Reducing Uncertainty in Subsalt Imaging with Gravity and FTG

Salt structures are challenging geophysical interpretation issues and need to be addressed properly. In this paper we discuss how non-seismic data can be integrated in the cycle of iterative depth migration and model updating leading to better seismic imaging results and a more reliable prospect evaluation. Especially areas involving complex salt geometries as in the Gulf of Mexico are affected by issues limiting the success of pre-stack depth migrations (PreSDM). Our approach to tackle these problems is the integration of data from independent geophysical techniques that are linked to the same lithological model but respond to different geophysical properties, like density, susceptibility, or resistivity.

Gravity, gravity gradient, magnetic, or magnetotelluric datasets are often available. Initially, a coarse evaluation of their applicability is recommended, particularly regarding the availability of constraining information. Further workflow steps include qualitative data analysis, primary model building with respective sensitivity tests, and geostatistics on property relationships. The main project phase usually consists of one or more joint seismic (e.g., PreSDM) and potential field interpretation cycles, leading to improved, integrated models, increased geological reliability, and reduced exploration risk.

Introduction

The experienced geoscientist is aware of the principle problem of ambiguity in geophysical/geological interpretations, particularly in the case of potential field data. For gravimetric and magnetic techniques it is essential to be correlated to other data in order to minimize the number of possible solutions by boundary conditions (or a-priori information). If this is the case – and some requirements are met – potential field methods often contribute considerably to a better understanding of crucial subsurface structures, enhance joint interpretation by adding supplementary information – specific to the method – and thus improve accuracy and reliability of the geomodel, as discussed in many publications (e.g., Pedersen, 1979; Lines et al., 1988; Henke, 1996; Krieger et al., 1998; Li and Oldenburg, 1998; Fedi and Rapolla, 1999; Colombo and DeStefano, 2007; Jacoby and Smilde, 2009).

Within the detailed implementation of this integrated approach (see Figs. 1 and 2) a considerable potential for optimization is evident for various applications, particularly for hydrocarbon exploration, as in many cases integration (or correlation) of interpretation techniques is found to be sporadic and qualitatively only.

From our experience even iterative approaches result in a significant increase of confidence in geoscientific interpretations: in a kind of feedback loop, results of a specific method are utilized as consecutively updated input parameters for the next one, in terms of forward modeling and inversion, aiming to minimize the residuals in both methods. However, an advanced concept of fully integrated interpretation could be realized by simultaneous joint inversion of multi-disciplinary data. First results, e.g., in 2D or with limited parameter correlations, are promising, but software and techniques have to be further developed.

Integrated interpretation workflow

For integrated multi-technology interpretation projects, e.g., in the Gulf of Mexico, typically 3D gravity, FTG (full tensor gradient), and magnetic modeling and inversion, as well as joint visualization of seismic, magnetotellurics (MT), gravity, FTG, borehole, and additional constraining data are applied. A combined interpretation approach improves existing depth models regarding geometry, velocity, density, or resistivity, with focus on salt features as main imaging problem zones.

In the case of Gulf of Mexico subsalt imaging the ingredients for a successfully integrated interpretation procedure are described in the following paragraphs, based on an example with 3D gravity, FTG, and MT data available, as well as seismic, borehole logs, magnetics, and stratigraphic concepts as constraining information at hand.

![Fig. 1 Integrated interpretation concept. Focus on potential field data.](www.terrasysgeo.com)
improve the model definitions by analyzing and adjusting the correlation of the 3D density-depth model with log data. User-controlled inversion routines could also be used for long-wavelength density optimization of regional gravity residuals.

Seismic data (inlines, crosslines, depth slices) as well as MT data (resistivity images or voxets) are integrated into the 3D environment for facilitating joint interpretation and model QC; this is particularly important for salt dome geometry optimization by forward modeling and inversion.

3D forward modeling and inversion for salt structures

Main emphasis of the procedure is placed on the control of the salt geometries. The computed gravity and FTG responses of initial salt models are analyzed by comparison with the observed (and filtered) gravity/FTG fields. Implications for necessary geometry improvements are given and discussed intermediately and during joint interpretation meetings, qualitatively and quantitatively. Therefore, sensitivity tests are applied, particularly for a better control of salt location and volume.

A refinement of the 3D model is achieved subsequently with iterative forward modeling and inversion. Revised model geometries and densities (including implications on the velocity distribution) are transferred in appropriate formats at predefined steps (e.g., after major changes), usually for a new pre-stack depth migration (PreSDM) run (often on target lines).

Beside a quantitative optimization of the salt extensions in close interaction with the seismic and MT processing and interpretation routines, further modifications or different scenarios could optionally be applied, e.g., lateral or vertical inhomogeneities, insertion of additional layers, special consideration of anhydrites (Krieger et al., 2000), or implementation of overpressured zones.

Advanced inversion technology

The consideration of a-priori information (seismic, MT, and well data, geological information, tectonic relations, etc.) is handled in many different ways within the usual potential field inversion routines. Sometimes regularization methods – unknown to the user – are applied which result in a unique solution, but without any geological relevance. Often the a-priori information is solely represented by an initial model which is expected to be unchanged (however this works) if potential field data contain no information of that area.
Our approach followed a different path: Since 1996 we have designed sensitivity studies and forward modeling techniques to evaluate if a given initial model is in correlation with observed gravity, FTG, or magnetic data, or if – and how – it could be improved, respectively (Krieger et al., 1998; Marschall et al., 1999; Henke and Krieger, 2000). To complement this methodology, over the years advanced inversion strategies have been developed and applied (Smilde, 1998; Jacoby and Smilde, 2009), which hold, combined with a-priori information, the following characteristics:

A-priori information can be defined in a very flexible way, i.e., the parameterization of the given problem can be properly adjusted to the existing information, allowing a detailed assignment of the known or estimated standard deviation of the information to the model, which prevents under- or over-representation. In such a way, for example, geological scenarios could be better represented by a layer/body-based parameterization, while continuous parameter values of a seismic tomography are modeled upon a grid.

Correlations between a-priori information, which were achieved by the extraction of the a-priori information itself (from possibly other inversion methods), can be considered as well. This type of correlations describes a-priori information more detailed, and, furthermore, express how other inversion methods would react on small changes, thus allowing to reduce the number of iterations needed between the different optimizations.

After each inversion optimized model parameters are available, but also detailed statistical information are calculated (a-posteriori [co]variances, resolution, data density), which refer to the quality of the initial model, of the a-priori information, and of the potential field data itself. This allows a much faster, targeted model optimization.

Having these tools at hand, it is possible to analyze in detail the correlation between a-priori information and potential field data, and to consider it together with the inversion results. Furthermore, important indications are also derived for improving survey technique parameters, as an optimized localization of observations, or the necessary, project-specific survey accuracy requirements.

**Results from integrated interpretation projects**

In the first case shown, cooperative multidirectional interpretation of high-resolution gravity and high-resolution magnetotelluric (HRMT) data integrated in the cycle of iterative seismic depth migration anisotropic model updating has been applied to improve depth imaging of a typical salt dome (Fig. 3), located within the South Permian Basin in northwest Germany.

The existing 3D seismic data are not suitable to image reflectors in the shallow subsurface, and ambiguities in the allochthonous salt imaging lead directly to large uncertainties (imaging, depth conversion) in the subsalt regions of the model. HRMT depth imaging clearly defined the top of salt and the shallow salt flanks geometries. Seismic depth migration provided a high resolution image of the sedimentary sequence surrounding the salt dome. Together with the new upper dome geometry those were used to constrain the interpretation of density anomalies at lower levels beneath the upper salt structure.

The cooperative interpretation of high-resolution gravity, HRMT, and seismic depth imaging has produced a significant increase in resolution of the complex geometry image of the salt structure, and consequently reduces cost and time required to complete the depth imaging workflow while increasing the likelihood of successful target identification.

Another effective application of integrated technology to enhance subsalt imaging is shown in an example from the Gulf of Mexico (Fig. 4). The depth imaging of salt pillow structures was subject to be improved by the integration of gravity, FTG, and MT data interpretation.

In order to constrain the gravity model, seismic velocities were transformed into densities utilizing geostatistical analysis of borehole data. Furthermore, seismic interpretation of top of salt sets boundary conditions to MT and FTG modeling. Ambiguities in the base of salt interpretation from seismic were minimized by interactive integration of MT and FTG interpretation. With the model...
geometry of the salt improved, the reliability and quality of subsalt imaging in subsequent seismic PreSDM processing were clearly enhanced.

**Conclusions**

Integrated interpretation technologies for potential field data have been consistently optimized, such as analytical 3D forward modeling with a flexible visualization, or innovative inversion techniques for increasingly complex geological scenarios. Many integrated studies, utilizing either an iterative or a joint approach, have been successfully applied, with data from the Gulf of Mexico or from the Barents Sea, from Gabon or from Germany, and their results encouraged us to continue to focus on multidisciplinary interpretation and to further develop these technologies.

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**References**


