Sub-Basalt exploration with Full Tensor Gradiometry

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Summary

Exploration of sub-basalt Mesozoic sediments in flood-basalt prone regions is challenged by complications of using seismic imaging to penetrate basalt. Though explorative wells managing to penetrate basalt often flowed oil and gas, such systems still remain poorly exploited due to complexity of delineating economic targets. Airborne Full Tensor Gradiometry (FTG) Technology is well suited to this geological problem as it measures lateral changes in the gravity field in three dimensions. This allows FTG to effectively image through basalt layers, and resolve structural complexity beneath. Marine FTG has proven successful in identifying sub-basalt Mesozoic structural formation in the Faroe-Shetland basin, offshore Europe. Forward Modelling from Faroe-Shetland Basin and Deccan Traps geological sections demonstrate that FTG data will assist with imaging the sub-basalt structures.

This paper simulates the application of FTG to resolving geological complexity beneath basalt sills.

Introduction

Mesozoic deposits have contributed to 54% of global recoverable hydrocarbon reserves and a series of discoveries in volcanic margins are disproving that volcanism is detrimental to petroleum systems (Nathaniel et al, 2013). Deccan trap flood basalts cover much of the Western Indian Continental Margin at various intervals in geological time. Late Cretaceous magmatism emplaced the K-T flood basalts, blanketing Mesozoic sediments in major areas of Western India, with significant spatial thickness variations (>3000m).

A sound geological basis exists for the existence of Mesozoic source and reservoir rocks below K-T flood basalts, inducing Triassic Karoo sands and shales, Jurassic marine shales and sands and Cretaceous marine shales, shelfal sands and potentially pre-K-T carbonates (Nageswara et al, 2013). Exploration of sub-basalt Mesozoic sediments in the region is challenged by complications of penetrating basalt with seismic (Pandey et al 2009; Pandey 2012; Nathaniel, et al 2013), though explorative wells managing to penetrate basalt often flowed oil & gas.

FTG Technology

FTG systems use six pairs of accelerometers to measure the rate of change of the gravity field in all three directions. It measures the rate of change in acceleration converse to gravity survey which measures acceleration. The end result is a more accurate representation of the gravity field being surveyed. On the other hand, a conventional gravity survey (Gravimeter) records a single component of the three-component gravitational force, usually in the vertical plane.

FTG gravity is a technology deployed on both marine and airborne platforms worldwide and has been used on both hydrocarbon and mineral exploration projects. Murphy (2010) describes the workings of the instrument and Murphy and Brewster (2007) discuss methods to extract detailed geological information from FTG Gravity data. Their ideas exploit the tensor nature of the data to create new representations that best identify sub-surface geological complexity, particularly geometry and orientation of target structures.

Integration of seismic data with potential fields to improve sub-basalt imaging is now widely promoted. (Smallwood et a 2001, Reynisson, 2007). FTG data acquired in the basaltic province of the Faroe-Shetland region, offshore NW Europe, images structural highs beneath a thick basalt pile (Murphy, 2012). Previous work (e.g. Cawley et al, 2005, and Goodwin et al, 2009) suggests that such highs are important as focal points for the accumulation of upward-migrating hydrocarbons, where overlying volcanic strata act as a regional seal.

FTG allowed structural highs (red colors, Figure 1) to be mapped, modelled and drilled. Results demonstrated that prospective sands occur above a Mesozoic aged ridge structure and were overlain by volcanic rock (Murphy, 2012). This is a clear example

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of how FTG Gravity is suited for mapping of similar structures in challenging exploration environments.

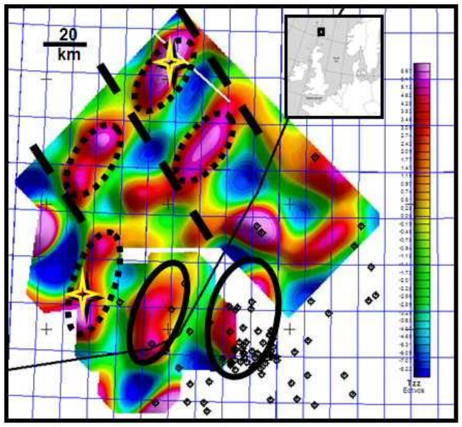

Figure 1: Wavelength filtered bathymetry corrected Tzz data from the Faroe Shetlands offshore Europe.

FTG forward modelling from geological sections

Based on published geological sections, a number of simple 2D models have been generated for both a Faroe-Shetland and Western Indian basalt-complicated basin environment.

Faroe – Shetland Model:

The Faroe-Shetland Basin, offshore NW Europe, is dominated by Tertiary basalts extruded over Mesozoic sedimentary basins. Exploration successes were largely restricted to where this basalt cover is thin and known discoveries are located on the flanks of major basement and/or Mesozoic ridges (Rippington et al 2014). Model section based on Rona Ridge, after Trice (2014).

The first model presents a basin stratigraphy exhibiting no basalt intrusions. A synthetic response is then forward-modelled for FTG and gravity. In a second model, a forward-modelled response is generated for the same environment with the addition of a basalt layer encroaching from the model-left between the Mesozoic and Tertiary formations (K-T boundary). The basalt pile is relatively flat, with gradually diminishing thickness towards the center of the model. Figure 2 shows the legend for the various geological formations in all models.

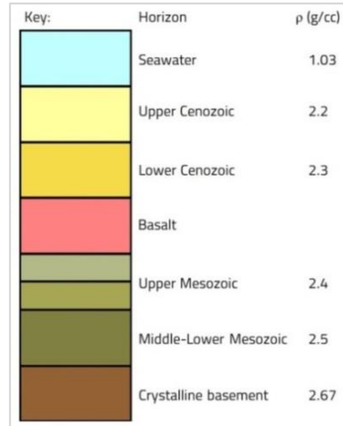

Figure 2: Legend for horizons in all model situations. Basalt density is 2.7 g/cc for Faroe-Shetland models and 2.9 g/cc for SW Indian models.

Figure 3 shows Gravity and FTG component response with no basalt presence. The upper window shows vertical gravity field (Tz) and Tensor components (Tzz, Txx, and Txz). Tz resolves deeper geological features and general basin structure very well. The Tensor components mainly highlight structural complexity within the section, particularly density contrast between horizons and more significant structural features. For example, deeper structural changes (folded/faulted basement) greater than 4km Lower Mesozoic formation are pronounced in the Tzz and Txx response. FTG response of top-basement structure is also well resolved. The model also shows sensitivity to known prospects on structural highs (i). The response of subtle basement structural high is also highlighted (ii).

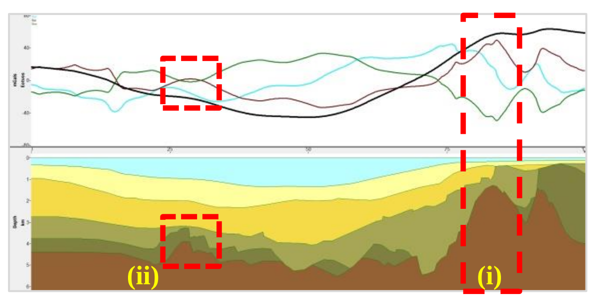

Figure 3: Faroe-Shetland model response; no basalt (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

Figure 4 shows FTG tensor component and Tz response when a basalt intrusion is present. Basalt, at

2.7g/cc, generates a density contrast of 0.4g/cc with enclosing sediments. There is a limited change in model response (longer wavelengths), but the inclusion of basalt as proposed does not alter the model responses from the various components or Tz.

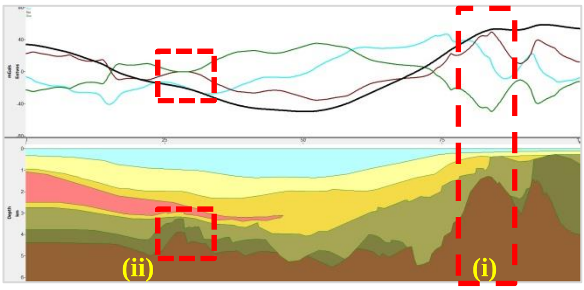

Figure 4: Faroe-Shetland model response; basalt presence (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

The model replicates basement structures similar to the previous model. The most marked impact on the model response occurrs where the basalt pile changes thickness rapidly or where the layer undulates, or has an inflection. Model responses in figures 3 and 4 demonstrate that in this scenario the basalt intrusion is not impacting on the modelled response, and though the signiture of the basalt is retained in the intermediate and long wavelength data, sub-basaltic changes can still easily be identified.

Western Indian Offshore (Deccan Traps K-T basalt):

Deccan trap flood basalts cover much of the Western-Indian continental margin at various intervals in geological time. Late Cretaceous magmatism emplaced K-T flood basalts, blanketing Mesozoic sediments over expansive areas of Western India with significant spatial thickness variations (600-1600m is appropriate for the model example area). This section of modelling simulates the response of FTG to this environment. The principal contrast to the Faroe-Shetland example is an increased depth to basement, which, though obstructed in many seismic surveys, is implied by a number of quantitative sources nearby.

Figures 5 to 8 show the FTG forward models using the published seismic section from Kerala-Konkala offshore basin, after Fainstein et al (2012).

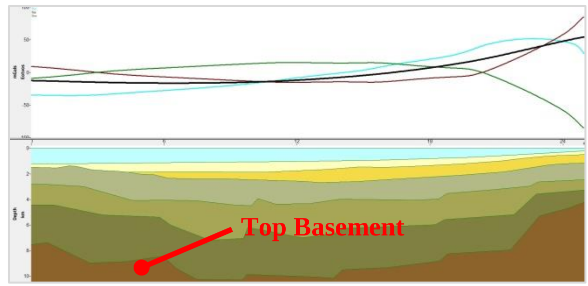

Figure 5: Western India offshore geological model and FTG response; no basalt (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

Figure 5 shows a simulated Gravity and FTG response where no basalt is present. The model assumes a basement depth at ~10km with limited density variation within the sediment pack, but gradual increase in density with depth. The model response for Tz is a gentle curve, which replicates the synclinal basin morphology of the model. Limited anomalous response is detected in the Tensor component responses, which again simply replicates basin morphology, though the shallowing of higher density basement to the right of the model yields a strong response in the tensor components. This is to be expected, as the basement depth used herein generally exceeds the effectiveness threshold of FTG.

The second model (Figure 6) introduces a 600m constant-thickness basalt layer between 1.4 km and 2.6 km depth. The density of the basalt is 2.9g/cc, generating a 0.5g/cc density contrast with surrounding strata. There is no significant change in the overall model response between a no basalt scenario and this model, except an elevated resposne in the tensor components where the basaltic layer is shallow and undulating (indicated, i).

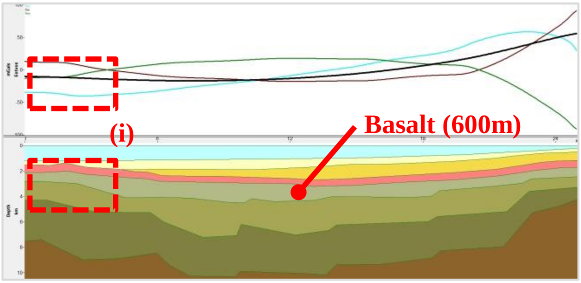

Figure 6: Western India offshore geological model and FTG response; 600m thick basalt (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

Figure 7 presents model responses where the basalt pile is 1600m thick, as this likely relates to the maximum thickness expected for prospects in the area. The basalt location is between 1.4 and 4.4km depth range. Similar to the previous model, other than elevation in Tzz values where the basalt reaches the near-surface, there is not much change in the overall response observed in the tensor component profile curves, or the gravity Tz. Models presented in Figures 5 to 7 present the conclusion that FTG gravity, though retaining an intermediate to long wavelength response is generally unresponsive to basalt presence, irrespective of thickness.

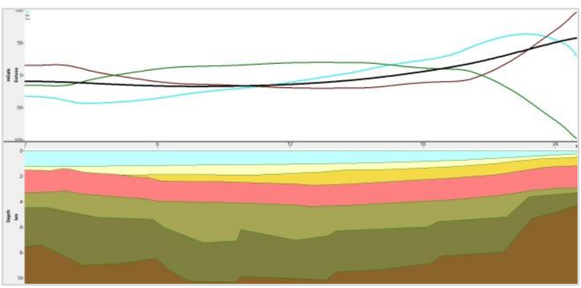

Figure 7: Western India offshore geological model and FTG response; 1600m thick basalt (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

Basalt thickness is unlikely to remain uniform, and a response of change in regional basalt thickness is shown in Figure 8. Basalt thickness in this model varies between 600m and 1600m, being thinnest at the centre of the section. In this model FTG component responses show sensitivity to this lateral thickness variation in the basalt. The response is a pronounced low over the thinned area (indicated, i) expressed in the Tzz and Txx components.

This observation can be used to identify sub-basaltic prospective structures, such as basalt-capped Mesozoic anticlines. If the basalt thins over the top of Mesozoic structral highs, this will be detectable.

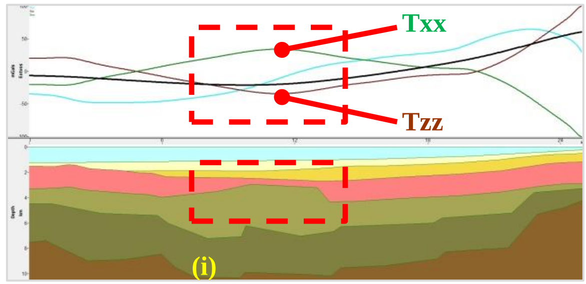

Figure 8: Western India offshore geological model and FTG response; Variable thickness, 600-1600m basalt (Model curve key: **Tz**, **Tzz**, **Txx** and **Txz**)

Conclusions

2.75D forward modelling provides an example of the response of FTG technology to the presenece of basalt in the idealised geological sections presented. The detection of geological information with FTG is dependant on variations in density in the section, both structural and stratigraphic.

From the Faroe-Shetland model examples we obseve that FTG is able to both detect the presence of intrusive basalt and subtle changes to a basalt pile, as well as image structural complexity at basement, and other geological intervals benath basaltic formations. Basement in this example is around 4-5km.

In K-T basalt (Deccan) models, the response of the basin is muted due to deep basement depth, low density contrast between horizons, and low dip of strata which yields a low amplitude response indicative of basin morphology. The response of the section with no basalt is very similar to the response when a uniform thickness of basalt is imposed, supporting the conclusions from Faroe-Shetland examples, that basalt will not impede FTG. Where there are lateral variations in basalt thickness, a significant response in FTG response is observed.

Specifically, where basalt thins, the model gives a lower density response. Conversely, this model response is be generated where Mesozoic anticlinal structures are present, reaffirming FTG sensitivity to sub-basalt structural complexity.

In the scenarios presented, 2.75D forward modelling demonstrates that FTG is able to detect multiple aspects of basalt-prone systems and has immense potenial for sub-basalt applications, specifically identifying structural features beneath basalt layers, as well as being able to detect changes in the basalt isopach. It is particularly suited to integration with seismic imaging and other geophysical methods, and for the forward planning of aquistion programmes.

Acknowledgements

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