INVERSION OF HIGH-RESOLUTION 3D FULL TENSOR GRADIOMETRY (FTG) DATA FOR RESERVOIR MONITORING

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Abstract

High-precision high-resolution Three-Dimensional Full Tensor Gradiometry (3D FTG) data can be produced in the course of reservoir monitoring, and may be used for large-scale production history monitoring. We have developed a regularized inversion algorithm for detection of lateral density contrasts in subsurface layers at shallow and moderate depths. Numerical results demonstrate that FTG data can be used for dynamic reservoir monitoring in conjunction with time-lapse seismic data.

Introduction

3D FTG technology has improved dramatically over the past five years with advances in both acquisition and processing methods. Although the pioneers of gravity in exploration routinely exploited gradiometric methods using instruments such as the Eötvös torsion balance, Bell et al. (1997) were the first to write at any length about the potential applications of FTG. In the United States, this technology has already been applied to sub-salt exploration in the Gulf of Mexico. Coburn (2002) describes some case studies that used FTG and 3D seismic imaging to delineate the base of salt. 3D FTG monitors the first derivative of the gravity vector field (Figure 1).

The instrument consists of a multiple accelerometer system comprising three gravity gradient instruments (GGIs). The system measures the full spectrum of the multi-component gravity gradient field as well as the magnitude of the gravity field itself. In principle, nine tensor components mathematically arranged in a $3 \times 3$ matrix are measured. However, four tensor components are redundant, so only five independent tensor measurements (say, $\widetilde{G}_{XX} = G_{XX} - G_{YY}$, $G_{ZZ}$, $G_{XZ}$, $G_{YZ}$, and $G_{XY}$) are recorded. The unit of gravity in common use is the mGal, equal in SI units to $10^{-2}$ $\mu$ms$^{-2}$. For gravity gradients, the unit in common use is the Eötvös (Eö) which is equivalent to 0.1 mGal/km.

In addition to the ability to derive horizontal gradient vectors, FTG surveys also offer greatly increased bandwidth that captures the relatively short-wavelength signals generated by gravity sources at shallow and intermediate depths. Recently, resolutions of less than 5 Eö over 400 m spatial...
wavelength have been achieved using airborne gravity gradiometers. High-resolution FTG data acquired on a well-stabilized platform seems to be capable of achieving resolutions of better than 1 Eö at wavelengths of tens of meters (Colm Murphy, pers. comm.). In contrast, traditional airborne gravimetry produces data with resolutions of a few mGal, at wavelengths of a few km. Typical ground-based gravimetry can provide gravity gradient information with a noise level of about 10 Eö. This performance is suitable for large-scale regional studies. Better performance can be obtained using micro-gravimetric methods, but the costs are such that these methods are rarely used outside of small-scale engineering contexts.

**Method**

The goal of 4D FTG is to exploit high-resolution measurements of the tensor at different times to characterize changes in density (alternatively, movements of mass) within the rockmass during the intervening intervals. Interpretation of high-resolution FTG data requires reliable and efficient inversion methods that focus on the additional value provided by horizontal component information in imaging local targets. Following our recent feasibility study (Vasilevsky et al., 2003), we have developed a regularized inversion scheme designed to enhance production-related density anomalies within the reservoir. The components of the gradient tensor are used to constrain the reservoir model at a prospect level by defining the edges and shape of the time-lapse anomaly as well as estimating lateral density changes that might otherwise be masked by acquisition and processing artifacts.

To distinguish between two surveys, we use the subscript “I” to denote the quantities at the reference time (base survey); the subscript “II” is used to denote the quantities at the monitor time (repeat survey). The 4D inverse gravity problem of estimating the density change $\Delta \rho = \rho^{II} - \rho^I$ from the observed gravity difference $\Delta G_{obs} = G^{II} - G^I$ may be formulated using Tikhonov’s regularization method of undetermined Lagrange multipliers (Tikhonov and Arsenin, 1977) with the regularization parameter $\alpha \to 0$. The method permits the incorporation of a priori information about the maximum compactness of anomalous sources along several axes (Barbosa and Silva, 1994).

**Figure 1**: Geometry of the Teal South producing reservoir derived from 3D seismic data (courtesy of ChevronTexaco) and rescaled to the depth range from about 400 to 500 m below MSL.

**Figure 2**: Output of reservoir simulation (Subbey et al., 2002) for the target area in Figure 1: pressure map before production (legacy) and during phase 1 of reservoir monitoring.

The optimization search performed over a range of $\alpha$ values incorporates information into the inversion process by minimizing the functional $P_\alpha(\Delta \rho)$ subject to forward solution $\Delta G(\Delta \rho) \to \Delta G_{obs}$, within a tolerance imposed by the a priori estimate of signal-to-noise ratio. Previous tests (Vasilevsky et al., 2003) have shown that the results are not strongly dependent upon the precise value of $\alpha$. The minimization problem has a simple appearance, but its numerical implementation is not trivial due to the following features: (1) the size of data and model vectors can be quite large; (2) inversion suffers
considerably from the problem of nonuniqueness, as reported by many authors; and (3) linear matrix calculations may be time-consuming because of the large matrix size. Additionally, to minimize the cost function efficiently, it is necessary to have its gradient available.

**Results**

We considered a realistic example from the Teal South 4D study (Pennington et al., 2001). To enhance FTG anomalies, the actual horizon map was scaled to a moderate depth (Figure 1). Subbey et al. (2002) used a three-phase 3D reservoir simulator to generate pressure and saturation maps that account for uncertainties in history matching models and resemble the production history of the Teal South reservoir (Figure 2 shows the pressure map for the target zone in Figure 1). These maps were transformed into corresponding density changes (Figure 3) using empirical relations between densities and pore pressure (Batzle and Wang, 1992). The $G_{ZZ}$ and $\tilde{G}_{XX}$ components that emphasize the bounding faults are shown in Figure 4. In this model, values of the $G_{ZZ}$ component range from about +2.7 to -0.27 Eö. Both $G_{ZZ}$ and $\tilde{G}_{XX}$ components were employed in the inversion algorithm along with *a priori* information regarding the source regions.

Direct application of the inversion method described allowed us to obtain the density contrast model shown in Figure 5. Despite a relatively poor initial guess, the inversion achieves a solution quite close to the true density anomaly. It took about 30 iterations to achieve a model error of less than 3% and a field error of less than 1% for the initial density change of $-0.15 \text{ g/cm}^3$. The optimal value $\alpha = 0.1$ was estimated on the basis of the speed of the decrease of the solution misfit as $\alpha \rightarrow 0$. Clearly, the sensitivity of high-resolution FTG instruments as well as the accuracy of inversion in Figure 5 are sufficient to map the movement of the GOC in Figure 2. It is important to note that density anomalies were adequately retrieved without pre-processing.

**Conclusions**

Based on our feasibility analysis (Vasilevsky et al., 2003), we have developed a regularized 3D FTG inversion algorithm that permits the effect of oil production processes on the density of reservoir rocks to be monitored. The algorithm has been tested on a realistic reservoir model. Potential 4D applications include CO$_2$/steam injection, heavy oil reservoir recovery, gas cap expansion, and temperature monitoring at shallow or moderate depths.

**Figure 3**: The density difference between the reference (legacy) and the monitor (phase 1) density maps due to pressure and saturation changes.

**Figure 4**: FTG response $\Delta G(\Delta \rho)$ to the density change $\Delta \rho$ in Figure 3: (a) $G_{ZZ}$ and (b) $\tilde{G}_{XX}$ components.
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References


![Figure 5](image_url)

**Figure 5**: Exact density changes (solid contour lines) compared with the results of the iterative regularized inversion applied to the data in Figure 4 (dashed contour lines): initial guess, iterations 1, 5, and 20, final result after iteration 30, and percentage of density error.