Gravity Gradients in PreStack Depth Migration

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Summary
Subsurface de-risking is presently almost exclusively done by methods using seismic data. Indeed all other data collected at the surface is referred to as 'non-seismic' data expressing this fact. However, there are emerging gravity measurement technologies that could fundamentally change the game of subsurface risk management. Gravity gradiometer data have been fully integrated in the cycle of iterative prestack depth migration (PSDM) anisotropic model updating to arrive at a high-fidelity subsurface model which can be used both for improved seismic imaging as well as seismic amplitude related studies. We share our experiences with interpreting gravity gradients and discuss methods of inverting them. In particular, we address the issues: (1) Do gravity gradients add useful information? (2) Should gradients be used directly in interpretation? (3) Which gradients should be used in inversion? We conclude that gravity-gradient data have changed the way pre-stack depth migrations are being done in Shell. The data provide a high-resolution seismically independent way to validate models that has resulted in model improvements that would not have been feasible on the basis of seismic data only. These model improvements in turn have led to better time-to-depth conversion. In one demonstrable case, the incorporation of gravity-gradient data resulted in cost reductions for PreSDM of at least $200,000 and reduced the project turn-around time by at least two months. Uncertainties in the densities in the near surface geology remain a concern.

Introduction
Conventional gravimeters usually determine only the vertical component $T_z$ of the 3-component gravity acceleration vector at each measurement point. Gradiometers, in contrast, can measure directly the changes in all directions of the gravity field. The acquired data can be arranged in a nine-component tensor, $T_{ij}$, encoding the first order changes in the gravity vector in three orthogonal spatial directions. Because of symmetry only five of the nine components are independent.

The main benefit of a gravity gradiometer is its ability to account for the noise from vertical accelerations during surveys. As the difference field is measured by pairs of accelerometers, common mode (linear) accelerations of the instrument ‘drop out’ from the data. This is crucial, as it is notoriously hard in a conventional gravity field measurement to resolve accidental instrument accelerations (such as vessel heave) from true geological signal. A gradiometer thus has a fundamentally better signal-to-noise ratio than a gravimeter, hence is able to resolve subtle density contrasts that may be ‘lost’ in the background signal measured by conventional gravimeters. However, the strength of the gradient field diminishes faster with increasing distance ($\sim R^{-3}$) than the gravity field itself ($\sim R^{-2}$), effectively limiting the advantages of having a higher S/N for gradient signals to 'shallow' targets, say shallower than 3000 m.

Although it may seem that the tensor gradients provide additional information about the gravity field, this is fact not the case. Mathematically all information contained in the gradient field is identical to information contained in the gravity field vector. It is the practical impossibility (due to low S/N) to recover all that information accurately from the gravity vector. At the same time, though, the five independent gradient data sets provide redundancy in the data that is not present in a gravity data set. It has recently become clear that this redundancy may be used to improve the inversion of gravity gradient data to obtain a density/depth model in similar way a redundancy in seismic data is used.
(exploiting common image gathers) to optimize the velocity/depth model. This is a fundamental property not shared by conventional gravity data.

**Methodology**

In 1998 Expro acquired a marine gravity gradiometer data set in the Southern North Sea, as part of a NAM/Expro pilot to potential use of BGI’s new gradiometer. The survey partially overlapped a high-resolution conventional gravity data set acquired by LCT the previous year. The results are displayed in Figure 1, showing both the unfiltered LCT TZ gravity data and the unfiltered vertical gradient (TZZ) data. Analysis of the power spectra of both data sets shows that noise suppression on the LCT data requires a high-cut filter removing spatial correlation lengths shorter than 3000 m, while the gradient data requires filtering of length scales below 600 m. This implies an improvement of resolution in the gradient data of almost an order of magnitude. This is shown clearly below, where computed gravity TZ from BGI’s gradient data (by integration) together with LCT’s measured Tz gravity is shown as well as the computed gradient TZZ from LCT’s gravity data with BGI’s measured TZZ gradient. The “crisp” trends imaged by the BGI instrument are not always as easily detectable in the LCT data (Figure 2). Significant additional improvement can be obtained by tensor processing methods.

![Figure 1](image1.png)

**Figure 1.** On the left the measured Tz gravity data. On the right measured TZZ gravity gradient data. Both are unfiltered.

![Figure 2](image2.png)

**Figure 2.** Data after noise removal. On the left the Tz gravity data, on the right the TZZ gradient data.

One characteristic feature of the horizontal components of gradient data can easily be seen. The elongated high anomaly shown in the gradiometer data is associated with a large reverse fault in the Chalk section, see Figure 3. The Top and Base fault (throw ~ 500 m) has been mapped on PSDM data. In Figure 4 the response, without any further processing, of the combination of horizontal gradients is shown. In fact this combination can be used as a scanner for linear features in the data similar to a Hough transform for 3D seismic to delineate linear structures). The figure shows the result at which the highest resolution occurs. Superimposed on it is the Top and Base fault outline as picked on seismic, and we observe from the correlation a similar resolution as the seismic interpretation. Furthermore, the data in the SW corner suggests a possible update of the Base of the fault that may have important implications for a further PSDM iteration. This type of analysis requires a high resolution in the horizontal gradient data, which is beyond what can obtained from computing these from conventional gravity data.
Figure 3. Seismic PreSDM line (SW-NE) showing the reverse fault in the Chalk.

Figure 4. Horizontal gradient component (spin-2 field see text) with the interpreted fault from seismic.

Figures 5a-c show the gravity and gradients over another salt dome. The seismic data did not allow a safe interpretation of the Top Salt. Obvious resolution improvements can be seen between gravity data and gradiometer data. (The gravity data was acquired by BGI at the same time). More importantly, after careful processing (Figure 6), the remaining TZZ signal is superimposed on the seismic data, clearly showing correlation with seismic. The lateral resolution in the gradient data is indeed similar to the seismic data a clearly providing a guide to interpret Top Salt more accurately.

Figure 5. a) Top Salt Map from PSDM. b) Measured Tz. c) Measured Tzz
Using a proprietary inversion algorithm developed by Talwani at Rice University, we have investigated using gravity, gradients, combinations of gradients, and joint gravity plus gradient inversion to image a salt flank. Choosing between gravity and gradient inversion involves three elements: the relationship between gravity and gravity gradients as a function of distance from the source of the anomaly, the accuracy and signal-to-noise ratio with which each of these quantities can be measured, and the spectrum of wavelengths for each of these quantities. The suitability of using gradients for very short wavelength anomalies and gravity for long wavelength anomalies is obvious, but for many geologic structures the situation is more complicated because the signal encompasses a spectrum of wavelengths. The use of two complementary measurements may be desirable. In our modeling we have shown that gradients can be used to image the top of the salt, but the total salt thickness is best recovered by gravity data. In this case, using both sets of measurements would be the best approach to defining the geometry of the salt body. We believe that quantities exhibiting symmetry about a vertical axis simplify interpretation, and that inversion can be improved by a suitable choice of tensor elements and their combinations.

References