Simultaneous joint inversion of 3D seismic and magnetotelluric data from the Walker Ridge

Elena Medina,1* Andrea Lovatini,1 Federico Golfrè Andreasi,1 Simone Re1 and Fred Snyder1 present a case history from the Gulf of Mexico of multi-dimensional simultaneous joint inversion of wide-azimuth 3D seismic and marine magnetotelluric data to improve subsalt imaging.

Several deepwater areas of the Gulf of Mexico represent difficult geological imaging environments due to diverse and repeated salt tectonic episodes that have resulted in the formation of complex allochthonous salt bodies. Building reliable earth models is essential for properly assessing exploration potential, and in such areas this must include accurate characterization of the salt bodies. However, seismic methods alone cannot always properly image subsalt reflectors, in part due to inherent issues of ray-path divergence at salt boundaries, and limitations in achieving feasible and cost-effective acquisition geometries that will properly illuminate these boundaries.

Non-seismic information such as magnetotelluric (MT) data can be used to augment seismic imaging workflows. This is an electromagnetic (EM) method used to map the spatial variation of the Earth’s subsurface resistivity by measuring naturally occurring electric and magnetic fields at the surface. The measurements are used to determine specific ratios of electric to magnetic field. The MT method can probe to depths of several tens of kilometres; however, the spatial resolution of MT surveys is limited by the diffusive nature of EM propagation, and is usually in the order of hundreds of metres to kilometres.

The inclusion of MT data in seismic imaging projects 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 different data types. They are independent in that the 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 seismic 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. This article describes a project that applied simultaneous joint inversion of wide-azimuth (WAZ) 3D seismic and marine MT data to improve subsalt imaging in an area of complex geology in the deepwater Gulf of Mexico.

Walker Ridge 3D SJI project

During 2007, WesternGeco acquired the E-Octopus Phase-II multi-client 3D WAZ seismic survey in the deepwater Gulf of Mexico. Processing – including multi-azimuth sediment tomography incorporating anisotropy and sub-salt tomography using angle gathers – was completed in 2008. The survey includes areas of the Keathley Canyon, Walker Ridge, and Green Canyon. Water depths range between approximately 1150 and 2000 m, giving seabed two-way travel times of 1600 to 3000 ms. The geology is characterized by extensive salt sheets with intervening deepwater sediment-filled mini-basins. The salt canopy is characterized by simple to complex salt features, some of which have thicknesses up to 9000 m and some that are extremely shallow, i.e., just under the water bottom.

During 2007 and 2008, WesternGeco acquired marine MT data at more than 2000 receiver sites in the deepwater, 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 continuous time series of the electric and magnetic fields were originally processed onboard the acquisition vessel with a remote reference approach (Egbert, 2007) and then modelled using 3D MT blind inversions (Sanberg, 2008).

In 2009, simultaneous joint inversion pilot tests (De Stefano et al., 2011) were performed using E-Octopus wide-azimuth seismic and marine MT data. The tests focused on an area of the Walker Ridge covering two blocks that encompass the Shenandoah Lower-Tertiary discovery well. The results were very promising and a larger 52 block (1200 km²) depth imaging project was planned and initiated in 2010 that encompassed an expanded area around the well (Figure 1). The objectives of the new project included the refinement of the base-of-salt interpretation, validation of theories on suspected salt feeder structures, improving subsalt imaging at the reservoir level, and better understanding of the deep salt from a petroleum system standpoint.

1 WesternGeco.
* Corresponding author, E-mail: emedina8@slb.com
Flattening the residual moveout on the CIP data would indicate the construction of a correct base-of-salt and subsalt velocity field. Due to the weakness of the signal below the salt, a CIP tomography approach by itself would struggle to construct such a model. However, adding information from the MT method was expected to help determine the position of the salt/sediment boundary, as it is sensitive to the resistivity contrast between resistive salt and conductive sediment, and also has full illumination capability. Simultaneous joint inversion (SJI) with MT data can compensate for a lack of seismic signal through 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 km², were inverted. The complete resistivity model covered an area of more than 100,000 km², while the velocity model covered an area of approximately 4500 km². Prior to the inversion, soundings were subject to data editing – carefully muting poor data quality points to be removed from the inversion while preserving spectral data coverage. The processed MT data covered a two-decade range from 0.001 Hz to 0.01 Hz for the majority of sites.

Simultaneous joint inversion workflow
The SJI workflow applied is summarized in Figure 3. As an initial step, several single-domain inversions were performed to investigate the capabilities of the measurements involved and determine 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 by resampling the finely-gridded 3D velocity model into a mesh of adequate dimensions to solve the MT forward and inverse problem. Data sensitivity and inversion reliability were assessed by testing different resistivity starting models. These models differed though having different levels of seismic a-priori information injected, as shown in Figure 4. They ranged from a simple salt-flood model in which all the cells below the top-of-salt horizons were

Common image point (CIP) residuals were obtained through anisotropic migration of the 3D wide-azimuth seismic data using a ‘salt-for-sure’ starting velocity model (Figure 2). Two main horizons were used to build this model: the interpreted top of salt and the salt-for-sure horizon, a layer interpreted as an intra-salt reflector with a high level of reliability based on previous imaging efforts. Only the region between these two horizons was characterized by salt velocities.

The usual assumption that salt bodies are one homogenous constituent with a constant velocity has in the past simplified the process of model building. However, it is not uncommon to find that a large salt mass consists of one or more smaller discrete bodies sutured together and exhibiting reflections at the suture boundaries. In addition, there are known situations where salt and sediment mix together. The presence of such embedded sediments results in a ‘dirty salt’ complication in many salt bodies. In the subject study area, indications of widespread isolated bright sediment inclusions have been observed in the seismic data. To incorporate this heterogeneity into the model, the salt was populated with a heterogeneous distribution of velocity (dirty salt) to account for possible sediments and inclusions, leading to relative acoustic impedance variation within the bodies themselves.
given high resistivity values associated with salt, through to more complex salt models where salt body geometries based on 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, through 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 filtering 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 salt-for-sure horizon to the legacy interpretation of the salt base, the relationship was derived from single-domain inversion results.

**Results**

Once the three streams were parameterized, they were jointly inverted, providing a multi-property earth model fitting the 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 5). Finally, a reverse time migration was performed using the updated velocity model based on the new interpretation from the SJI output.

The workflow applied in this project delivered a clearer image of the salt and subsalt structures (Figure 6) through rigorously integrating WAZ seismic technology, SJI of reflection seismic and MT data, careful earth model interpretation, dirty salt velocity compensation, and reverse time migration (RTM).

In addition, the work helped to confirm earlier theories as

---

**Figure 4** Integration strategy followed in resistivity model building. Model 1: simple salt-flood where all cells below top-salt are filled with salt resistivity value; Model 2: using available seismic horizons to define shallow details; Model 3: using the salt-for-sure base to define soft locked cells. The resistivity models are co-rendered with benchmark RTM seismic data.

**Figure 5** 3D Simultaneous joint inversion input (left) and output (right) resistivity model along two lines co-rendered with benchmark RTM seismic data. Pink horizons in the right sections are the salt body geometry from the previous seismic imaging. Blue horizons are from the post-SJI interpretation.
to the nature and extent of several deep autochthonous salt feeders, as well as provide a better understanding of the overall salt tectonic development in the area. Improving the understanding of salt geometries is essential in mitigating exploration risk in deepwater areas with complex geology such as the Gulf of Mexico. Integrated SJI workflows using multiple geophysical data types provide a valuable tool for reducing risk, particularly in high cost drilling environments.

**References**

