Reducing Uncertainty in Subsalt Interpretation: A Non-Seismic View from Integration*

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Abstract

Significant hydrocarbon discoveries have been made in subsalt structures, and the potential for further discoveries is driving exploration after risky targets. However, salt formations 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 or offshore Brazil, are affected by issues limiting the success of pre-stack depth migrations; e.g., reduced data quality, incorrect structural concepts, unresolved geometries, or inaccurate velocities. Our approach to tackle these problems is the integration of data from independent geophysical techniques, which are linked to the same lithological model but respond to different geophysical properties, like density, susceptibility, or resistivity.

Key ingredients for a successful application of this concept - besides a reasonable seismic coverage - are: adequate high-resolution non-seismic data, constraining geological boundary conditions, a flexible software environment for integrated 3D modeling, inversion and visualization, experienced interpreters with excellent inter-disciplinary communication skills, and a proven workflow, adjustable to the specific project requirements.

Having gravity, magnetic, gravity gradient, EM, and/or magnetotelluric data at hand, a typical study starts with a coarse evaluation of their usability for the given objectives and expected targets, particularly with regard to the availability of a-priori information. Further workflow steps include qualitative and quantitative data analysis, the initial model construction with respective sensitivity tests, and a geostatistical approach for defining property relationships. The main project phase consists of cooperative PreSDM and non-seismic interpretation, aiming to define an integrated model with improved geometries and reduced uncertainties, in order to minimize exploration risk.

Examples from different regions show where multi-disciplinary 3D modeling helped to delineate the allochthonous salt distribution. As in many cases, the base of salt could not be clearly identified from seismic data, but the integrated approach revealed its geometry and salt thickness, a major step for better imaging of target structures below salt.

Introduction

The experienced geoscientist is aware of the principal 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 (Figure 1), 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, a considerable potential for optimization is evident for various applications, particularly for hydrocarbon exploration. This is due to the fact that in many cases integration (or correlation) of interpretation techniques is found to be sporadic and qualitatively only.

From our experience, even an iterative approach results in a significant increase of confidence in geoscientific interpretations: here, 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 (Figure 2). 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 techniques and software have to be further developed.

Integrated Interpretation Workflow

For integrated multi-technology interpretation projects, e.g. in the Gulf of Mexico, aiming to increase imaging quality and geological reliability, 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. In a combined interpretation approach, updates, refinements, and improvements of existing depth models regarding geometries and geophysical properties as velocity, density, and resistivity could be achieved, with focus on salt features as main imaging problem zones.

In the case of GoM sub-salt 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.

Gravity/FTG Data Preparation and Analysis

Initially, the available gravity/FTG data might have to be prepared for further usage, depending on their status. This comprises data homogenization, projection induced transformation, gridding, visualization, and QC. Subsequently, rather qualitative data analysis tools (also called "direct methods") allow a rough definition of possible sources for the observed potential fields and assist further interpretation of model-dependent 3 D calculated fields, e.g. by applying directional gradients, wavelength filters, upward continuations, etc.

As an example, the second vertical derivative (SVD) of gravity data can be utilized as a first approximation of lateral extensions of existing salt structures. A selection of bandpass-filtered maps of the observed gravity fields is helpful for separating "regional" and "residual" components, i.e. effects originating from different depths and/or geometries; these maps are also needed for direct comparison with the 3D calculated anomalies caused by the target structures within the used model cube (with a limited vertical extension, adjusted to the specific exploration purpose).

Construction of the Structural Model

The 3D model is defined by a set of horizons and independent geo-bodies, as well as their respective density distribution functions; alternatively, (if horizons have not been interpreted) standardized density-depth functions (of various complexity) can be used or a velocity cube analysis/conversion can be performed in order to assure a complete and consistent density assignment. Usually rather complex structures like salt geometries are defined as geo-bodies.

If well data within the surrounding area with density/sonic logs are available, these could be optionally utilized for a regionally adapted velocity-density conversion. Existing borehole information (density and stratigraphy) is visualized and utilized to 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 the 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 pre-defined steps (e.g. after major changes), usually for a new 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 recognition of overpressure zones.

Advanced Inversion Technology

The consideration of a-priori information (seismics, MT, 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. Quite 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 for 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 an advanced inversion strategy has been developed and applied (Smilde, 1998; Jacoby and Smilde, 2009), which holds – in combination 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 not only the a-priori information more detailed, they furthermore express how the other inversion methods would react on small changes, thus allowing to reduce the number of iterations needed between the different optimizations.

After running an inversion not only optimized model parameters are available, but detailed statistical information are calculated (a-posteriori (co)variances, resolution, data density, etc.), 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 optimization of the model.

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.

Integration Case

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

The existing 3D seismic was not suitable to image reflectors in the shallow subsurface, and ambiguities in the allochthonous salt imaging led directly to large uncertainties (imaging, depth conversion) in the subsalt regions of the model. HRMT depth imaging clearly defined the top of salt (Figure 3a) 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 (Figure 3b).

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.

Conclusions

Integrated interpretation technologies for potential field data have been consistently optimized, such as the analytical 3D forward modeling methodology 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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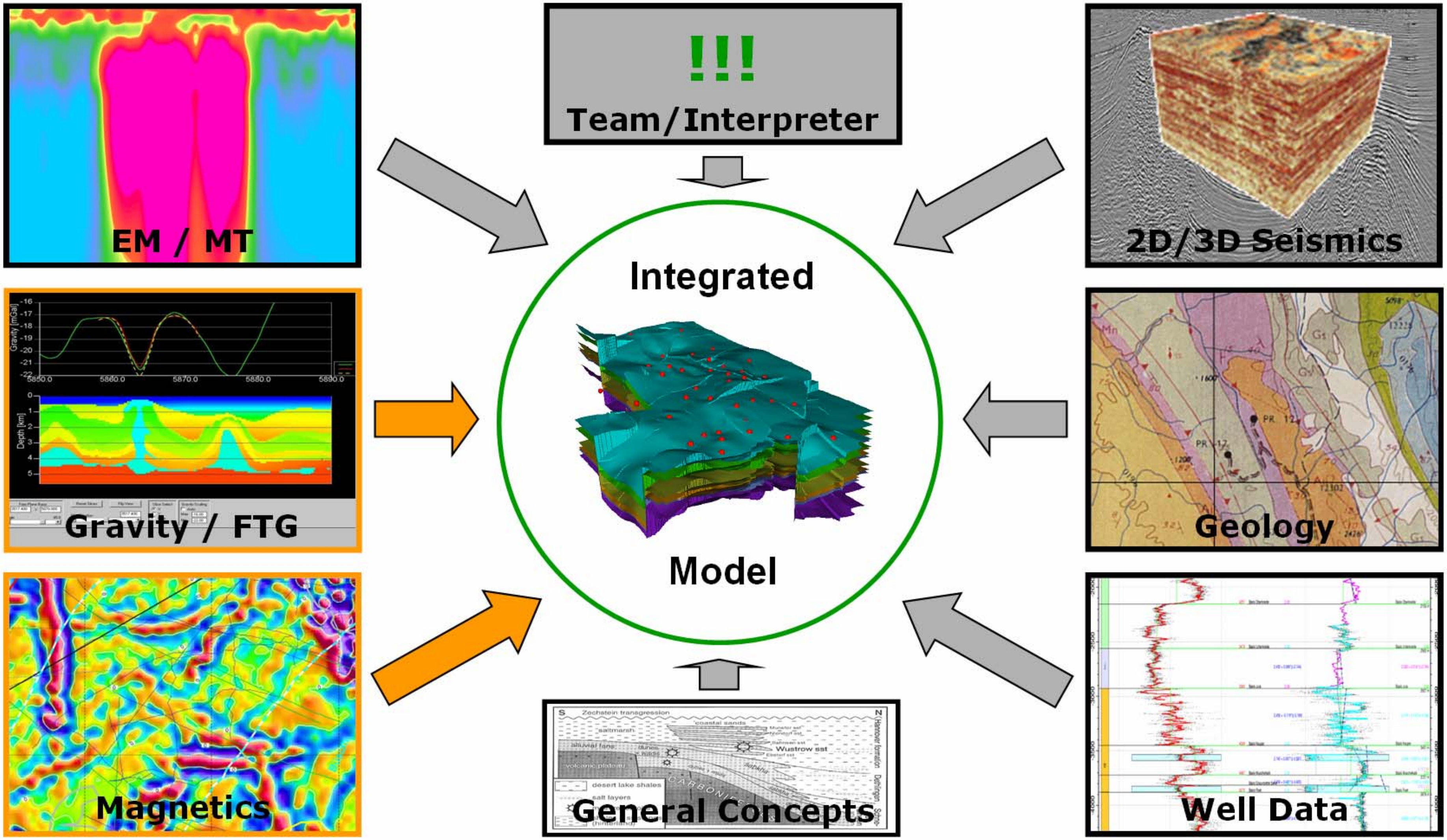

Figure 1. Integrated interpretation concept; focus on potential field data.

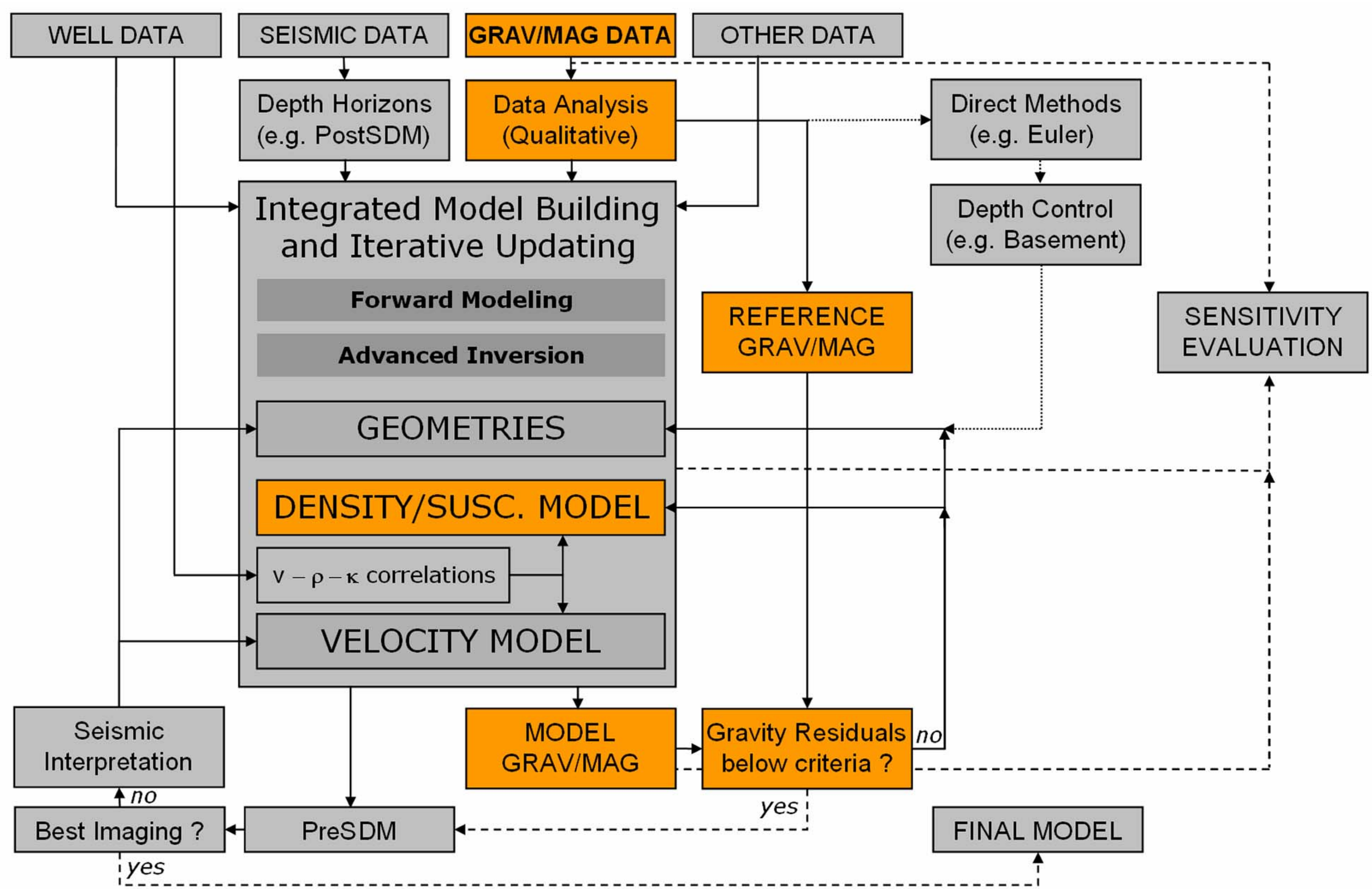

Figure 2. Integrated interpretation workflow; focus on potential field data.

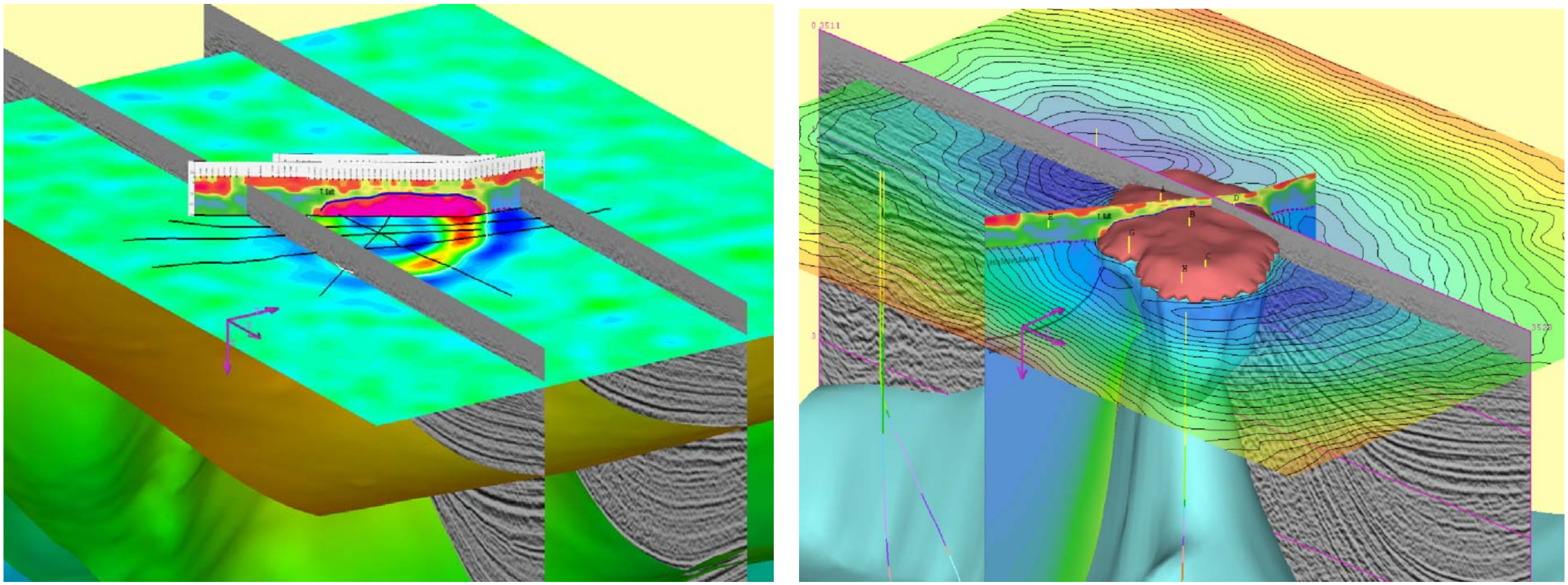

Figure 3. Integrated visualization: (a) Second vertical derivative of gravity, HRMT profiles, seismic sections, and horizons jointly define the salt geometry. (b) Seismic section, HRMT line, and surface gravity field over the optimized target salt (blue), with anhydrite cap rock (red).