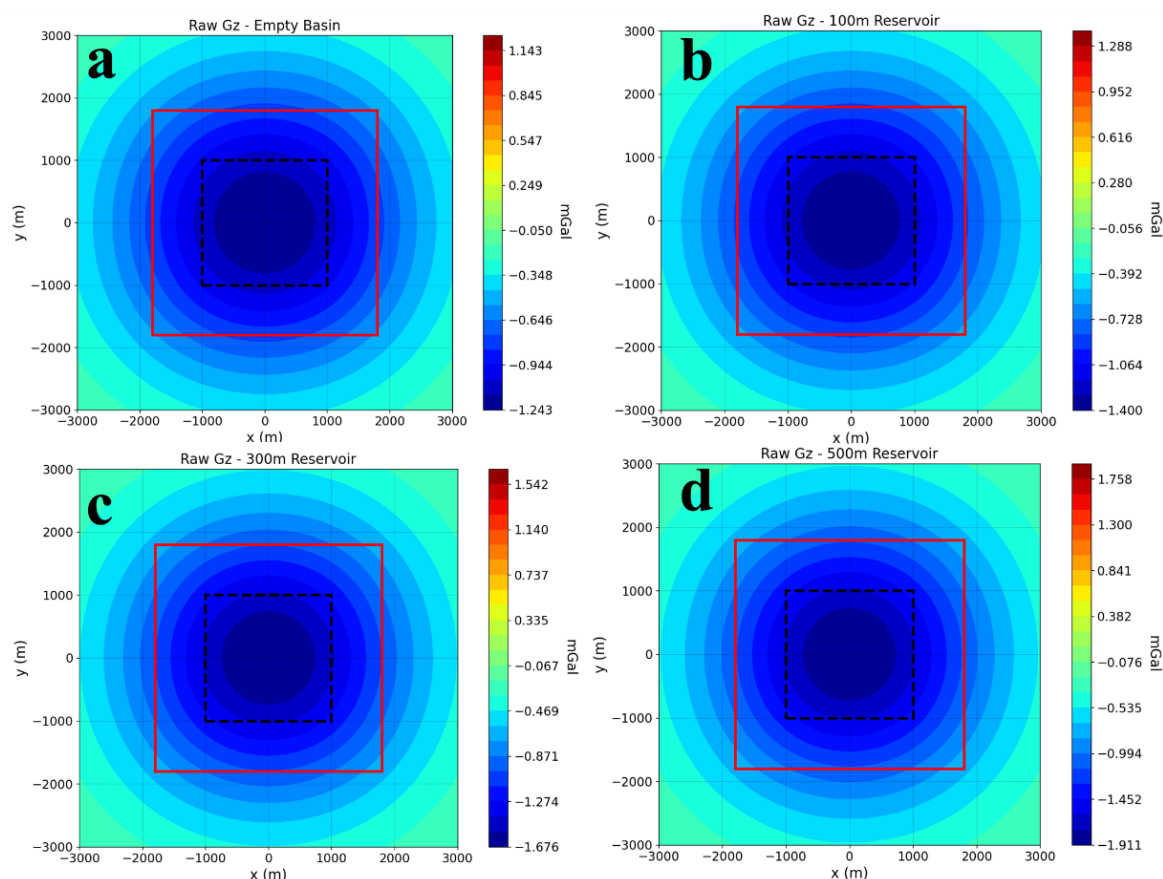


Figure 2.

Cross-section of the $Y=0$ coordinate path of a synthetic sedimentary basin model (yellow indicates bedrock, grid pattern indicates sedimentary material). This model shows a variety of geometric trap conditions of the basin including: (a) Empty sedimentary basin with a density of 2.60 gr/cc without the presence of hydrocarbons; (b) Injection of a methane-saturated reservoir (density of 2.36 gr/cc) with a vertical thickness of 100 m; (c) Gas-saturated reservoir with a thickness of 300 m; and (d) Gas-saturated reservoir with a maximum thickness of 500 m.

To validate that the sharp anomalies originate purely from the gas reservoir and not from basin margin effects, the analysis continued by extracting difference maps. The difference maps isolate the reservoir fluid response by subtracting the reservoir data from the unfilled basin background response. The conventional gravity difference maps are still highly susceptible to interpretation ambiguity due to the biased distribution of anomalies (Figure 4). In contrast, the FTG difference maps, including both the vertical-gradient components (Figure 6) and the horizontal-gradient components (Figure 8), strongly confirm that the strongest anomaly responses are concentrated along the reservoir boundaries. This finding qualitatively eliminates the interpretation ambiguity that is inherently common in conventional gravity methods.

3.3 Quantitative sensitivity analysis

The qualitative evaluation demonstrating the superior spatial resolution of FTG was further validated through a quantitative sensitivity analysis. This analysis quantified the percentage change in the maximum anomaly magnitude between the unfilled basin scenario and the methane-saturated basin scenario at various compartment thicknesses. This linear change in magnitude profile with respect to reservoir thickness can be precisely observed through a 1D curve cross-section. The comprehensive tabulated calculation results are summarized in Table 2.

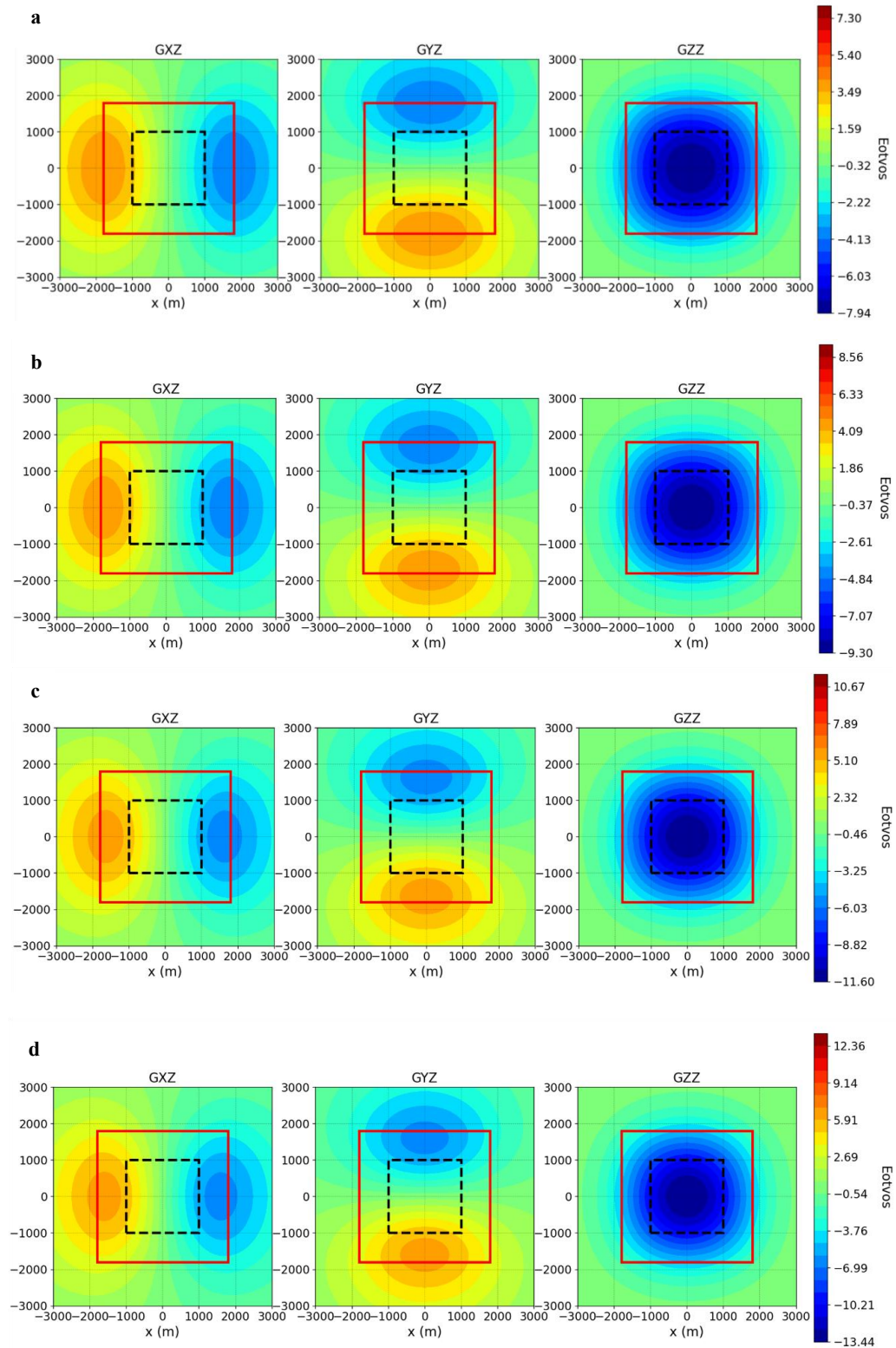


Figure 3.

Spatial response maps of full tensor gravity (FTG) gradiometry components for a empty, 100, 300, and 500 m thick gas-saturated reservoir model. The vertical components (G_{xz} , G_{yz} , and G_{zz}) shown at (a) empty, (b) 100m, (c) 300m, and (d) 500m thick gas-saturated reservoir. The horizontal components (G_{xx} , G_{yy} , and G_{xy}) shown at (e) empty, (f) 100m, (g) 300m, and (h) 500m thick gas-saturated reservoir, where the G_{xx} and G_{yy} components clearly delineate the reservoir geometry boundaries through the narrowing of the anomaly contours. (Red box: Basin Boundary, Black Dashed Box: Reservoir Boundary).

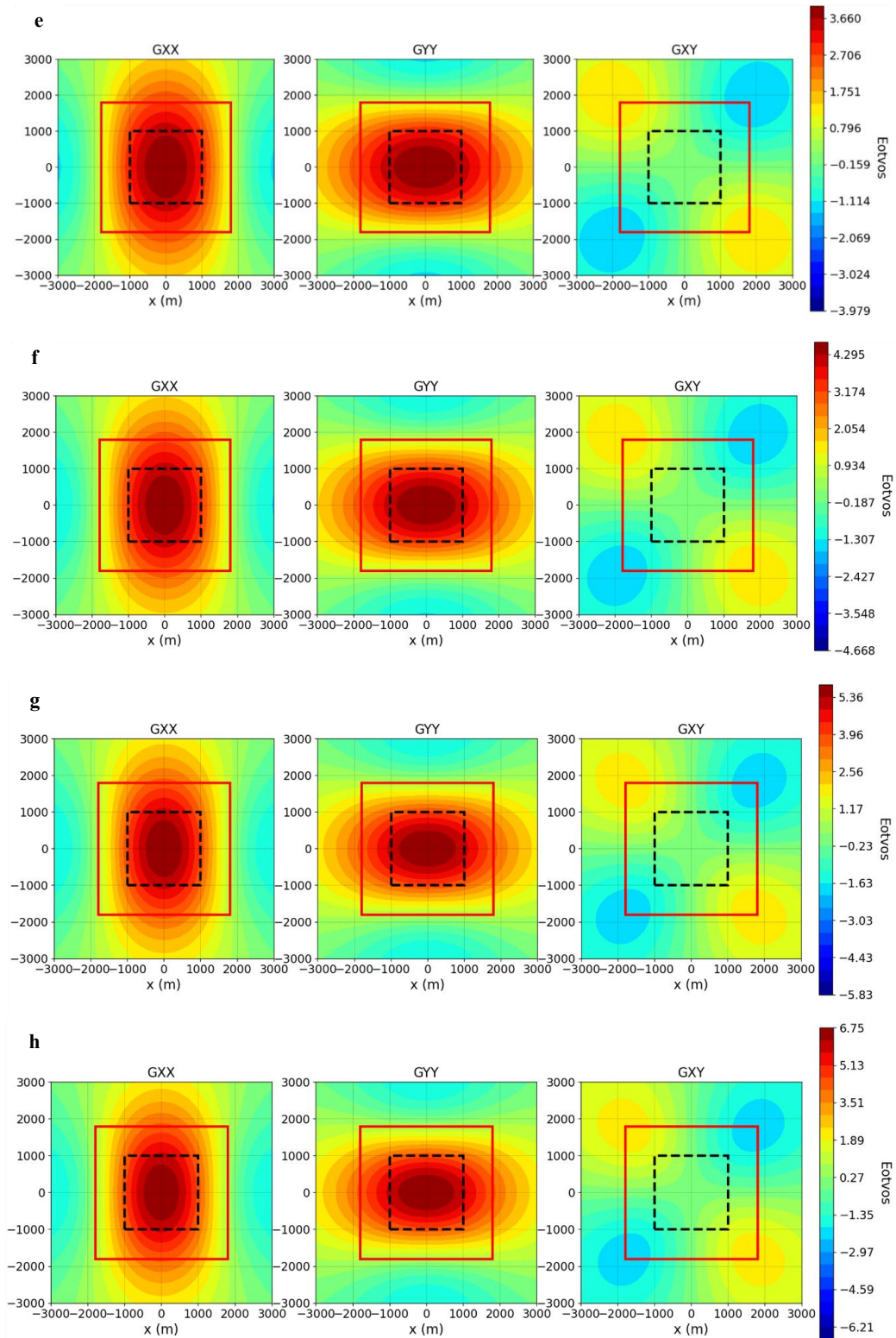


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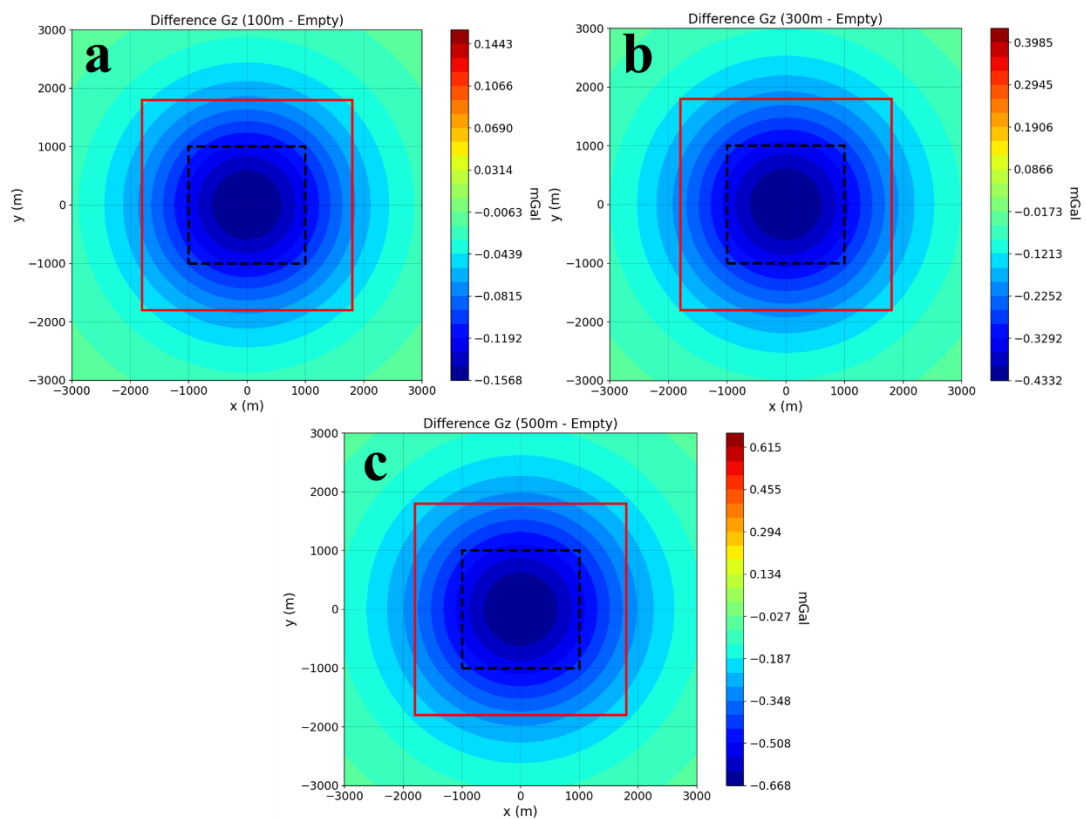


Figure 4.

Difference maps between the gas-saturated basin model (100, 300, and 500 m) and the empty basin model. The panels represent the isolated fluid responses to: (a) Conventional gravity (Diff Gz), (b) Principal vertical gradient (Diff Gzz), and (c) Principal horizontal gradient (Diff Gxx). (White Box Basin Boundary, Black Dashed Box: Reservoir Boundary).

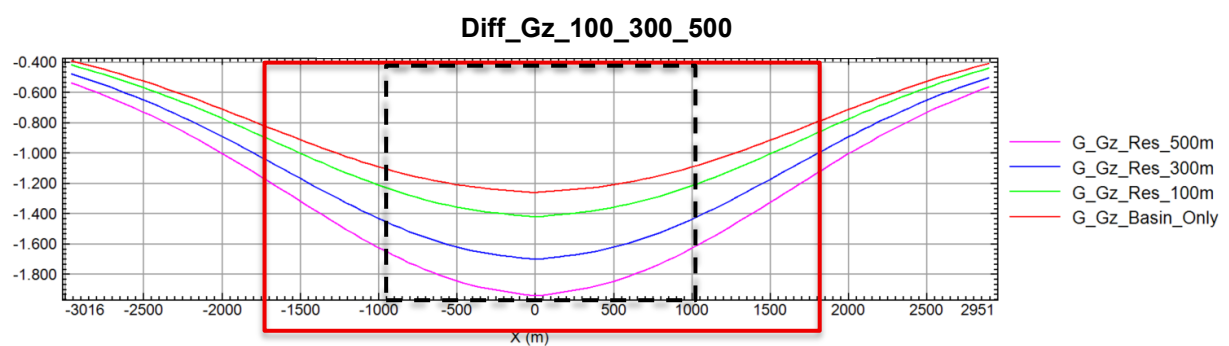


Figure 5.

1D profile curve graph (line profiles) from the results of conventional gravity difference analysis (Diff Gz) extracted across the center of the reservoir compartment on the $Y = 0$ trajectory. This graph quantitatively compares the magnitude of anomalies in reservoir thickness variations of 100 m, 300 m, and 500 m against the baseline value of the empty basin in mGal units (Red Box: Basin Boundary, Black Dashed Box: Reservoir Zone).

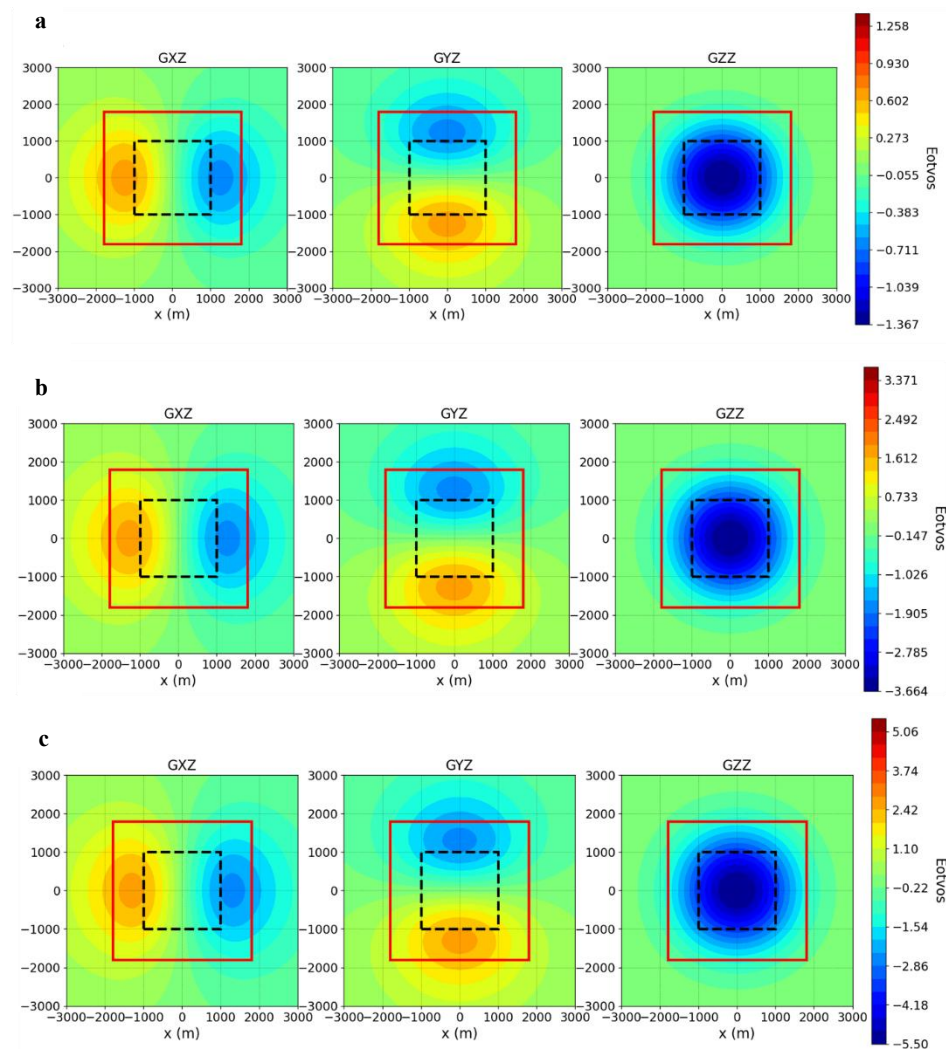


Figure 6.

Difference maps of vertical and cross-plane gradient components of FTG in Eötvös units, including Diff Gxz, Diff Gyz, and Diff Gzz components. This map isolates the dipole and centered anomalous responses due to the presence of target fluids at various reservoir thickness variations. a) 100m thickness, b) 300m thickness, c) 500m thickness (White Box Basin Boundary, Black Dashed Box: Reservoir Boundary).

Table 2. Anomaly Changes Observation Table for Initial Condition Compared to Saturated Condition.

Observed anomaly	Empty basin value	Change at 100 m	Change at 300 m	Change at 500 m
Gz	-1.25 mGal	-0.15 mGal (12.0%)	-0.45 mGal (36.0%)	-0.65 mGal (52.0%)
Gzz	-8.0 Eotvos	-1.4 Eotvos (17.5%)	-3.5 Eotvos (43.8%)	-5.0 Eotvos (62.5%)
Gxz	+4.0 Eotvos	+0.6 Eotvos (15.0%)	+1.5 Eotvos (37.5%)	+2.2 Eotvos (55.0%)
Gyz	+4.0 Eotvos	+0.6 Eotvos (15.0%)	+1.5 Eotvos (37.5%)	+2.2 Eotvos (55.0%)
Gxx	+4.2 Eotvos	+0.8 Eotvos (19.0%)	+1.8 Eotvos (42.9%)	+2.8 Eotvos (66.7%)
Gyy	+4.2 Eotvos	+0.8 Eotvos (19.0%)	+1.8 Eotvos (42.9%)	+2.8 Eotvos (66.7%)
Gxy (+)	+1.4 Eotvos	+0.2 Eotvos (14.3%)	+0.5 Eotvos (35.7%)	+0.8 Eotvos (57.1%)
Gxy (-)	-1.4 Eotvos	-0.2 Eotvos (14.3%)	-0.5 Eotvos (35.7%)	-0.8 Eotvos (57.1%)

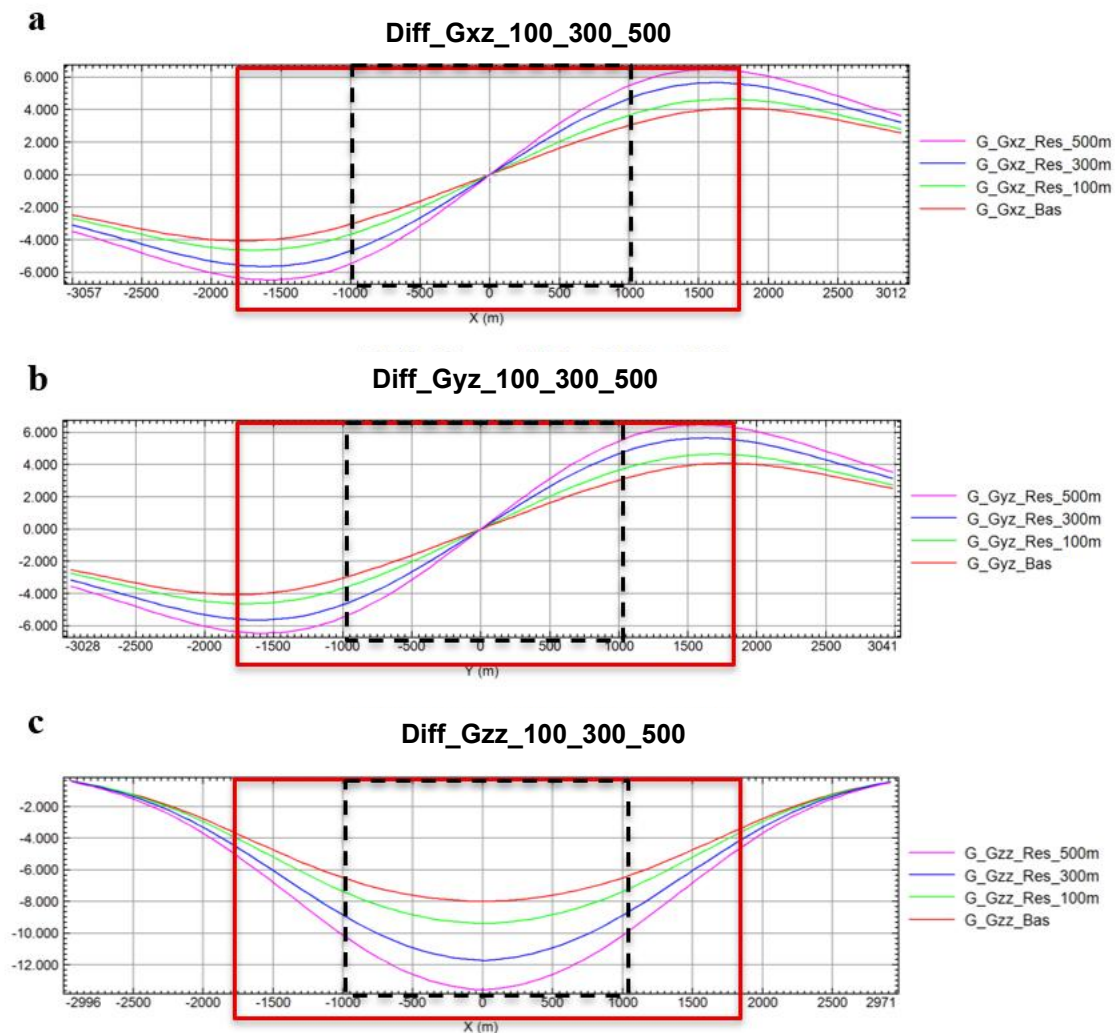


Figure 7.

1D line profile curve graph of the results of the vertical gradient component difference analysis of FTG extracted across the center of the reservoir compartment. The graph represents the $\text{Diff } G_{xz}$, $\text{Diff } G_{yz}$, and $\text{Diff } G_{zz}$ components in Eotvos units which show a sharp spike in magnitude above the center of the anomaly. (Red Box: Basin Boundary, Black Dashed Box: Reservoir Zone).

Physically, the presence of methane gas significantly reduces the bulk density of the reservoir, generating a mass deficit relative to the surrounding rocks and consequently decreasing the observed gravity response. The results show that the percentage change in anomaly amplitude increases systematically with increasing reservoir thickness from 100 m to 500 m, confirming a direct relationship between the gravity response and the volume of the gas-saturated reservoir.

For the model with a maximum reservoir thickness of 500 m, the conventional gravity field (G_z) method exhibits a reduction in anomaly amplitude of -0.65 mGal, equivalent to a 52.0% decrease relative to the baseline value. Although these changes are quite large, the effect of signal attenuation spreading over vertical distance causes the changes to be less sharp in gradient terms, as seen in the steepness of the difference profile curve (Figure 5).

On the other hand, the FTG tensor component responds to this density contrast with far superior sensitivity, even in layers as thin as 100 m. The vertical gradient component (G_{zz}) curve shows a sharp systematic spike in changes directly above the anomaly center (Figure 7), reaching 62.5% (an absolute decrease of -5.0 Eotvos) in the 500 m reservoir. The highest percentage change is demonstrated by the main horizontal gradient components, G_{xx} and G_{yy} , which recorded a maximum percentage change of 66.7%, with an extreme anomaly peak at the

transition zone of the structural boundary (Figure 9). The high value of the change in the horizontal component is mathematically explained by its ability to measure the rate of change of gravity along the lateral axis, where the gradient will peak sharply at the vertical boundary of the fault or reservoir edge ($\Delta\rho$). This quantification proves the hypothesis that FTG gradiometry has higher analytical sensitivity to capture minor density changes (subtle density contrasts) that are often missed by conventional gravity methods.

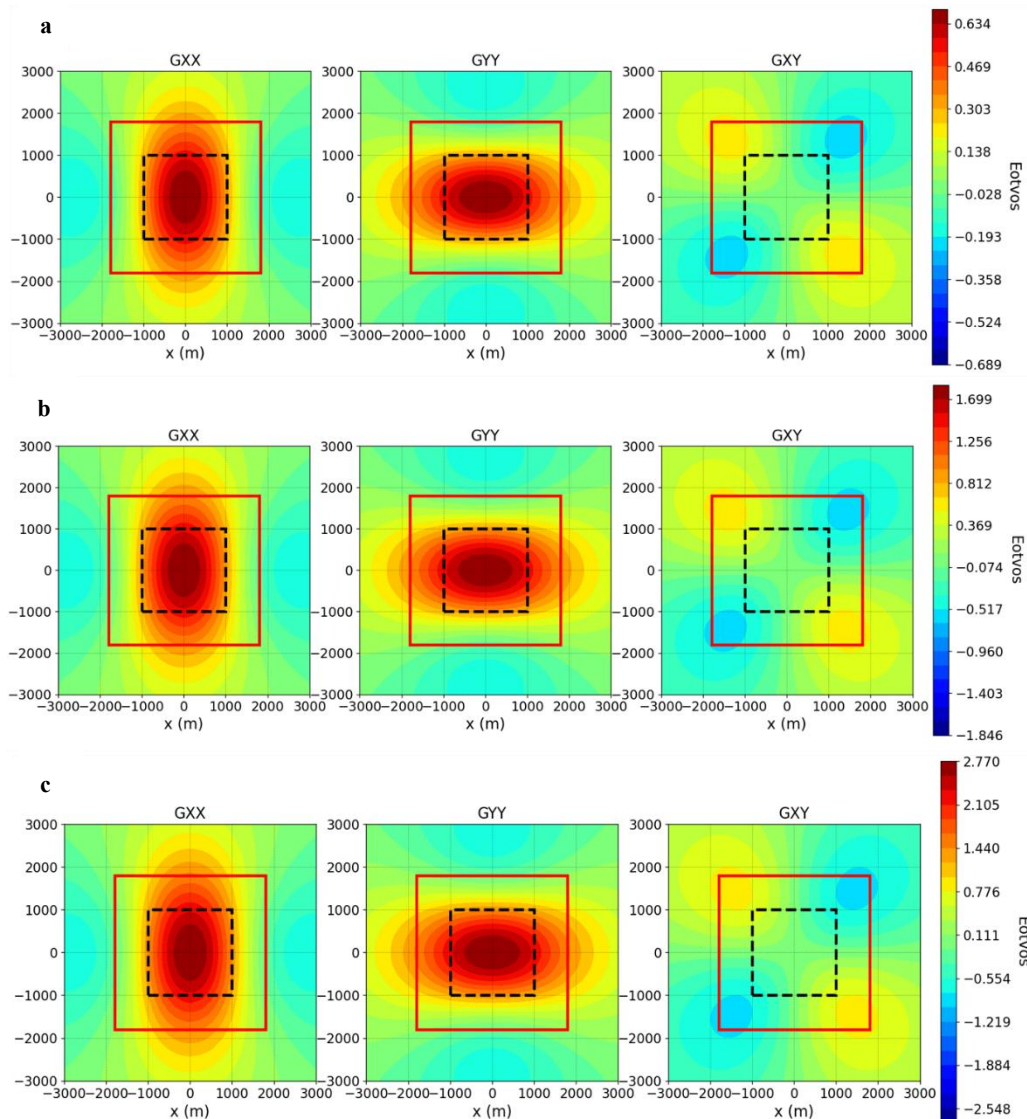


Figure 8.

Difference maps of the main horizontal gradient components of FTG in Eotvos units, including the Diff G_{xx} , Diff G_{yy} , and Diff G_{xy} components. The extreme value contours laterally frame and delineate the edge of the reservoir area; a). 100m thickness, b). 300m thickness, c). 500m thickness (White Box Basin Boundary, Black Dashed Box: Reservoir Boundary).

3.4 Field data application and validation

Based on the understanding of the physical behavior of the synthetic model, FTG gradiometry principles were then applied to field data to validate its ability to delineate the basin geometry. The initial interpretation was based on the complete bouguer anomaly (CBA) map and residual anomaly maps (Figure 10). In the CBA data, the interpretation focused on the low-anomaly response, indicated by specific polygons, which were interpreted as potential depocenters associated with thick accumulations of low-density sedimentary rocks.

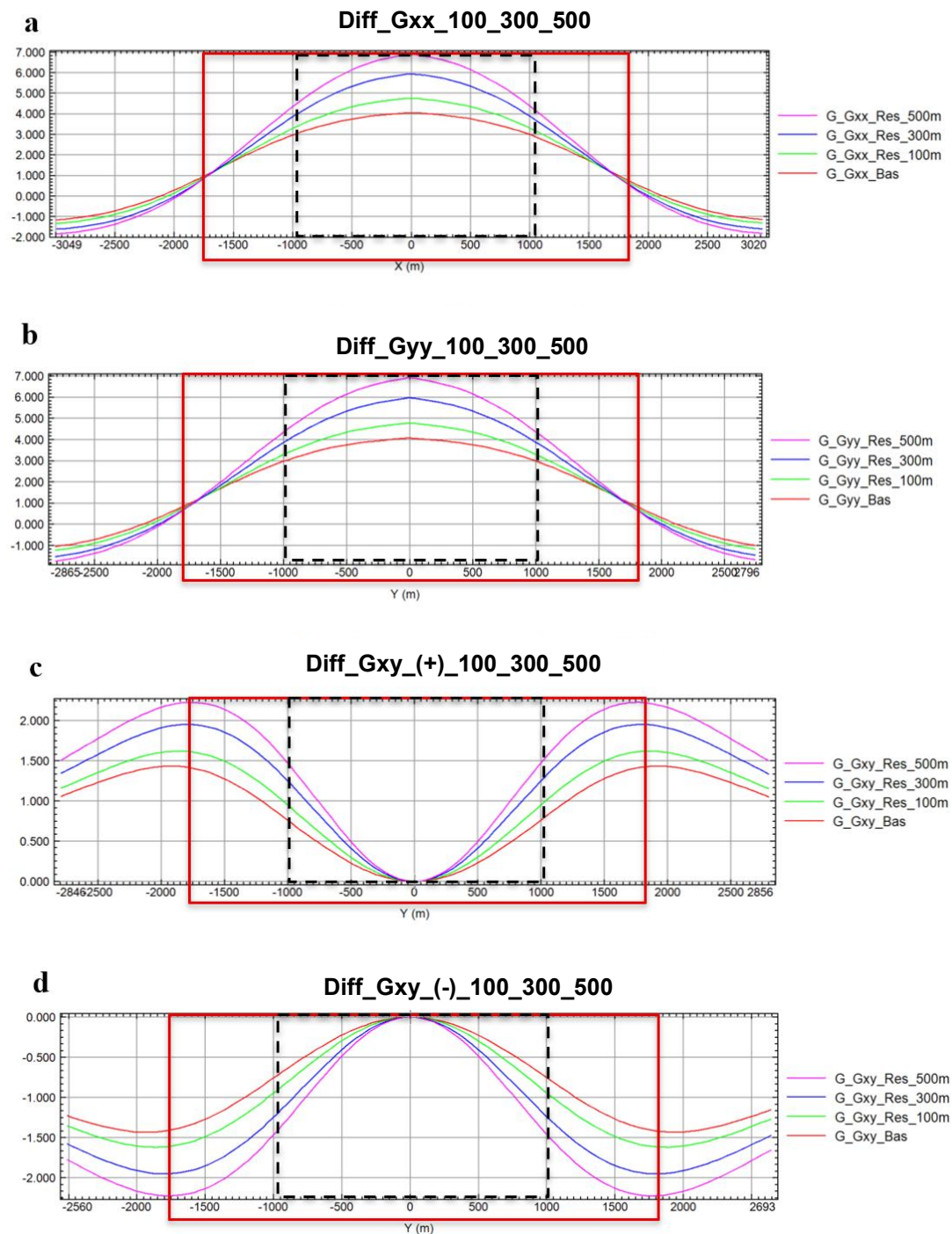


Figure 9.

1D profile curve graph (line profiles) from the results of the analysis of the difference in horizontal gradient components of FTG extracted across the center of the reservoir compartment. The graph represents the components of $\text{Diff } G_{xx}$, $\text{Diff } G_{yy}$, and $\text{Diff } G_{xy}$ in Eotvos units which show the peak of the extreme gradient precisely at the density transition zone of the structure boundary (Red Box: Basin Boundary, Black Dashed Box: Reservoir Zone).

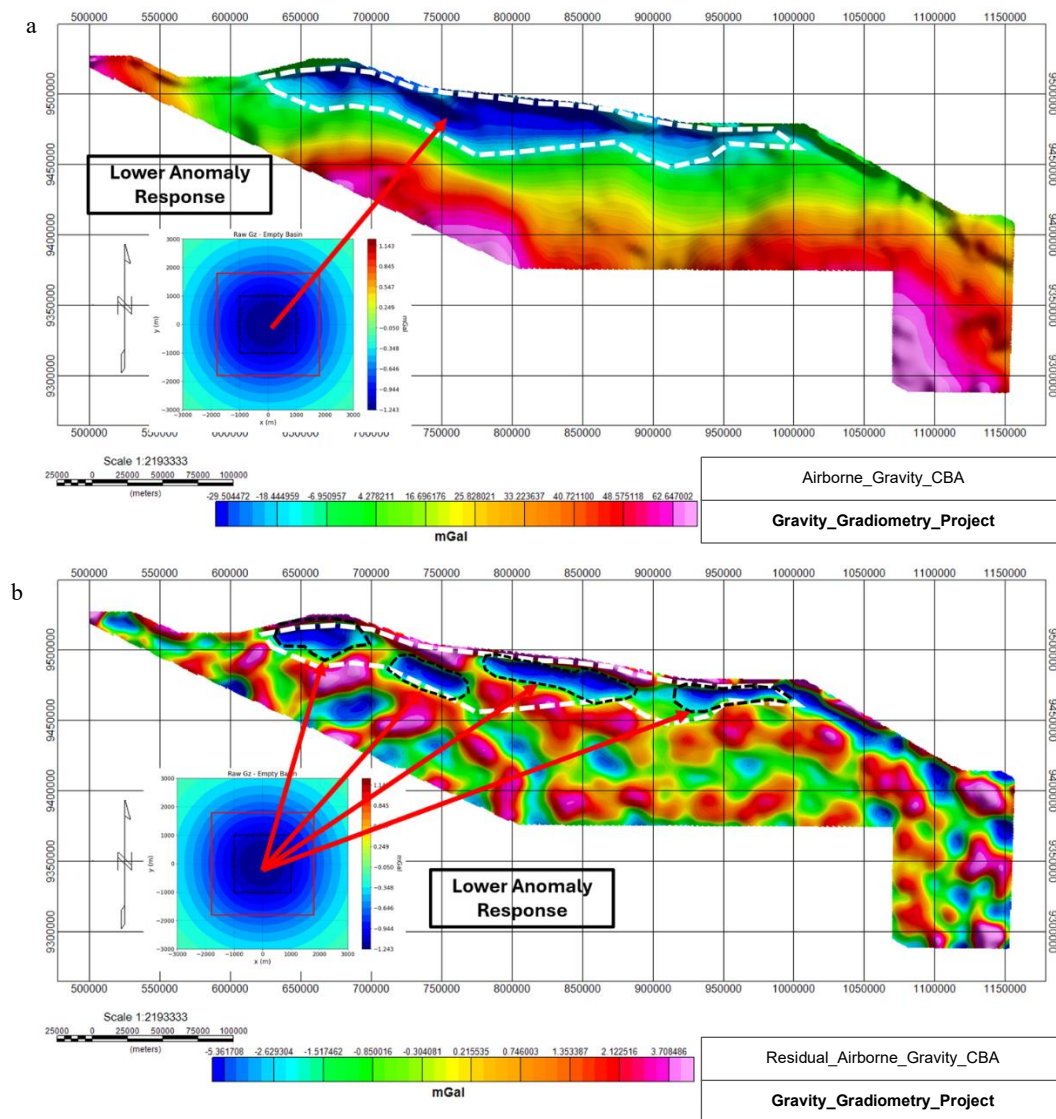


Figure 10.

Gravity anomaly map from actual field data used as a validation basis.

The figure shows: (a) Complete Bouguer Anomaly (CBA) map in mGal units where the initial target zone was identified based on the presence of low anomalous response.

The anomaly response in the field data showed very strong agreement with the simulation result predicted by the synthetic models (Figure 11). The field-derived vertical components (pseudo- G_{xz} and G_{yz}) exhibit behavior consistent with the synthetic FTG responses, effectively highlighting lateral density transitions and structural boundaries. Furthermore, when compared directly to the residual anomaly data (Figure 12), the G_{zz} component in the target zone has a higher frequency spectrum and much sharper boundaries between the low anomaly zones, indicating the presence of a previously blurred deficit density compartment.

The superior capability of FTG in detecting lateral density variations was again clearly confirmed in the mapping of the field's horizontal components (pseudo- G_{xx} , G_{yy} , and G_{xy}). The responses of the G_{xx} and G_{yy} components consistently aligned with the simulated anomaly patterns, where the straightening and narrowing of the contours precisely mapped the edges of the subsurface structure.

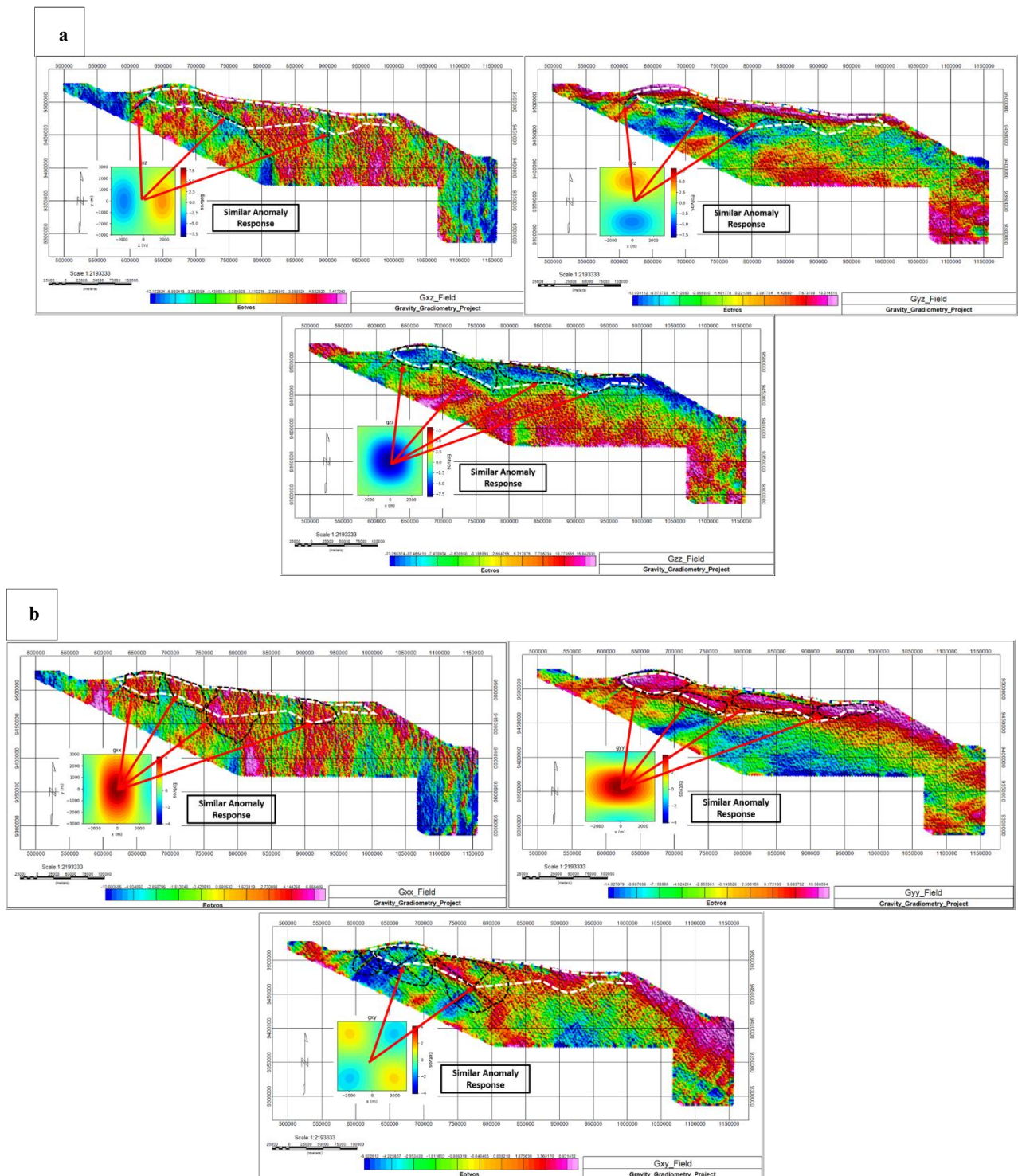


Figure 11.

Full tensor gravity (FTG) map of the field in Eotvos units highlighting the similarity of the anomaly response pattern to the synthetic model. This combined image displays: (a) The vertical gradient components of the field (G_{xz} , G_{yz} , and G_{zz}) exhibiting a centralized and double-pole anomaly pattern that resembles the physical behavior of the model; and (b) The horizontal gradient components of the field (G_{xx} , G_{yy} , and G_{xy}) consistently exhibiting a similar contour narrowing pattern, demonstrating the good match of the delineation characteristics between the synthetic and real-world data.

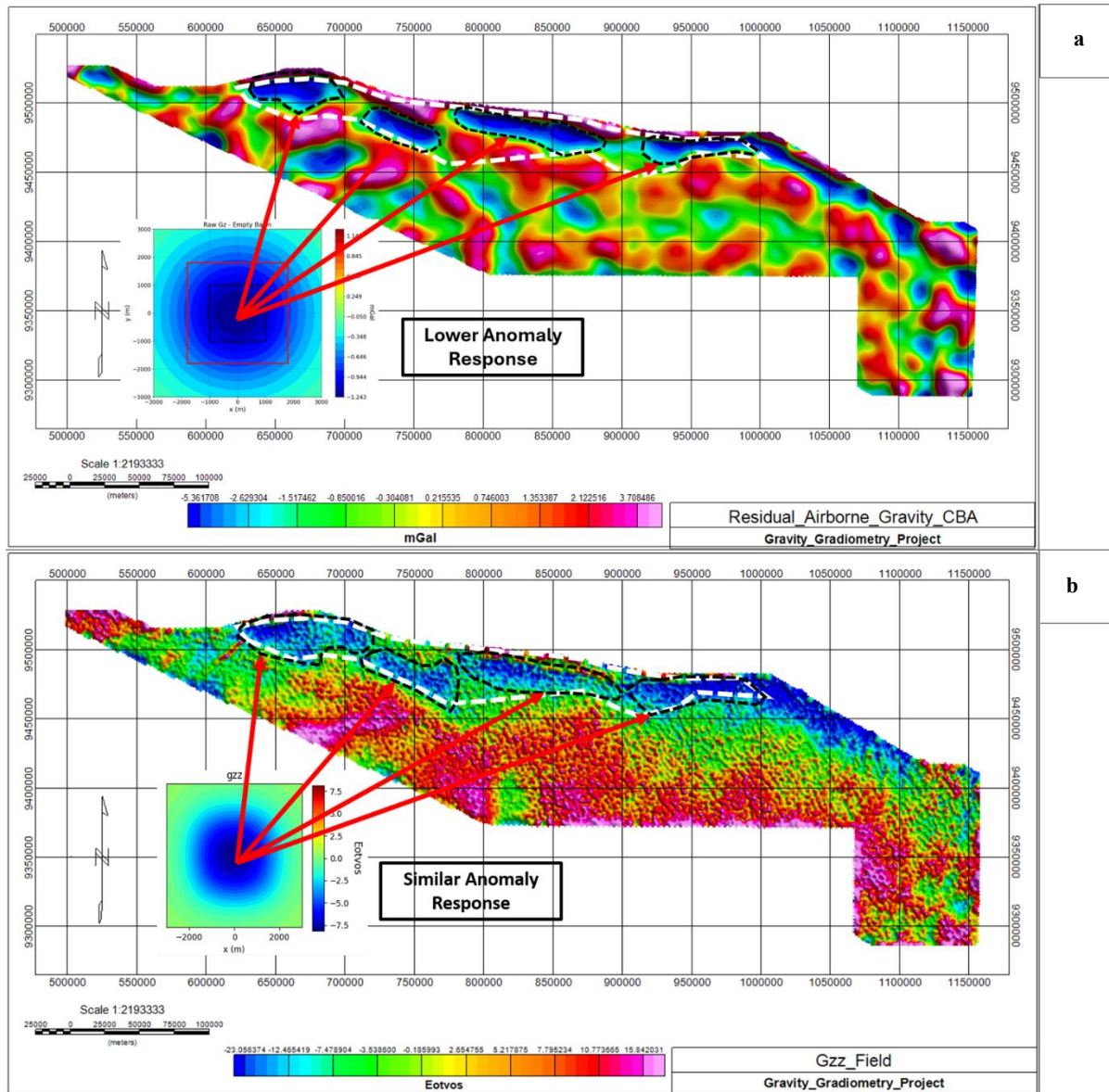


Figure 12.

Direct visual comparison map between: (a) conventional Residual Gravity Anomaly, and (b) vertical derived Gzz field component in the main target zone. This comparison validates that the Gzz component has a higher frequency spectrum and much sharper and more precise delineation boundaries in representing the Similar Anomaly Response compared to conventional residual data.

To further enhance the interpretability of the FTG data, the multidirectional gradient components were calculated into magnitude-based data, namely total horizontal gradient (THG) and total horizontal curvature (THC) (Figure 13). These attributes are directly derived from the FTG tensor components using the following mathematical formulations:

$$THG = \sqrt{G_{xz}^2 + G_{yz}^2} \quad (5)$$

$$THC = \sqrt{\left(\frac{G_{xx} - G_{yy}}{2}\right)^2 + (G_{xy})^2} \quad (6)$$

where G_{xz} and G_{yz} are the horizontal gradient component of FTG. And G_{xx} , G_{xy} , and G_{yy} are the horizontal curvature component of FTG respectively.

The THG map provides a significantly sharper and more detailed representation of the lower basin boundary than the residual CBA map. The THG map provides a significantly sharper and more detailed representation of the lower basin boundary than the residual CBA map. Meanwhile, the THC map showed an inversely proportional correlation with G_{zz} response within the prospective zone (Li, 2015), further strengthening the certainty of the localization of the basin target. All these findings from the application of field data demonstrate that the integration of gradiometric analysis plays a crucial role in improving interpretation resolution and significantly reducing structural ambiguity in oil and gas exploration.

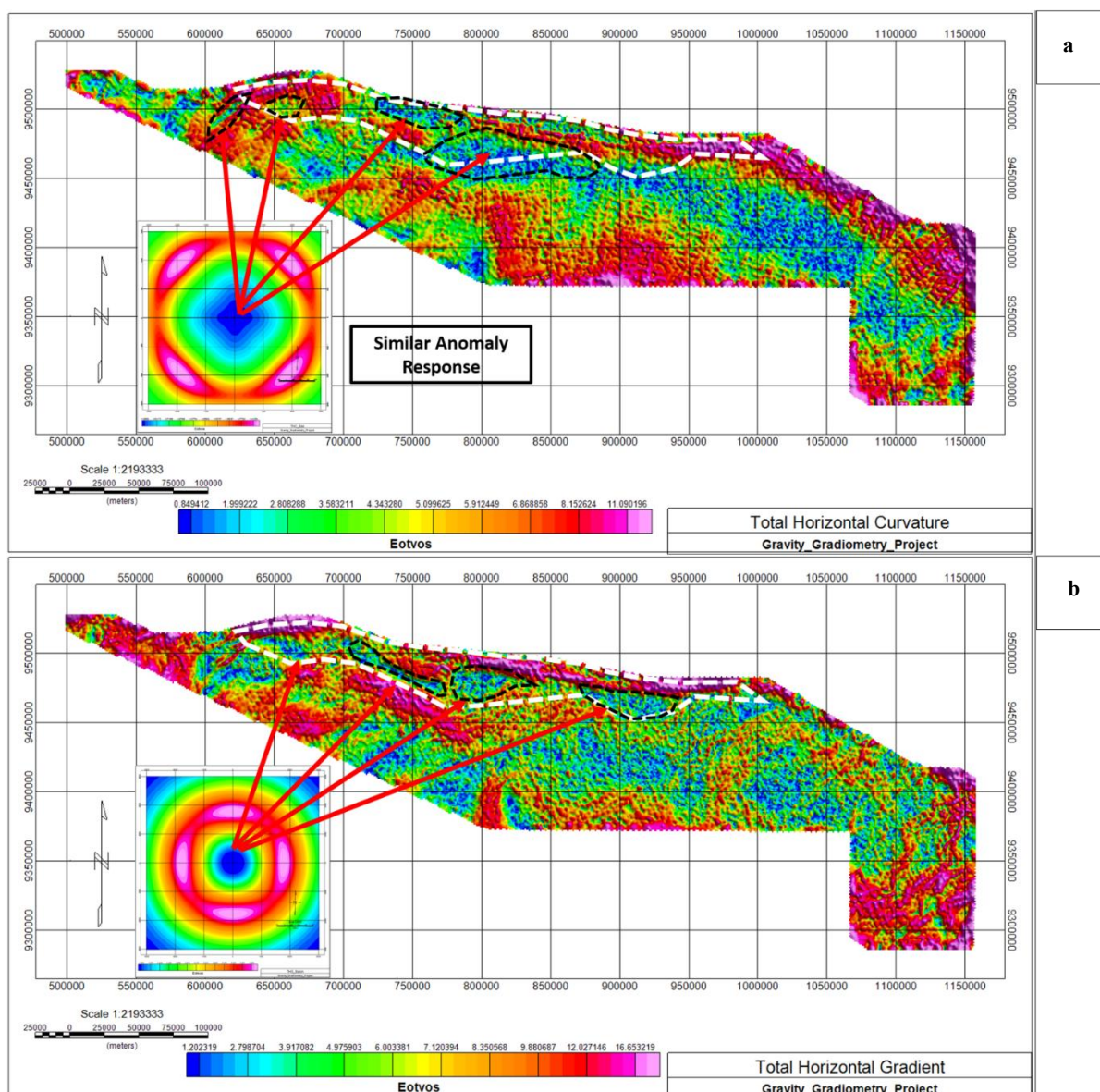


Figure 13.

Magnitude-based derived analysis maps of field data in Eotvos units for optimizing structural interpretation.

The panels represent: (a) Total horizontal gradient (THG) map and (b) Total horizontal curvature (THC) map.

The appearance of identical anomaly patterns in these attribute maps confirms that the spatial sensitivity of the synthetic modeling is actually applicable to field data.

Overall, the findings from the field data application confirm the results of previous studies regarding the capabilities of FTG. The success of the horizontal gradient component in constraining basin boundaries sharply aligns with the study by Montesinos-Flores et al. (2023), who demonstrated that tensor-based gravity analysis and inversion provide substantially higher spatial resolution of shallow subsurface structures than conventional gravity. Furthermore, the sensitivity of the G_{zz} component to local anomalies demonstrated in the field data

reinforces the conclusion of [Kebede et al. \(2022\)](#) that the integration of spatial derivatives is crucial in reducing ambiguities in basin geometry, which regional Complete Bouguer Anomaly data often fail to resolve. Furthermore, the inverse correlation between THC and G_{zz} within the prospect zone is consistent with the curvature attribute principle outlined by [Li \(2015\)](#).

While FTG data, particularly the G_{zz} component, demonstrate exceptional capability in delineating subtle density contrasts with high spatial resolution for shallow targets, it is important to acknowledge its depth-dependent limitations. Based on fundamental potential field theory, conventional gravitational acceleration (G_z) attenuates at a rate proportional to the inverse square of the distance from the source ($1/r^2$) ([Blakely, 1996](#)). In contrast, the spatial gradients of the gravity field, such as G_{zz} , represent the second derivatives of the gravitational potential and attenuate much faster, at a rate proportional to $1/r^3$ ([Blakely, 1996](#)). Because of this rapid $1/r^3$ decay, FTG measurements are heavily dominated by the nearest sources, producing short-wavelength signals that can only originate from shallow depths ([Brewster & Murphy 2017](#)). Conventional gravity, however, retains long-wavelength features that can arise from both shallow and deep regional sources ([Brewster & Murphy 2017](#)). Consequently, the resolution of the G_{zz} component degrades rapidly as target depth increases. This theoretically confirms that while conventional gravity remains essential for mapping deep basement architecture, FTG analysis is most appropriate for prospect-scale anomaly delineation and shallow reservoir characterization ([Grandis & Dahrin 2014](#)).

4. Conclusion

This study quantitatively and qualitatively demonstrates that full tensor gravity (FTG) gradiometry can overcome the fundamental limitations of conventional gravity methods in delineating shallow subsurface structures characterized by very low-density contrasts. Through high-resolution spatial numerical modeling of a gas-saturated sedimentary basin, the horizontal components of the FTG (G_{xx} and G_{yy}) demonstrated the highest sensitivity to reservoir-induced density variations, with a change rate of 66.7%. This significantly outperformed the conventional method (G_z), which only responded to signal attenuation of 52.0%. Spatially, these tensor components not only successfully isolated the fluid response from the dominant regional basin anomalies but also precisely mapped the lateral edges of hydrocarbon reservoir compartments.

Furthermore, the application of the spatial derivative approach to the complete bouguer anomaly (CBA) field data validated the effectiveness of this gradiometry physics concept in practical applications. The use of curvature attributes and spatial gradients in the field proved effective in detecting basin-boundary fault zones and reducing ambiguity in subsurface structure interpretation. The significance of this research provides technical justification for the exploration geophysics industry that the integration of gradiometry analysis—both through direct FTG data acquisition and through the efficient manipulation of higher-order derivatives of conventional gravity data—is an essential analytical tool. The application of this comprehensive method is highly recommended to minimize the risk of structural uncertainty in the identification and development phase of future shallow prospects.

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6. Declarations

6.1 Author contribution

K. O. Mahendra: Conceptualization, Methodology, Develop Code and Algorithm, Formal analysis, Data curation, Visualization, Writing – original draft. M. N. A. Zakariah: Supervision, Methodology, Validation, Writing – review & editing. S. Satiawan : Supervision, Validation, Methodolgy and Writing – review & editing. B. N. Suwardi: Supervision, Validation, review & editing, providing software. E. Widjanarko: Supervision, Validation, review & editing, providing software.

6.2 Funding statement

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6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-Assisted technologies

During the preparation of this work, the authors used Google Gemini to assist with sentence restructuring, academic translation, and improving the overall readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

7. Glossary of terms and symbols

Terms & Symbols	Definition	Unit
CBA	Complete Bouguer Anomaly	mGal
FTG	Full Tensor Gravity Gradiometry	Eotvos
SimPEG	Simulation and Parameter Estimation in Geophysics (Open-source Python framework)	-
THC	Total Horizontal Curvature	Eotvos
THG	Total Horizontal Gradient	Eotvos
G _z	Vertical component of the conventional gravity anomaly	mGal
G _{xx} ,G _{yy}	Horizontal diagonal components of the gravity gradient tensor	Eotvos
G _{zz}	Vertical diagonal component of the gravity gradient tensor	Eotvos
G _{xy} ,G _{xz} ,G _{yz}	Off-diagonal cross components of the gravity gradient tensor	Eotvos
r	Spatial distance between the observation points and the center of mass	m
V	Gravitational potential	m ² /s ²
γ	Universal gravitational constant	m ³ /(kg·s ²)

$\Delta\rho$	Spatial density contrast between different rock volumes	gr/cc
$\Delta\rho_{\text{res-bas}}$	Density contrast of the reservoir rock relative to the surrounding basin	gr/cc
$\Delta\rho_{\text{res-back}}$	Density contrast of the reservoir rock relative to the background basement	gr/cc
ρ_{bulk}	Volumetric bulk density of a rock formation	gr/cc
ρ_{fluid}	Density of the saturating fluid (e.g., water, oil, gas)	gr/cc
ρ_{ma}	Matrix density of the rock framework	gr/cc
ϕ	Matrix porosity of the rock	%

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