Completing the image with borehole gravity gradients

New instruments for measuring gravity gradients are being developed and deployed. As their strengths are particularly on the short to medium distances to the sources, borehole utilizations are obvious. We pick three possible applications, design the appropriate 3D models with right rectangular prisms, and calculate all relevant parameters. These results are evaluated in terms of interpretation value and better understanding of subsurface structures.

In the first case we prove that 4D reservoir monitoring is feasible up to distances of 10s to 100s of meter. The second example demonstrates the advantage of surveying directional gradients in the well for identification of dipping horizons. Finally, the benefits of integrating borehole gravity gradient data into classic 3D structural interpretation are estimated by applying advanced inversion evaluation tools. It is shown that the base of salt horizon from the SEG salt model can be defined significantly better if gradient data from a well are available.

Introduction

Over the last one or two decades potential field methods have overcome their classic limitation to reconnaissance studies; they became standard procedures for prospect level applications, and reservoir scale studies are no longer exotic. With new instruments for precise surveys of gravity and magnetic fields and their directional gradients at hand, novel scenarios for enhanced subsurface imaging can be designed. Particularly borehole implementations are appealing, as gradient surveys would benefit from the closer distance of the instrument to the sources, compared to surface measurements.

Twenty years ago, Nekut (1989) described the utilization of the gravity gradient tensor in boreholes, and many studies addressed possible applications. However, with advanced 3D modeling, inversion and visualization tools available (e.g. Krieger et al., 1998, Smilde, 1998, Henke and Krieger, 2000, Jacoby and Smilde, 2009), the integration of gradient data from wells into modern interpretation workflows can be realized, and their benefits for model reliability evaluated.

Thus the focus of this study is on the interpretation side, motivated by novel instrument developments aiming to reduce subsurface uncertainty (or model ambiguity). A selection of three scenarios is presented. All forward calculations are based on a 3D model consisting of right rectangular prisms, with a flexible density allocation; geometries are defined via horizon grids and/or geobodies with triangulated surfaces (see fig. 1).

Case A: 4D reservoir monitoring

A scenario for simulating two time-lapse borehole gravity gradient surveys, in order to identify oil in a reservoir replaced by water over the time, is defined by the following parameters: The reservoir dimensions are 3 km by 3 km by 50 m (thickness) in a depth of 2,000 m (top), and a density contrast of 50 kg/m³ is assumed between the two runs (based on a porosity of 0.22 and an oil-water density difference of 225 kg/m³). An array of 15 well locations are placed along the x-axis from x = -1.500 km (center of reservoir) to x = +1.500 km, with the OWC at x = 0.000 km.

For these wells the borehole gravity (Gz), all gradient tensor components, and two rotational invariants are calculated, from the surface to a depth of 4,000 m. The results for well #7 at x = +0.025 km, i.e. 25 m beyond the OWC, are shown in figure 2. Note that the density contrast is zero at this location, as we are out of the changed zone. For this well and for three others the respective values are summarized in table 1.

These results show that the edge of detectability for gravity gradiometry (approx. 5 E) is reached within 10s of m for OWC scenarios; further calculations for a GWC simulation (larger density contrast) reveal that in this case the identification can be extended to several 100s of m.
**Case B: Dipping horizon recognition**

Another value borehole gravity gradient data adds to geological interpretation is information on dipping horizons in the vicinity of the well.

Shown in figure 3 is the gravimetric response of a layer with a density contrast of 100 kg/m$^3$, tilted 10° in direction 22.5° NNE. The information from the borehole gravity gradient tensor components $Gxz$, $Gyz$ and $Gxy$ can be utilized to determine the azimuth (magenta) and dip (cyan) of the layer (Nekut, 1989), as shown in the right column. Please be aware that this is an ideal scenario, chosen for illustrating the potential value of borehole gravity gradiometer data, as they contribute additional information and confidence, e.g. for a base of salt dip and azimuth interpretation.

**Case C: Integration into 3D structural interpretation**

A classic task of gravity is the modeling of complex salt structures. To demonstrate the strengths of borehole gravity gradiometry a test model is created based on the SEG/ EAGE salt model.

Within the dimensions of 14 km by 14 km layers are defined with typical densities varying from 2,000 kg/m$^3$ to 2,450 kg/m$^3$ (fig. 4). The triangulated salt body cut into the layer cake with a density of 2,200 kg/m$^3$, contrasting at the base to the underlying sediment with 200 kg/m$^3$.

The gravity and gravity gradient effects are calculated from a discretized prism model at the surface and along the borehole path of Well-1,
which passes through the salt body. Figure 5 shows the geological model along with the applied densities (left column), deviation data (next to it), model response for Gz (blue) and Gzz (green) in the center, and for Gxx (green), Gyy (red), Gxz (yellow), Gyz (magenta) and Gxy (cyan) in the column next to it, and additionally three invariants of the tensor in the right column.

At the base of salt, which widely resides around 2 km of depth, 37 control nodes are defined for depth control in an inversion process (fig. 6). Each node controls the triangulated body in its neighborhood, decreasingly with distance.

For analysis of interpretation improvements by borehole gravity gradient data in 3D salt interpretation, the calculated model response is used as observed for the inversion process. Gravity data is assigned with an a-priori standard deviation (SD) of 0.05 mGal, and tensor gradient data with a SD of 5 Eotvos (0.5 mGal/km).

In the first tested scenario, only surface data (gravity and gradients) are used to analyze the resolution of the depth of the control nodes, thus the depth of base of salt. The resulting a-posteriori standard deviation of the control nodes defines the acceptable variation of each single control node whose response resides within the a-priori standard deviation of the observed data (fig. 7). In contrast, figure 8 shows the results with borehole data added at Well-1. An obvious increase in resolution of the control nodes is noticeable in the vicinity of the well. A significant improvement in determining the base of salt is recorded, and best seen in the residual plot (fig. 9), up to a radius of about 2 km around the well location.
The a-posteriori residuals of variables plot (fig. 10) displays the increase in resolution weighted to the a-priori standard deviation of the control nodes (green line). The well is located at node #28. Surrounding control nodes (e.g. #22, #27, #29, and #33) experience least residuals, increasing with distance from the well. Control nodes below #20 are mostly defined by surface data.

![Fig. 10 A-posteriori residuals of variables (control nodes 1-37)](image)

The resolution matrix (fig. 11) illustrates how well the depths of individual control nodes can be determined and how strong „smearing effects” must be expected. The numbers on both axes correspond to the node numbering in figure 9.

![Fig. 11 Resolution matrix of variables (control nodes 1-37)](image)

On the main diagonal the response of inversion of gravity/gradiometry observations due to a change in control node depth of one depth unit is depicted in a combined process of observation (gravity law) and inversion. – In the ideal case there is no influence of one control node to another: The observation and inversion process should not map the change of depth of one node onto another node; therefore all off-diagonal elements should have value 0.

The yellow element (14,20), for example, indicates, that the change of depth of one unit of control node #14 is additionally mapped into a change of depth of 0.2 units (in the same direction) of control node #20, which is the right neighbor of #14. Similar influences are observed for most control nodes up to #20, meaning these cannot be determined very well individually, because the observation points are too distant (for their given accuracy).

On the other hand, node #28 and its direct neighbors can be reproduced pleasantly well (diagonal elements near to 1), and changes of these depths do not smear out onto other control nodes: The borehole observations are close enough, that these variables can be resolved individually.

Conclusions

Although borehole and near field effects have not been addressed in this study, the three cases show that subsurface modeling can increasingly benefit from the application of borehole gravity gradients, not only due to the decreased distance to the target, but also due to its lateral sensitivity. Proper constraints and parameter correlations as well as appropriate modeling and inversion tools are required to gain maximum advantage of the method, extend its limitations, and fully integrate it into joint interpretation workflows.

Acknowledgments

We thank our colleagues in Hamburg and Houston for an excellent cooperation and fruitful discussions.

References


