B033

Improving Subsalt Imaging by Incorporating MT Data in a 3D Earth Model Building Workflow - A Case Study in Gulf of Mexico

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SUMMARY

In this work we present the simultaneous joint inversion of seismic and EM data in WalkerRidge area, Gulf of Mexico. The deep-water Gulf of Mexico can be a difficult geologic and imaging environment due to the diverse and repeated salt tectonic episodes that have resulted in complex allochthonous salt formation. Accurate salt body characterization and careful earth model building are key objectives for properly assessing the exploration potential of the area. Seismic methods alone, cannot always properly image the subsalt reflectors. The inclusion of non-seismic data, such as magnetotelluric (MT) is very useful in complex salt provinces where the method can leverage the differences between salt and sediment resistivity as well as between seismic velocity.
Introduction

The deep-water Gulf of Mexico can be a difficult geologic and imaging environment due to the diverse and repeated salt tectonic episodes that have resulted in complex allochthonous salt formation. Accurate salt body characterization and careful earth model building are key objectives for properly assessing the exploration potential of the area. Seismic methods alone, in part due to the inherent issues of ray path divergence at salt boundaries as well as with acquisition limitations, cannot always properly image the subsalt reflectors.

The inclusion of non-seismic data, such as magnetotelluric (MT), to augment seismic methods is not a new concept. Various 2D and 3D integrated inversion approaches have been discussed and published since the early 1990s. The power of a linked multi-domain approach has long been attractive and lies in the relational as well as the independent nature of the data. Independent in that the electromagnetic (EM) data are sampling a completely unique source, frequency and spectral bandwidth, while at the same time, attempting to resolve exactly the same object as the other data. And, although the EM data are inherently lower in resolution, when included as part of a 3D simultaneous joint inversion (SJI) workflow in combination with seismic or other data, their contribution is effectively enhanced. This proves to be very useful for improving earth models, particularly in complex salt provinces where the method can leverage the differences between salt and sediment resistivity as well as between seismic velocity and density.

The Walker Ridge 3D SJI project

In 2007 and 2008, WesternGeco acquired over two thousand marine MT receiver sites in the deep-water northern Gulf of Mexico. The goal was to use these data in conjunction with seismic data to improve the earth model (and, thereby, the final seismic image) in challenging salt-imaging areas. The measured electric and magnetic fields continuous time series were originally processed onboard the acquisition vessel with a remote reference approach (Egbert 2007) and then modeled using 3D MT blind inversions (Sanberg 2008).

In 2009, simultaneous joint inversion (De Stefano et al. 2011) pilot tests were performed over two blocks around the Walker Ridge Block 52 area encompassing the Shenandoah Lower-Tertiary discovery well. The results were very promising and a larger 1200-km$^2$ depth imagining project surrounding the same area (Figure 1) was planned and initiated in 2010.

![Figure 1](image-url) From left to right: Walker Ridge area in Gulf of Mexico; MT station location (red square) and blocks (yellow circles) considered in the project. In both pictures, the white square represents the 52 Blocks area boundaries and the black symbols on the right show the Shenandoah well position.

The objective of this new project was to refine the base of salt interpretation, validate theories on suspected salt feeder structures, improve subsalt imaging at the reservoir level, and to better understand the deep salt from a petroleum system standpoint.

Common image point (CIP) residuals were obtained through anisotropic migration of the 3D wide azimuth seismic data, using a velocity salt for sure (SFS) model (Figure 2). To build this model, two
main horizons were used: the interpreted top of salt and the SFS horizon, a layer interpreted as an intra-salt with a high level of reliability thanks to previous imaging efforts. Only the region between these two horizons was characterized by salt velocities. The salt was populated with a heterogeneous distribution of velocity (“dirty salt”) to account for possible sediments and inclusion within the salt bodies, causing relative acoustic impedance variation within the bodies themselves. To flatten the residual moveout on these data, a correct base of salt and subsalt velocity field are necessary.

A CIP tomography alone, due to the weakness of the signal below salt, would struggle to reconstruct such a model. However the magnetotelluric method, being sensitive to the conductive/resistive contrast between salt and sediment as well as to its full illumination capability, can help in accurately detecting the position of conductive sediments below resistive formations.

SJI will compensate for this lack of seismic signal, feeding the inversion with the MT data and simultaneously updating the velocity and resistivity models to fit the MT impedance tensor components as well as flattening the CIP residuals. In this project, 485 marine MT stations, covering an area of approximately 3300 km$^2$, were inverted. The complete resistivity model covered an area of more than 100000 km$^2$, while the velocity model covered an area of approximately 4500 km$^2$.

**Figure 2** Tomography starting velocity model: Heterogeneous velocity in the salt for sure bodies.

**Simultaneous joint inversion: the workflow**

As an initial step of the SJI workflow, several single-domain inversions were performed to investigate the capabilities of the measurements involved and to find the optimal parameter set for each of them. In particular, for the MT methodology, the most appropriate starting model and inversion penalization scheme were investigated. The starting MT resistivity model distribution was built resampling the finely gridded 3D velocity model into a mesh of adequate dimensions to solve the MT forward and inverse problem. The data sensitivity and the inversion reliability were assessed by testing different resistivity starting models. As shown in Figure 3, the difference between the models consists of the amount of seismic a-priori information injected. From a simple salt flood model, where all the cells below the top of salt horizons were “flooded” with high resistivity values associated with salt, to more complex salt models where the salt body geometries from previous seismic imaging were used. Different minimization schemes were also tested in combination with the starting model tests. From a simple scheme searching for the smoothest variations within the output model or with respect to a reference model, to a constrained approach where the same salt-for-sure region excluded from the inversion domain in the acoustic domain was softly locked, i.e. resistivity variations were more penalized in the inversion process. The integration of the methods is beneficial for both domains. MT data compensates for the lack of seismic illumination, while seismic data mitigates uncertainty and the low-pass effect of deep water on high frequency MT data.
In addition to the data misfit, the SJI framework minimizes a relation linking the subsurface properties where such a relation can express a petrophysical or structural constraint.

In this case, the relationship between the resistivity and velocity models was a petrophysical one, varying with the different lithologies. For subsalt sediments, an empirical relationship was inferred from sonic and resistivity logs in the core area. For the region covering approximately the zone from the SFS horizon to the legacy interpretation of the salt base, the relationship was derived from single-domain inversion results.

![Integration strategy followed in resistivity model building](image)

**Figure 3** Integration strategy followed in resistivity model building: starting from a simple salt-flood model (Resistivity model 1), where all the cells below the top of salt are filled with salt resistivity value, to more complex salt models where available seismic horizons (Resistivity model 2) are used to define shallow details and the salt for sure base (Resistivity model 3) defines the soft locked cells. The resistivity models are co-rendered to benchmark RTM seismic.

**Results**

Once the three streams were parameterized, they were jointly inverted, thereby providing a multiproperty earth model, fitting MT data, flattening residual moveouts, and following the empirical relationship between resistivity and velocity. These output models were used to reinterpret the base of salt and deep feeders between the allochthonous salt bodies and the deeper autochthonous salt (Figure 4). Finally, a reverse time migration was carried out using the updated velocity model based on the new interpretation from the SJI output.
Figure 4 3D Simultaneous joint inversion input (on the left) and output (on the right) resistivity model along two lines co-rendered with benchmark RTM seismic cube. Pink horizons on the right sections are the salt body geometry from the previous seismic imagining, while the blue horizons came from the post-SJI interpretation.

Conclusions

By rigorously integrating wide azimuth (WAZ) seismic technology, simultaneous joint inversion of reflection seismic and magnetotelluric data, careful earth model interpretation, “dirty salt” velocity compensation, and RTM migration, a clearer picture of the salt and subsalt structures has emerged (Figure 5). In addition, the work has helped to confirm earlier theories as to the nature and extent of several deep autochthonous salt feeders, as well as to better explain the overall salt tectonic development in the area. This new understanding of the salt geometry is essential in mitigating the exploration risk in complex deep water areas.

Figure 5 Comparison between benchmark RTM and post-SJI RTM; the red circle underlines the main improvement in the post-SJI RTM.

References

