

THE FIRST FIVE YEARS

Marine 3D Full Tensor Gravity Gradiometry

3D Full Tensor Gradiometry (FTG) or high-precision moving platform gravity gradiometry measures the full gravity field in all directions. The technology was initially commercialised for the petroleum exploration industry to assist with defining complex salt structure/geometry, sub-salt play definition and the re-imaging of seismic data using techniques such as Pre and Post-Stack Depth Migration (PSDM). The scope of gradient data utility further ranges from prospect level to regional reconnaissance project evaluation. Integration with other geophysical datasets produces added value in the form of improved interpretation accuracy and risk reduction.

FTG data contains critical directional information and greater resolution than does conventional gravity data. Geologically, FTG maps those edges of stratigraphic or structural units generating density contrasts. Principal areas of data acquisition include the Gulf of Mexico OCS and the European UKCS North Sea and West of Britain, the Faeroes West of Britain, and the Barents Sea, where salt and basalt feature-imaging and basin analysis have been the primary focus of this marine-based technology. Bell Geospace developments include the addition

of airborne acquisition capability or Air-FTGTM, extending the technology to the minerals-exploration and water-resource industries. The airborne system has proven successful in kimberlite pipe and alluvial diamonds and precious metals exploration.

Gradient Data - Advantages over Gravity Data

Considerations for employing either Gradient or conventional Gravity data for a particular project are many and varied. However, gradiometer data represents multiple and distinct advantages over gravity data:

- 1. FTG data is best in terms of resolution and increased S/N.**

Resolution is always significantly better at shallow depths (~6,000 metres) and better or equal at all depths because of calculated Tze (an enhanced form of gravity data which effectively integrates the measured gradients). This is achieved via a better-stabilised Gravity Measuring Assembly, or GMA, which allows for better compensation of horizontal ship accelerations. The multi-component gradient measurement provides for further noise reduction as compared to gravity alone.

- 2. Gravity measurements degrade with increasing sea-state.**

Ship accelerations cannot be separated from gravity measurements unlike FTG data. Gravity measurements assume that over a sufficiently long period of time the average vertical acceleration of the survey ship will negligibly small. When sea-state degrades, the choice is between increased averaging time and hence poorer resolution or increased noise in the data. These effects reduce the ability to recover higher frequencies.

- 3. FTG surveys can be acquired faster and with more certainty.**

Gravity surveys must be acquired at slower ship speeds due to ship acceleration effects. FTG data can be acquired at greater line spacing for equivalent resolution as compared to gravity surveys. Because FTG data is less affected by sea-state, the time required to accomplish the survey is more certain. FTG data is acquired utilising a dedicated vessel, unlike gravity surveys, which are typically run alongside seismic acquisition.

- 4. FTG surveys are less expensive than stand-alone gravity surveys.**

Due to the potential for increased speed, greater line spacing and less concern about sea-state, FTG surveys are less expensive than equivalent stand-alone gravity surveys.

- 5. The FTG system provides for near real-time data review and interpretation.**

Rapid data review is enabled by the interpretation potential of the gradients and near real-time processing of the data. This may be employed to make decisions regarding where more or less detailed survey is required, as well as providing for repeat of questionable data. Quick-look capability provides additional certainty in the data and reduces the potential for increased cost.

FTG Resolution

Resolution both in terms of spatial wavelength and amplitude are dependent upon the attributes of the specific geological target, including its dimensions, depth of burial and density contrast. Gradiometry data contains higher frequency signal than does gravity data and is thus by nature higher in terms of resolution. An example from the North Sea (See Figure 2) testifies to the greater signal bandwidth of FTG over conventional marine gravity. The measured Tzz clearly contains more identifiable trends than that computed from gravity data. Hence the benefit in measuring, rather than simply computing, gradients from gravity data.

Utilisation

Gradient data utilisation is varied but typically the technology is considered an enabling one, rather than stand-alone. Areas of subsurface structural and stratigraphic 2/3D seismic ambiguity are ideal situations for the deployment of gradient data. Thus integration with seismic

and log data in a forward model environment enables improved interpretation accuracy and risk reduction. The following are examples of gradient utilisation themes:

Subsurface Imaging

- top and base salt
- complex salt geometry
- basalt geometry and characterisation
- image sub basalt; define sub basalt sediments and basement geometry.

Cost-effective regional mapping at prospect resolution

- bridges 2D/3D economic chasm
- allows 3D mapping from 2D seismic control.

Increase value of seismic migrations/velocity depth models/PSDM

- improve initial accuracy
- savings in iteration time and money, more rapid convergence.

Shallow geo-hazard detection

- part and parcel of processed data without reprocessing
- enhances site surveying seabed geophysical interpretation.

Reservoir prediction and Time lapse 4D

- current research ideas.

FTG data discerns near-vertical density contrast edges of the salt feature as shown in the 2D response or sensitivity model (See Figure3). The tensor component responses shown above the geologic cross-section represent components T_{xz} (blue) and T_{xx} (green) which are utilised to predict mass axes and edges in the north-south orientation respectively. T_{zz} (brown) indicates the overall negative vertical downward all-edge response of the salt feature. All five independent components are used to interpret the respective edges and overall definition of the complex salt geometry in conjunction with the measured T_{zz} map. Isolation and analyses of key geology can be achieved either quantitatively with a 3D forward model or qualitatively using 2D FFT frequency-filtering techniques. Bell has developed specialised visualisation tools to implement rapid analyses and integration of full tensor gradient data.

Case Study: West of Britain & Faeroes Exploration

Geologic Setting

The West of Britain & Faeroe Islands offshore shelf area are located on the European North Atlantic margin and form an offshore component of the British Tertiary Igneous province (BTIP). The BTIP is part of a much larger igneous terrain that developed in response to North Atlantic Ocean seafloor spread and related Greenland-Northern Europe continental break-up. Within this province are igneous centres, extensive sill complexes and widespread flood basalts that present substantial challenges for geophysical exploration. Critically, seismic reflection techniques are limited in their ability to recover and properly image intra and sub-basalts in order to map prospective structural and stratigraphic traps, thereby increasing exploration risk.

Reducing Exploration Risk

Gradient data can reduce risk by enhancing seismic imaging when the two are integrated within a forward model utilising depth structure and density data. The 3D model balances mass and thereby provides a quantitative solution for structural configuration and thickness, as well as lateral density variability. Gradient data is also utilised qualitatively to gain valuable insight into key geological features using the full tensor to define multidirectional mass information such as structural and stratigraphic edges and lineaments. A good example of this is frequency filtering, which allows separation of signal from causative geology. This enables discrimination of the igneous high-density features (see Figure 4) at various depths and so enables interpretation of sub-basalt geology without seismic control.

Measured Gradient Data and Surveys

Three speculative (red outline) and two proprietary (blue outline) FTG surveys were acquired in the Faeroe-Shetland Basin (see Figure 5) from 1999 to 2002. All surveys were acquired with 750m in-line spacing oriented NW-SE apart from License 005, which was oriented E-W. Bell Geospace, using a combination of commercial and proprietary software, did the data processing. Objectives of the surveys were to determine basalt complexity, sub-basalt and basement structure. Because each of the tensor components responds uniquely to size, shape and thickness of density anomalies, each are employed in the overall interpretation process. However, T_{zz}, the vertical downward edge tensor component, is the most easily related directly to subsurface geology. Typically, T_{zz} gradient highs (red) relate to structural highs and the lows (blue) to areas of thickening basin sediment.

Frequency Filtering and Sub-Basalt Geology

The technique is applied to the 3D FTG T_{zz} data to quickly assess the geological complexity of the region: i.e. to identify and map the key geological features resolved in the data. A Fast Fourier Transform (FFT) approach is used to extract frequency slices, which are then used to qualitatively assess particular characteristics attributed/related to subsurface geology. Typically, high-frequency anomalies tend to be shallow-sourced while low-frequency anomalies arise from depth. Estimated depth to source mass is approximately a third to a quarter of the spatial wavelength. Three slice maps are used to assess shallow, intermediate and deep geology:

(Figure 6a)

The high frequency slice captures all geological features generating wavelengths from 3km to 10km. The strong amplitude signal arises from the near surface geology where bathymetry is relatively shallow. The indicated anomaly on the edge of License 006 corresponds to a buried channel at about 1,500m depth.

(Figure 6b)

The intermediate frequency slice captures geology generating wavelengths between 10km and 20km. The high amplitude anomalies follow the known geological trends in the area and are interpreted as reactivation of underlying structure during inversion episodes affecting the basalt. The indicated anomaly pattern is interpreted as the edge or limit of the flow basalts.

(Figure 6c)

The low frequency slice contains all wavelengths greater than 20km that are associated with regional scale geology, sourced either as large shallow bodies or deep events. All known tectonic trends (NE-SW, Caledonian, NW-SE, transfer zones, N-S, & ESE) in the area are clearly visible. The shorter wavelength anomalies in the deep slice are interpreted as Mesozoic blocks sitting on a deeper basement. The two known major discoveries are proximal to these highs: i.e. Foinaven-Schiehallion-Suilven and Marjun (both areas highlighted as solid polygons). Others may exist within Licenses 006 and the Callisto survey area (dotted polygons).

Conclusions

Identifying the known geology quickly allows the end-user to target specific areas for:

- detailed interpretation using all 3D FTG tensor components
- constraint against other geophysical data: i.e. seismic, magnetic, MMT, well log, etc.
- 3D forward modelling to examine validity of models and to determine best location for potential drilling targets.

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Note by the editor: The original submitted feature, which included more (theoretical) information (incl. figures) on the technology can be obtained from the author.

<https://www.hydro-international.com/content/article/marine-3d-full-tensor-gravity-gradiometry>
