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Airborne Full Tensor Gravimetric Surveys: Challenges and Opportunities for Switzerland

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Abstract

Exploring the subsurface for energy and minerals requires extensive data collection to mitigate risks. The oil and gas industry follows a structured exploration and production cycle, reducing uncertainty as data improves, from high-risk exploration to lower-risk reservoir management. In contrast, geothermal energy development follows a similar process with comparable risks and costs but lacks the same financial rewards, creating investment challenges. We present a technology that allows companies and mineral rights owners to assess large regions at a relatively low cost, improving exploration efficiency.

Zusammenfassung

Die Erkundung des Untergrunds nach Energie und Mineralien erfordert eine umfangreiche Datenerfassung, um Risiken zu minimieren. Die Öl- und Gasindustrie folgt einem strukturierten Explorations- und Produktionszyklus, der die Unsicherheit mit zunehmender Datenlage reduziert – von der risikoreichen Exploration bis hin zur risikoärmeren Lagerstättenbewirtschaftung. Im Gegensatz dazu folgt die Entwicklung der Geothermie einem ähnlichen Prozess mit vergleichbaren Risiken und Kosten, bietet aber nicht die gleiche finanzielle Rendite, was zu Investitionsproblemen führt. Wir präsentieren eine Technologie, die es Unternehmen und Inhabern von Mineralrechten ermöglicht, große Gebiete relativ kostengünstig zu bewerten und so die Explorationseffizienz zu verbessern.

1 Introduction to FTG

Full Tensor Gravimetry gradiometry (FTG), initially developed by Lockheed Martin for military purposes, has been widely adopted in mining and petroleum exploration over the past two decades. FTG measures the gradient of the gravitational field in all three spatial dimensions, capturing subtle variations caused by density contrasts in subsurface materials. Unlike traditional gravity surveys that measure the total gravitational acceleration, FTG provides a tensor that describes how gravity changes in different directions, offering a more detailed picture of subsurface features. FTG offers two key advantages over traditional land-based gravity surveys: (1) Airborne data acquisition allows the survey to be completed in a significantly shorter time frame compared to conventional land-based methods, and (2) FTG directly measures the gradient, or 'rate of change', of the gravity field in all directions, known as a Tensor.

This Tensor measurement is taken simultaneously with scalar gravity, improving the efficiency of the data acquisition process as well as enhancing modelling capabilities. The Tensor measurement of the gravity field leads to a remarkable improvement in the resolution of abrupt subsurface density variations, often associated with geological features like faults, graben margins, volcanic intrusions, and particularly salt intrusions and diapirs.

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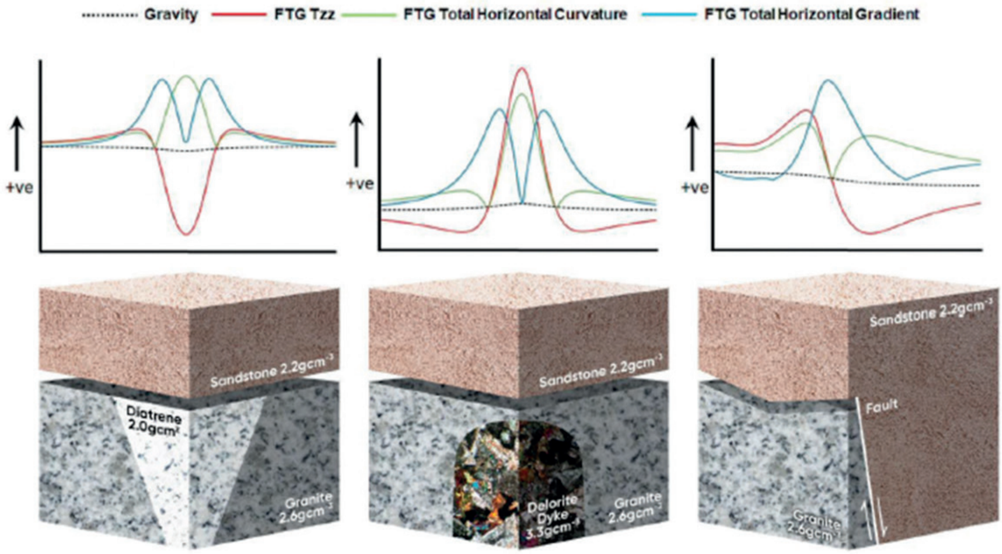

Figure 1: The expected response of each derived component from the FTG tensor, alongside scalar gravity, for various rock types, with various contacts and density contrasts. While scalar gravity shows only minor variations for different stratigraphic relationships, FTG measurements (Tzz, THC, and THG) exhibit distinct and distinguishable responses, providing enhanced subsurface characterization. Figure courtesy of Bell Geospace.

Figur 1: Die erwartete Reaktion jeder abgeleiteten Komponente des FTG-Tensors zusammen mit der Skalargravitation für verschiedene Gesteinsarten mit unterschiedlichen Kontakten und Dichtekontrasten. Während die Skalargravitation bei unterschiedlichen stratigraphischen Beziehungen nur geringe Abweichungen zeigt, zeigen FTG-Messungen (Tzz, THC und THG) deutliche und unterscheidbare Antworten, die eine verbesserte Charakterisierung des Untergrunds ermöglichen. Figur mit freundlicher Genehmigung von Bell Geospace.

2 What is FTG?

FTG measures a tensor field describing gravity's rate of change in all directions. The components Txx, Txy, and Tyy capture horizontal (X-Y) variations, while Txz and Tyz measure vertical changes in X and Y. Tzz represents the vertical rate of change in the Z direction.

These tensor components are often simplified into three key elements: Total Horizontal Curvature (THC), Total Horizontal Gradient (THG), and the Vertical Gradient (Tzz). THG, derived from Txz and Tyz, highlights geological lineaments (Murphy et al., 2023). The peak of the THG accurately traces faulted or stratigraphic contacts, marking near-vertical edges in geological structures. THC, defined by Txx, Txy, and Tyy, outlines geological formations such as salt bodies, carbonate buildups, and channels. Tzz captures vertical gravity changes, mapping density variations to identify structures like salt domes, carbonate reefs, or low-density channels within higher-density rock.

Figure 1 illustrates the value of tensor gravity measurements in subsurface exploration - whether defining fault frameworks with THG, structure mapping with THC, or detecting density changes with Tzz. Gravity data derived from the tensor components, along with scalar gravity, is used to map the total gravity field, thus capturing a broader signal bandwidth that is typically not accessible through detailed ground-based gravity surveys, increasing the ability to detect and map sub-surface geological complexity.

3 FTG survey data

FTG surveys capture a broad gravity signal bandwidth that surpasses conventional ground-based methods. This capability enables:

- Lithological Mapping – Determining basin geometry, carbonate and salt deposits, and basement depth.
- Structural Analysis – Identifying intrusive units, sand channels, and shallow hazards.
- Fault Detection – Mapping fault locations, patterns, offsets, and alteration zones.

Airborne FTG surveys mitigate land-based exploration challenges. Conducted from aircraft, they are non-invasive, adaptable to diverse terrains, and deployable over vast areas without extensive ground infrastructure. This efficiency makes FTG cost-effective compared to 2D and 3D seismic surveys, particularly in regions with limited accessibility, dense vegetation, or environmental restrictions, and a perfect tool for exploring in urban communities. Ground surveys can require several different permits, leading to additional costs and delays, while airborne surveys often require only a single permit, facilitating the process of getting the information you need.

The ability to gather quality data while minimizing exploration risks positions FTG as a strategic asset in the geothermal sector, particularly as the demand for sustainable energy solutions increases. For geothermal exploration, FTG's sensitivity to density variations aids in mapping crucial features such as fault zones and fractures, which influence geothermal fluid flow and the exploitation of hot dry rock reservoirs. The technology's ability to enhance geological understanding makes it a valuable tool in optimizing drilling locations, enhancing resource management, and reducing exploration costs.

4 Application in Geothermal Exploration

ZeroGeo Energy GmbH, a Swiss-based independent geothermal development and production company, was founded in 2021 to develop geothermal baseload electricity projects by deploying reservoir-independent geothermal 'hot dry rock' technologies. In 2022, ZeroGeo Energy GmbH was the first geothermal project developer in Europe to acquire an airborne FTG survey for Projekt THERMO in Niedersachsen, Germany.

The FTG survey was acquired and processed by Bell Geospace Limited, who have since acquired two more FTG surveys for geothermal exploration in Germany. Bell Geospace is the longest serving provider of FTG data, with over 500 surveys, 2 million+ Air-FTG line kilometers flown, and 0 HSE Accidents. They have four instruments that represent an investment of over US $21 million.

The Projekt THERMO survey acquired 4'730 km flight lines of FTG, gravity, and magnetic data. The objective was to image and delineate reservoir sequences for hot dry rock geothermal exploration, assess basement complexity, and map mobile salt structures to mitigate drilling risks. The FTG data is being utilised by TerraThermo Limited, a subsidiary of ZeroGeo, to build an integrated subsurface 3D geological and reservoir model incorporating 2D/3D seismic and borehole data.

5 Results

While the Lower Saxony Basin has been extensively explored for oil and gas - with numerous 2D and 3D seismic surveys and thousands of boreholes - much of the data predates 1960, leaving significant gaps in subsurface knowledge (Figure 2). FTG serves as a cost-effective tool to bridge these gaps, refining subsurface models without the high costs of seismic surveys.

On a first pass, the mapped salt structures, particularly the salt domes, show a strong correlation with the low-density zones identified in the FTG survey (Figure 3). However, some regions exhibit significant mismatches: areas where previously mapped salt formations do not align with FTG anomalies and zones where FTG indicates low-density anomalies with lineaments on either side but no previously mapped salt structures (see Figure 3D). These discrepancies highlight the potential for FTG to refine and update existing geological models, reducing exploration uncertainty.

In addition, FTG data can successfully be used to model the structure of the underlying rocks, particularly in areas where seismic reflections disappear beneath salt formations. As an initial test, we created two models to assess whether the salt structure was a large, thick vertical body or a smaller diapir. When modelled as a large vertical body, the gravity response (Tzz) did not align with the FTG survey results (Figure 4: Model 1). However, when the salt body was reinterpreted as a true diapir, featuring a thick bulbous top and a thin feeder (Figure 4: Model 2), the modelled FTG signal closely matched the observed gravity gradiometry at the salt domes. This refined interpretation allows us to extend our modelling into areas without seismic data, enhancing regional assessments of reservoir extent, depth, and heat flow.

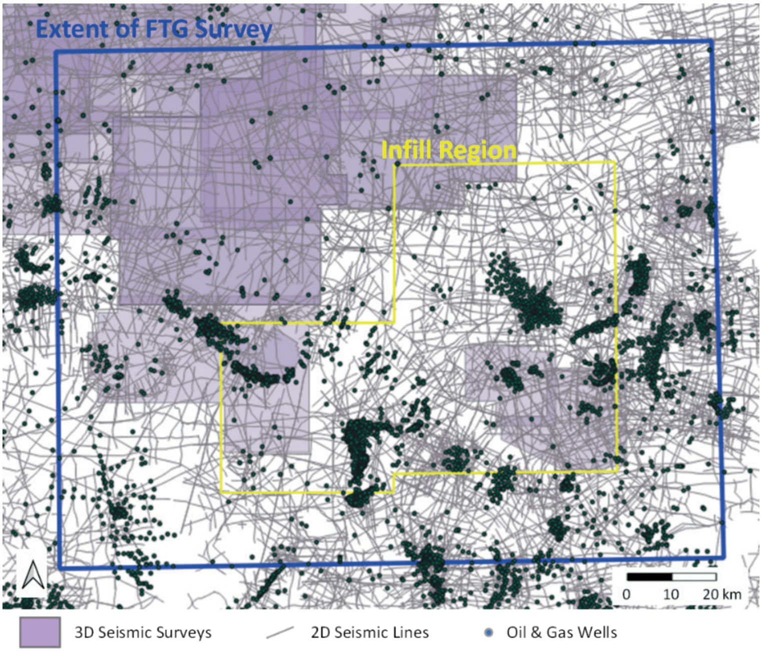

Figure 2: Full extent of publicly available subsurface data in the area of interest, including 3D seismic surveys (purple), 2D seismic lines (grey), and boreholes (green). The dataset is incomplete, with large zones lacking reliable subsurface information. The FTG survey was designed to fill these gaps, employing a tighter line spacing in the yellow infill region to enhance data coverage.

Figur 2: Vollständiger Umfang öffentlich verfügbarer Untergrunddaten im Untersuchungsgebiet, einschließlich 3D-Seismik (lila), 2D-Seismiklinien (grau) und Bohrlöchern (grün). Der Datensatz ist unvollständig, da in großen Bereichen zuverlässige Untergrundinformationen fehlen. Die FTG-Untersuchung wurde entwickelt, um diese Lücken zu schliessen. Zur Verbesserung der Datenabdeckung wurde im gelben Füllbereich ein engerer Linienabstand verwendet.

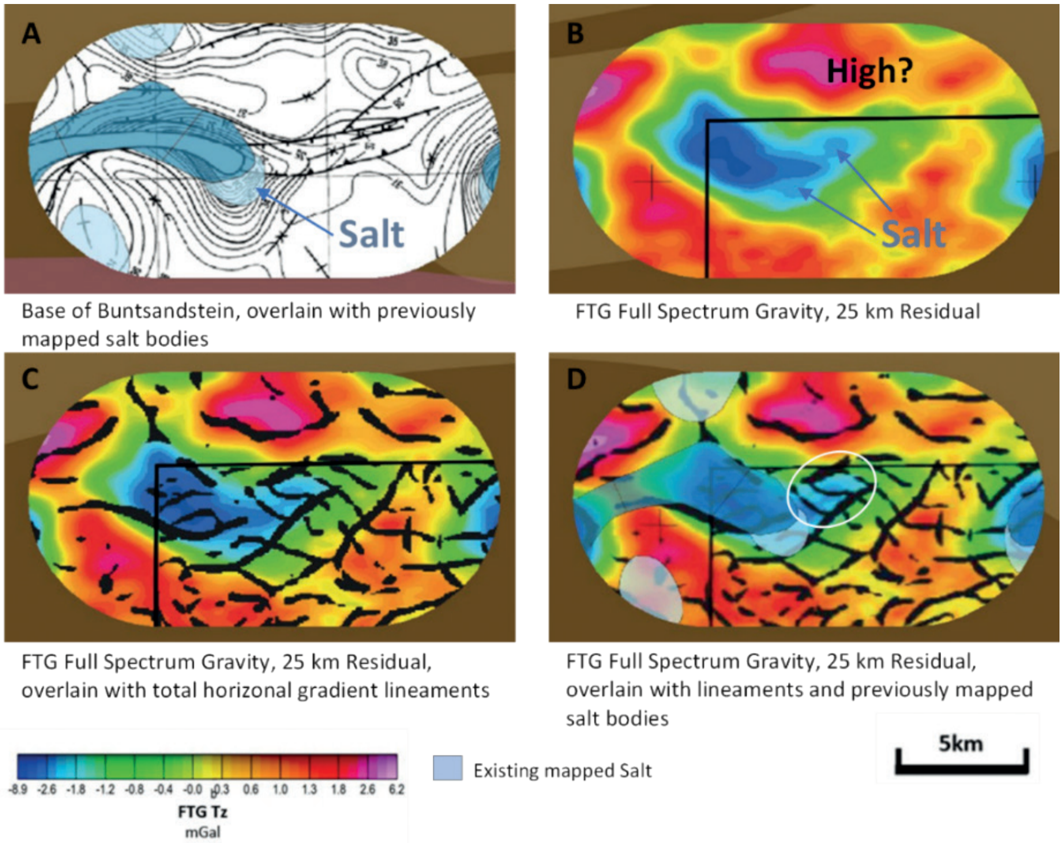

Figure 3: (A) Previously mapped subsurface salt structures (Reinhold et al., 2008) overlaid on a 2001 contour map of the Base Buntsandstein (Baldschuhn et al., 2001). (B) Low-density structures are shown in cool colors (blue), while higher-density structures appear in warm colors (red). Since salt has a lower density than the surrounding rock, it is expected to appear in blue to green hues. (C) Lineaments derived from FTG processing highlight areas of strong density contrasts, which may indicate potential faults, salt diapirism, or variations in rock composition. (D) The new FTG data correlates well with previously mapped salt bodies in many locations but also reveals areas where earlier mapping may have overlooked salt structures (white circle).

Figur 3: (A) Zuvor kartierte unterirdische Salzstrukturen (Reinhold et al., 2008) überlagert auf einer Konturkarte des Basisbuntsandsteins aus dem Jahr 2001 (Baldschuhn et al., 2001). (B) Strukturen geringer Dichte werden in kühlen Farben (blau) dargestellt, während Strukturen höherer Dichte in warmen Farben (rot) erscheinen. Da Salz eine geringere Dichte als das umgebende Gestein hat, wird erwartet, dass es in blauen bis grünen Farbtönen erscheint. (C) Durch FTG-Verarbeitung abgeleitete Lineamente heben Bereiche mit starken Dichtekontrasten hervor, die auf potenzielle Verwerfungen, Salzdiapirismus oder Variationen in der Gesteinszusammensetzung hinweisen können. (D) Die neuen FTG-Daten korrelieren an vielen Stellen gut mit zuvor kartierten Salzkörpern, enthüllen aber auch Bereiche, in denen bei früheren Kartierungen möglicherweise Salzstrukturen übersehen wurden (weißer Kreis).

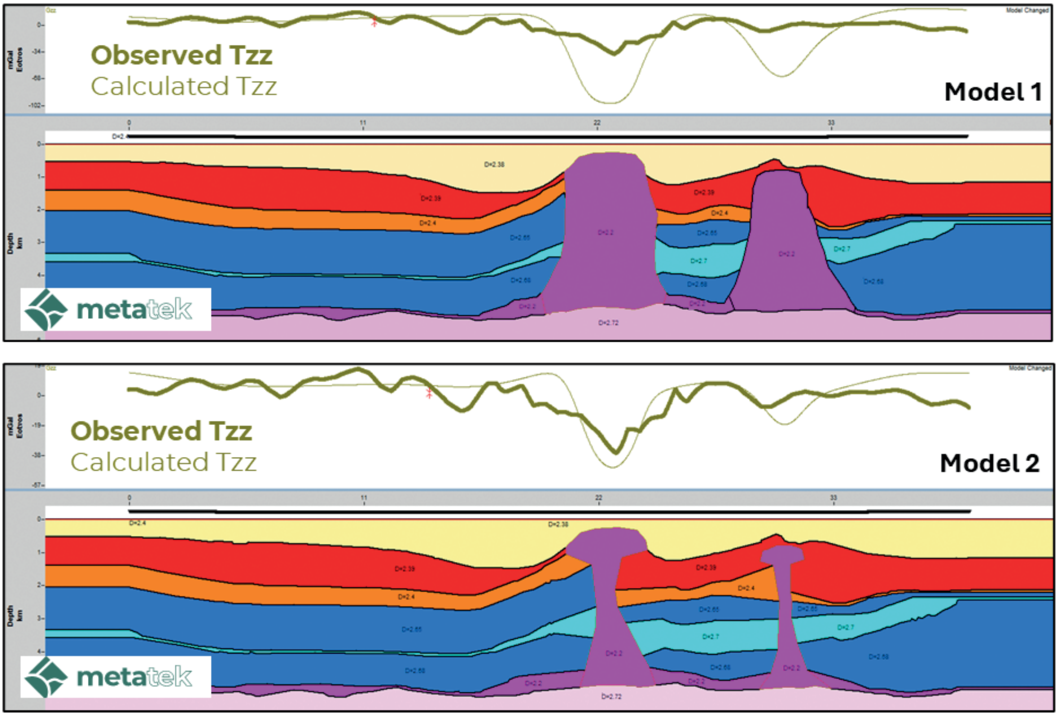

Figure 4: (A) Model 1: A salt diapir represented as a large vertical body, where sediments terminate at the seismic signal boundary. The modelled gravity response (Calculated Tzz, light green) exhibits a greater gravity drop at the salt domes than observed in the FTG survey (Observed Tzz, dark green). (B) Model 2: A salt diapir with a thin feeder channel and a bulbous salt dome at the top. In this model, the modelled gravity response (Calculated Tzz, light green) more closely aligns with the FTG survey data (Observed Tzz, dark green), better capturing the gravity variation at the salt domes (note the change in scale from Model 1). Modelling conducted by Metatek Group Ltd.

Figur 4: (A) Modell 1: Ein Salzdiapir, dargestellt als großer vertikaler Körper, dessen Sedimente an der seismischen Signalgrenze enden. Die modellierte Schwerkraftreaktion (berechnete Tzz, hellgrün) zeigt einen stärkeren Schwerkraftabfall an den Salzstöcken als in der FTG-Untersuchung beobachtet (beobachtete Tzz, dunkelgrün). (B) Modell 2: Ein Salzdiapir mit einem dünnen Zuleitungskanal und einem bauchigen Salzstock an der Spitze. In diesem Modell stimmt die modellierte Schwerkraftreaktion (berechnete Tzz, hellgrün) besser mit den Daten der FTG-Untersuchung überein (beobachtete Tzz, dunkelgrün) und erfasst die Schwerkraftvariation an den Salzstöcken besser (beachten Sie den geänderten Maßstab gegenüber Modell 1). Modellierung durchgeführt von Metatek Group Ltd.

6 Application to Swiss Confederation Geology

Permo-Carboniferous Basins

The Permo-Carboniferous basins in the Molasse basins of northern Switzerland commonly have densities lower than the surrounding basement and overlying Mesozoic sediment (Garrard, et al., 2021; Weber et al., 1986). Early-stage modelling suggests that FTG can readily identify these basins, even when buried under 3 - 4 km of complex overlying geology. Following an FTG survey, forward modelling can refine estimates of basin depth and thickness, guiding future exploration and drilling campaigns.

Carbonate detection

FTG has potential applications in detecting carbonate reefs, which are high-density geological formations ideal for FTG imaging. In the Mesozoic section of Switzerland, detection feasibility depends on size, volume, and burial depth. While carbonate reefs are typically high-density, porous zones exhibit lower density, resulting in a negative FTG response-indicating potential targets for hydrothermal geothermal development.

A relevant example comes from offshore Malaysia, where FTG surveys over the Luconia Carbonate province successfully mapped variations in porosity and gas content. Initial surveys at 2 km flight line spacing revealed correlations between high porosity and negative FTG Tzz responses. Follow-up surveys with 500 m flight line spacing provided even greater resolution, identifying smaller gas zones and internal reef complexity. These findings were validated with seismic data, demonstrating FTG's effectiveness in detecting high-porosity reservoirs.

7 Conclusion

Full Tensor Gravity Gradiometry (FTG) is a powerful tool for geothermal exploration, offering high-resolution subsurface insights that enhance resource identification. Its non-invasive, cost-effective nature makes it a valuable addition to the geophysical exploration toolkit, particularly when integrated with other methods.

FTG bridges knowledge gaps in existing datasets, refining subsurface models and optimizing drilling and seismic survey strategies, especially when followed by forward modelling of the results. By identifying key geological hazards such as faults and salt domes, FTG improves exploration efficiency and reduces costs. As demand for sustainable energy grows, FTG stands as a critical technology for advancing geothermal energy projects worldwide.

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