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Integrated Interpretation and Simultaneous Joint Inversion of 3D Marine CSEM and Seismic Datasets

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SUMMARY

One of the most complex seismic challenges is the imaging of thick salt bodies, the detection of their base and flanks, and imaging underlying units. To achieve good seismic imaging, the complementary use of non-seismic methods is one of the recommended solutions. Electromagnetic (EM) methods, such as magnetotellurics (MT) and controlled source electromagnetics (CSEM) are sensitive to the presence of salt bodies thanks to the high resistivity contrast with respect to sedimentary units. We present an integrated workflow applied to re-image wide azimuth (WAZ) seismic data acquired by Schlumberger using EM data acquired by EMGS over 35 blocks in the Keathley Canyon, in the Gulf of Mexico to reduce risk in exploration decisions and improve seismic deliverables. Seismic and EM data are utilized first in a cooperative workflow through localized seismic imaging reverse time migration (LSI RTM) to validate new salt structures highlighted by the single domain 3D anisotropic CSEM and MT inversions. They are then fed into a simultaneous joint inversion (SJI) to update a multi-property earth model (velocity and resistivity) by jointly minimizing the CSEM data misfit, the seismic residual move-outs and a relationship between the two properties.

Key words: SJI, WAZ, MT, CSEM, Integrated interpretation.

INTRODUCTION

Salt provinces have proven to be very fruitful for hydrocarbon exploration, very effective petroleum systems, for both post and pre-salt prospects in several areas worldwide (e.g. Gulf of Mexico, Brazil, Red Sea). In particular, deep-water prospects below the salt in the Gulf of Mexico (GoM) are nowadays conventional targets for exploration. Nevertheless there are still many challenges associated with reducing drilling risks, one of the most critical is having a good subsurface seismic image to start with.

In salt environments, the seismic wave propagation may be characterized by several problems that eventually could affect the imaging quality, such as scattering, internal multiples, mode conversions, poor penetration, attenuation. Essential basis to mitigate such problems is the acquisition of seismic data rich in offsets and azimuths to provide the best illumination and the largest nominal coverage in terms of seismic signal. However, in areas where the salt structures are extremely complex, the seismic signal to noise ratio (SNR) may still be limited and therefore complicate the estimation of the velocity field variations that could be used to correctly migrate the seismic data and recover a good image. Additional geophysical measurements can provide complementary information to constrain and estimate the salt geometry and thus improve the seismic imaging through an enhanced velocity model. Controlled Source Electromagnetic (CSEM) and Magnetotelluric (MT) data in particular can provide information on the resistivity contrast expected between resistive salt and conductive sediments **.**

METHOD AND RESULTS

The EM survey was acquired over a 3 month period from 2012 to January 2013. The survey consists of 372 EM receiver nodes in a 1.5 by 1.5 km grid (
Figure **1**) acquiring CSEM and MT data. The survey layout was optimized to provide significant azimuthal data coverage in order to image both horizontal and vertical resistivity contrasts. The broad frequency spectrum of the active source waveform was designed to generate a dataset with high resolution in a structurally complicated salt environment. In addition, the waveform contained lower frequencies to ensure overlap between the CSEM and the MT response extracted from the same dataset.

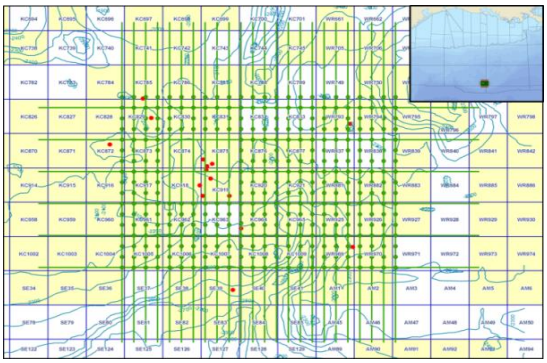

Figure 1: Survey layout for the EM acquisition (location of the survey areas in the GoM on the top right image).

The CSEM data underwent a multi-frequency 3D anisotropic inversion inverting all the available inline and offline data with different starting models to infer all the independent information on the allochthonous salt geometry from the output anisotropic resistivity models. The models showed in general a high degree of geological consistency with respect to the seismic image for what concerns the salt structures, although inverted independently and without constraints. The CSEM models were interpreted, together with the resistivity model obtained from the 3D MT inversion that provided deeper autochthonous salt structures information thanks to the lower frequency content. Interestingly often in zones where the legacy seismic image did present quality deterioration issues, especially pre-salt, the new EM driven interpretation highlighted the major differences with the previous interpretation of the salt structures. The new interpretation was initially validated from a geologic standpoint using a structural sequential back stripping and restoration process and subsequently testing the corresponding velocity model through LSI RTM. The full integrated workflow is reported in Figure 2.

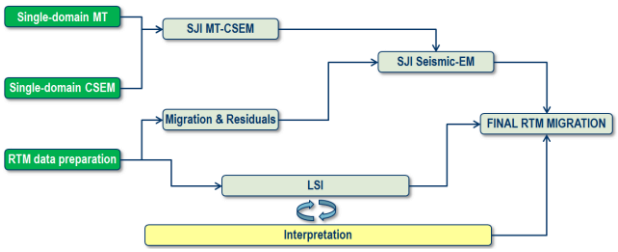

Figure 2: Diagram of the integrated seismic-EM imaging workflow of the Sunshine project

All 300+ EM receivers passed through a quality control phase: all CSEM and MT soundings were edited, muting noisy points and removing outliers. The lateral consistency of the MT dataset was assessed using pseudo-sections and constant-period maps; similarly, the CSEM dataset was checked by the means of pseudo-sections and common-offset at selected frequencies. The scope of this qualitative data imaging process was twofold:

- check mutual consistency of the datasets;
- check the information contained in the processed data prior the inversion;

In order to verify the information contained in the data before passing it to the inversion process, pseudo-sections and maps were compared with existing geological information, such as seismic sections and the interpreted seismic horizons obtained from the WAZ dataset, looking for similarities. The comparison of the EM maps with the interpretation carried out from the seismic showed a good match between the interpreted salt top and the amplitude/phase variations of the EM data, proving that the method is sensitive to the geological structures (Figure 3). The comparison also showed that in some areas the EM information was slightly different from the seismic one, suggesting that the non-seismic information could lead to a different seismic interpretation.

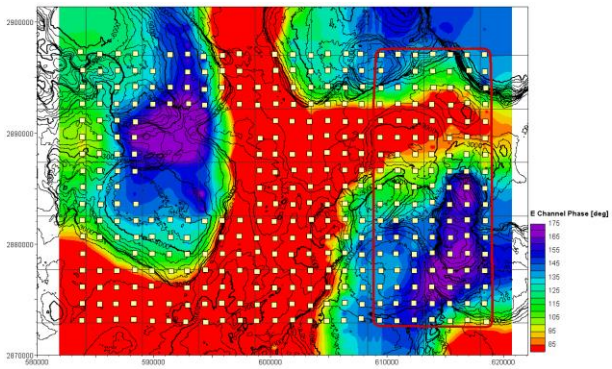

Figure 3: Electric field Phase Common Offset Map of inline data, extracted at 5km, 0.24Hz (grid), with elevation contour lines of the interpreted Top of Salt. The yellow squares are EM receivers, the magenta rectangle highlights the area were SJI was performed.

MT and CSEM data were modeled first in single domain, then in a multi-domain fashion through Simultaneous Joint Inversion. The first step needed to understand the level of information that could be extracted from the single dataset, which followed a different approach for the two methods. The MT data was inverted in a unique model, starting from a "salt-flood" resistivity model, using the interpreted Top of Salt. The background resistivity values were determined via 1D MT inversion: the results of smooth inversion for all the MT soundings, properly up-scaled and filtered, led to the background model that was used to populate the 3D model grid. The same resistivity distribution was adopted as background horizontal resistivity model for the CSEM 3D anisotropic inversion. The values of the vertical resistivity were determined through 1D CSEM anisotropic inversion, as well as 2.5D/3D CSEM anisotropic forward modeling. Differently from the MT data, the CSEM dataset was inverted without any a priori information on the salt geometry ("sediment-flood" approach). The reason of the two different modeling approaches is related to the different resolution and depth of investigation of the two methods. The MT data is characterized by a lower resolution with respect to the CSEM, both vertically and horizontally. Moreover, the thick conductive water column (~2000m) acted as a filter for the MT signal, depleting the richness of the signal content for frequencies above 0.1Hz, limiting the data control at shallow depth. On the other hand, the long recording time (3+ weeks) allowed acquiring low frequency data of good quality for most of the receivers. The scope of the MT inversion was then to determine information regarding the base of the allochthonous salt and on the deep structure (autochthonous salt/basement?), providing to the starting model the information regarding the shallow sub-surface. The CSEM data, instead, had a very high data coverage thanks to amount of transmitters/receiver pairs and to the broad signal transmitted (from 0.08 to 2.96Hz). The CSEM data showed a good response to shallow and thin features; the downside of CSEM data was the limited depth of penetration with respect to the MT data, hence the modeling approach was studied to obtain from the CSEM data the structure of the allochthonous salt, starting with no a priori information in the resistivity model. At first, the CSEM inversion was focused on 10 out of the 35 blocks, while the MT data was inverted over the entire survey area right from the beginning.

The Full Impedance tensor was inverted for all the MT sites, including frequencies from 0.1Hz to 0.001Hz, with up to 7

frequencies per decade. The Electric field of both inline and broadside data was inverted for the CSEM data, including 6 out of 10 available frequencies and considering around 3000 transmitters/receivers pairs over the whole 35 blocks.

The results obtained by the EM methods were good; the comparison of the resistivity models with the velocity model used to migrate the seismic volume showed a good correlation between the salt bodies identified by the seismic data and the high-resistivity zones in the EM models, even at shallow depths. In addition, the sediments below the allochthonous salt were quite well imaged, as were the deep structures (Figure 4). Moreover, the available well log data were consistent with the output models.

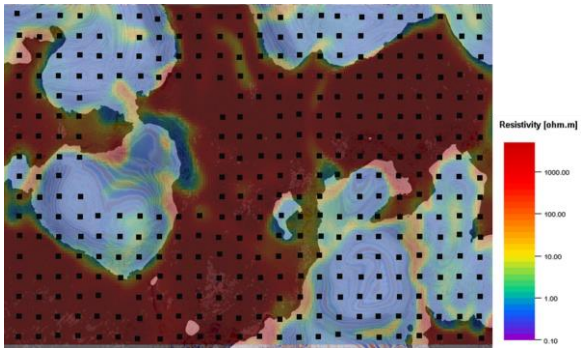

Figure 4: Seismic slice at –3,600 m above sea level co-rendered with final resistivity model (colours) and with the legacy velocity model over 35 blocks (grey shade). The black squares are the EM receivers. The resistivity anomalies are matching also small salt features

The results of the CSEM modeling highlighted areas were the velocity model and the resistivity structure were not consistent. In the zones where the discrepancy was also associated to a bad seismic image of the presalt layers, the velocity model was tested using localized seismic imaging (LSI) against a new scenario, interpreted using the EM model as a guide. As a first step, the current salt body in the areas of mismatch was checked and validated by a structural geology point of view; using a structural restoration approach, the nearby faults, caused by the displacement of the salt, were reactivated, back stripping in time the current interpretation. In case of an obvious problem in terms of mass balance, the interpretation was adjusted and cross-checked using the resistivity image as a guide to pick the salt body. To evaluate the new EM-driven interpretation, the adjusted velocity model was used as input for LSI RTM (Figure 5).

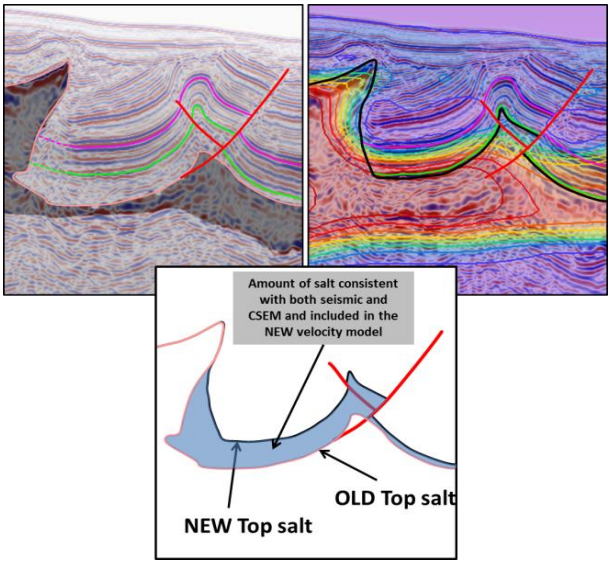

Figure 5: Example of interpretation revision guided by the CSEM results and validated through a structural restoration process. On the top left legacy velocity model and seismic image, on the right CSEM inversion output resistivity model and the derived new interpretation, on the bottom old and new salt top interpretation comparison

The final step of the workflow consisted of the Simultaneous Joint Inversion of seismic data with EM data. The two domains were inverted jointly, considering a geometrical link between the velocity model and the resistivity model. Due to time constraints, only a third of the full seismic volume passed through SJI. Using a RTM algorithm, the updated velocity model was used to migrate the seismic volume, which obtained the final stack. The comparison of legacy and post-SJI stacks showed a clear improvement in the presalt sections. In particular, the lateral continuity and flatness of the layers, the signal intensity, and the trend of the deep structures showed a clear benefit from the various steps of the workflow (Figure 6).

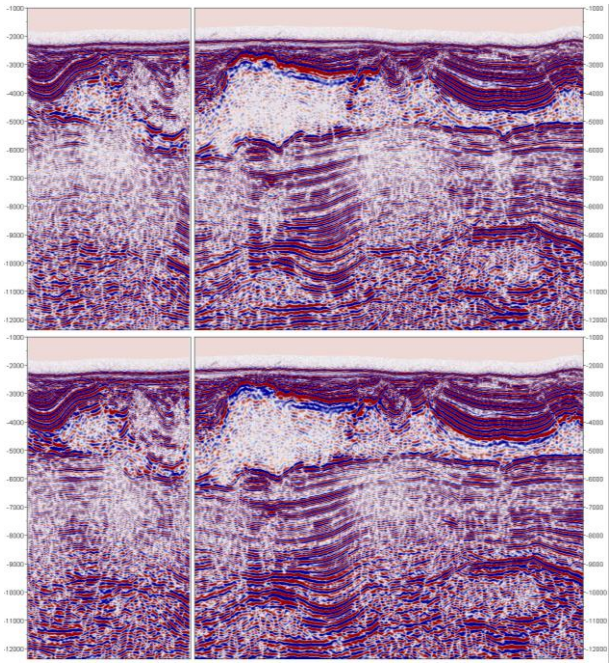

Figure 6: Legacy (top) and post-SJI (bottom) stack along a E-W and N-S line

CONCLUSIONS

In cases of complex geological assets, the use of seismic data alone may not solve imaging problems arising from the intrinsic limitations of the method. The use of non-seismic methods such as MT and CSEM can help overcome these issues, providing the missing information needed. A comprehensive workflow, integrating seismic and non-seismic data in different steps and combinations was presented, increasing the level of complexity at each step. Using LSI during intermediate steps allowed us to always cross-check the use of non-seismic measurements against seismic imaging. The positive result of obtaining better seismic data after all the steps, including SJI, is a good indicator of the quality of the proposed workflow.

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