Joint inversion of marine MT and seismic traveltime data using a 'structure'-based approach

Andrea Zerilli*, Schlumberger BRGC, Marco Polo Buonora, Petrobras E&P/GEOF/MNS, Tiziano Labruzzo, Schlumberger BRGC.

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Abstract

We present a 'structure'-based approach for the joint inversion of marine Magnetotelluric (MT) and seismic traveltime data which uses *a priori* information on the geometry to reduce the number of unknowns and improve the resolution of the reconstructed velocity and resistivity images. The 'structure'-based inversion can be used to refine the smooth model obtained using an 'image'-based approach. The regions of interest expressed as both surfaces and bodies defined by their vertices (nodes) are reconstructed along with their locations, velocities and resistivities. Only the data that contribute to the image in that local area are used in the process.

The 'structure'-based inversion adopts the multiplicative regularized Gauss-Newton method.

We show the advantages and drawbacks using synthetic data.

Introduction

Seismic depth imaging has been widely used as the main tool for hydrocarbon exploration because of the high resolution that one can obtain. However, in challenging geologies (such as subsalt, sub-basalts, sub-carbonates) seismic imaging is generally poor and may end up with wrong or inconsistent models. A potential approach to depth imaging enhancement and improved reservoir characterization is to perform collocated seismic and electromagnetic (EM) acquisition. EM fields easily penetrate through resistive (generally high velocity) 'barriers' such as salt, basalts and carbonates. Moreover, resistivity changes are largely caused by the displacement of resistive hydrocarbons by far less resistive salt water, and not by pressure changes.

The results from collocated seismic and EM acquisition are typically presented as separately constrained model or cooperatively reconstructed images of the subsurface. Due to complex geology and model non-uniqueness, it is not uncommon to find significant differences between the separately or cooperatively reconstructed interpretations. Much of the discrepancies faced by the standalone models may be significantly reduced using an appropriately coupled or joint inversion of the seismic and EM data sets. MT has been introduced in the offshore exploration to de-risk difficult seismic where high-impedance salt, volcanic or carbonate barriers are present, living up to the early expectations.

The 'structure'-based joint inversion approach

MT data can facilitate the task of velocity model building through implementation of a joint inversion of the seismic and MT domains where the seismic imaging conditions are taken and built in the joint inversion scheme. This is expected to produce better-migrated seismic in depth (generated by more reliable velocity fields) and seismic-scale resolution resistivity distribution.

Joint inversion of seismic and EM data can be classified into two categories. The first category is based on the link between resistivity (or conductivity) and seismic velocity through petrophysical relationships (e.g., fluid saturation, porosity, etc.) (i.e. see: Hoversten et al., 2006). The second category utilizes the structural similarity between resistivities and velocities of the targeted regions (i.e. see: Gallardo and Meju, 2007, Colombo and De Stefano, 2007). Recently, De Stefano et al. (2011) extended this approach for joint seismic, MT and gravity data in the marine environment for complex subsalt imaging. In the above approaches the inversion domain is subdivided into cells and by using an inversion method of choice, the properties distribution inside the domain is reconstructed. These cells-based inversions have shown to be able to retrieve reasonably good images. However, the reconstructed boundaries and velocities, resistivities of the imaged targets are often quantitatively poorly focused.

In our approach, the inversion domain is represented by surfaces and geobodies. This workflow quantitatively reconstructs the velocities, resistivities and shapes of regions of interest guided not only by the data but also by geological consistency preventing smoothing across them. Here, the shape of the various regions expressed as 'geobodies' defined by their vertices (nodes) are reconstructed along with their locations, velocities and resistivities. Although only seismic and MT data are simultaneously inverted in this work, incorporation of other data type (e.g. potential fields, Controlled Source EM) has been implemented and extended to 3D.

'*Gan*' synthetic data inversion

Here, we present the inversion results of the *Gan* synthetic data set. The *Gan* synthetic data is one of a series of modeled traveltime seismic-MT sets that were chosen as the most suitable to provide the 'best' case for the development of this joint inversion technology. The *Gan* long offset seismic an MT data line is collocated with an existing long streamer seismic line with 55 ocean bottom collocated seismic and MT receivers at 1 km spacing in the *Espirito Santo* ultra-deep water area, offshore Brazil (Figure 1).

P-wave velocity and resistivity/depth models were constructed that simulate a complex geologic cross-section across *Gan* (Figures 2 and 3). The model incorporates three main allochthonous salt bodies. The salt bodies are characterized by rugose top and base, steeply dipping flank walls, deep base and an Early Tertiary complex minibasin (salt B_G) that make imaging of standalone seismic and MT data challenging. Especially deeper parts of the salt flanks below the base Oligocene pose a high uncertainty in the interpreted base of salt requiring advanced depth migration such as prestack or VTI/TTI RTM. Wide aperture seismic traveltimes tomography may provide a preliminary velocity model appropriate for advanced depth migration in this complex setting because refracted or turning first arrival energy is generally present and usually strong. MT can further improve salt base definition because of the very high resistivity contrast between salt and the sediments around and below.

Synthetic MT data were computed at 18 frequencies from 0.0002 to 0.1 Hz. The ultra-deep conductive seawater along the line (~-2100 meters) has an attenuating effect on the incident MT source fields and acts as a low-pass filter limiting to 0.1 Hz the highest frequency measurable on the seafloor. Synthetic seismic traveltimes data were computed using a shortest path method as described by Vsermirnova (2004). 330 sources placed along the line at sea surface were fired at 200 meters spacing. The collocated receivers are indicated in Figures 2-3 by black triangles. The model provided from the seismic/geological interpretation is entered as surfaces and bodies. A common computational mesh is automatically generated from such specified parameters as: receiver and source locations, velocities (and velocity contrasts), resistivities (and resistivity contrasts) of the model. The synthetic seismic wide aperture and MT data sets with added three-percent white noise computed from this model were used in the inversion.

For the inversion, we choose a sub-domain that focuses on the salt body labeled B_G (Figures 2-3) located at a depth of approximately -2300 meters b.s.l. (-200 meters b.m.l.) with lateral extent of approximately 11 km. Interpreted salt base is at approximately -4600 meters b.s.l. (-2500 meters b.m.l.), salt velocity and resistivity are 4500 m/s and 400 Ohm-m, respectively. The initial models used in the inversions are shown in Figures 4 and 5. Top of salt, flanks geometry and background velocities and resistivities were considered *as prior* and held fixed during the inversion process. The initial B_G salt body velocity was set at 4000 m/s while initial resistivity was set at 80 Ohm-m and allowed to vary during the inversion process. Also the base of salt within the mesh bounded by the (blue-white) box (Figures 4-5) was set shallower by approximately 400 meters and allowed to vary. Figure 6 shows the standalone seismic inversion results after 10 iterations. We observe that the P-wave velocity of the salt body is well resolved (4500 m/s). However the base of salt is not recovered. This result is consistent with the observation that first arrival traveltimes are sensitive to high velocity zones but suffer from severe limitations when low velocity zones are overlain by higher velocity sequences. Figure 7 shows the inversion results for the standalone MT data. We observe that the resistivity of the BG salt body is recovered at 320 Ohm-m while the base of salt is overestimated at approximately -4800 meters b.s.l. after 10 iterations. Frequencies > 0.1 to ~ 3-5 Hz are needed to stabilize the inversion and enhance sensitivity to the salt base/sediment interface. Next, we simultaneously invert the seismic data with the MT set. The joint seismic-MT inversion results are shown in Figures 8 and 9. In these figures, we observe that the velocity and resistivity of the B_G salt body (velocity at 4500 m/s, resistivity at 400 Ohm-m) and base of salt (~ -4600 meters b.s.l.) are properly reconstructed with a significantly less number of iterations (5).

The results of the simultaneous 'structure'-based joint inversion demonstrate that significant improvement is achieved in terms of resolution, reduced ambiguity as well as a far better reconstruction of locations, velocities and resistivities of the region of interest.

Acknowledgments

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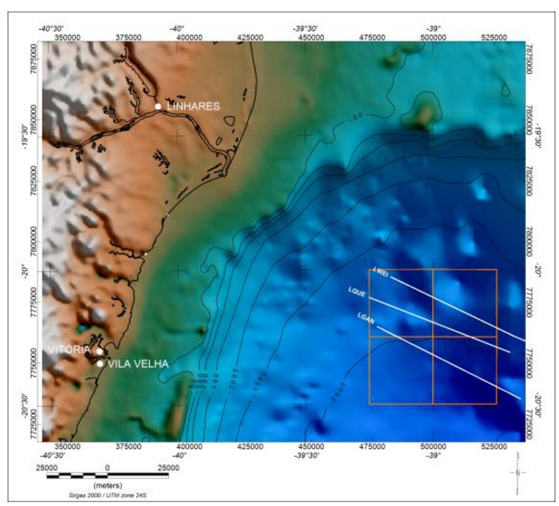

Figure 1. Espirito Santo collocated seismic-MT survey layout

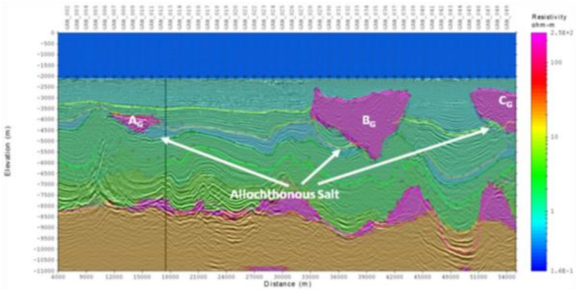

Figure 2. ***Gan*** – Horizontal resistivity model with superimposed Seismic Depth Image. Black triangles correspond to collocated seismic-MT receiver positions**.**

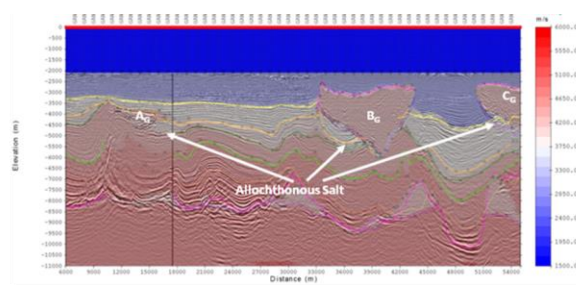

Figure 3. ***Gan*** – P-wave velocity model with superimposed Seismic Depth Image. Seismic source positions at sea surface. Source spacing 200 m.

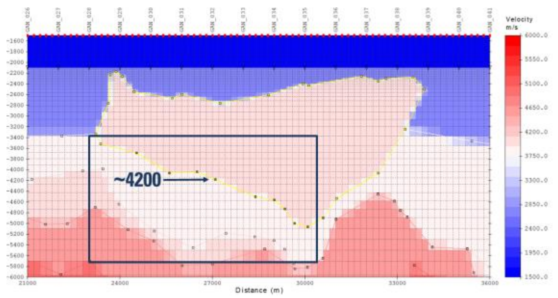

Figure 4. ***Gan*** – salt body B_G inversion sub-domain. Initial P-Wave velocity (4000 m/s). Base of salt set shallower by approximately 400 meters and allowed to vary within the blue box.

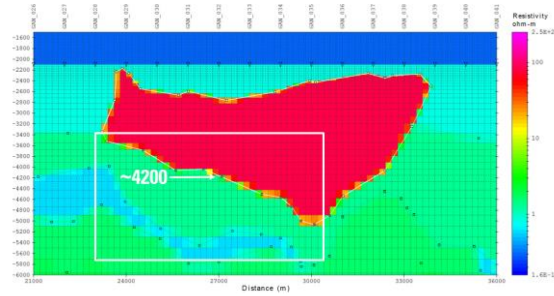

Figure 5. ***Gan*** – salt body B_G inversion sub-domain. Initial Horizontal resistivity (80 Ohm-m). Base of salt set shallower by approximately 400 meters and allowed to vary within the white box.

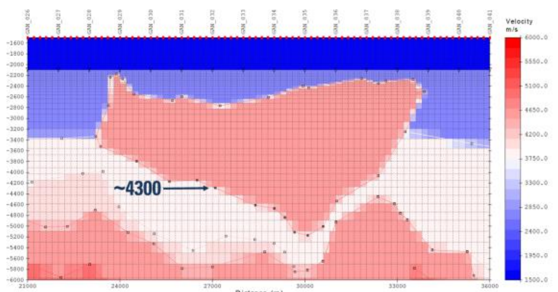

Figure 6. ***Gan*** – salt body B_G inversion sub-domain. Standalone seismic inversion. P-Wave velocity well resolved (4500 m/s). Base of salt unresolved.

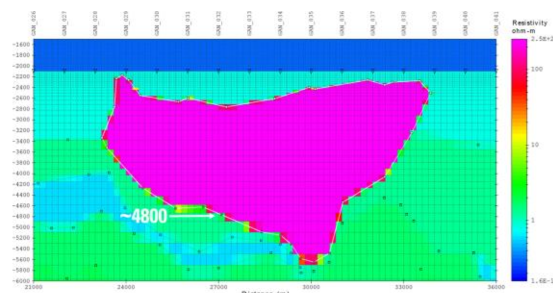

Figure 7. ***Gan*** – salt body B_G inversion sub-domain. Standalone MT inversion. Horizontal resistivity recovered at 320 Ohm-m, base of salt overestimated at approximately -4800 meters b.s.l.

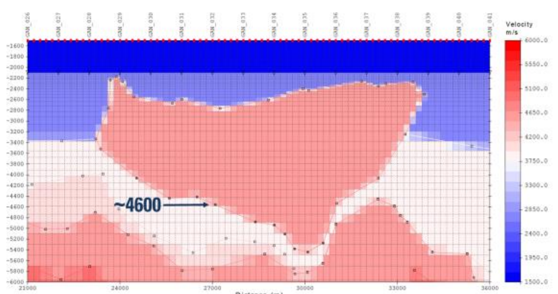

Figure 8. ***Gan*** – salt body B_G inversion sub-domain. Joint seismic**-**MT inversion. P-Wave velocity well resolved (4500 m/s), base of salt accurately reconstructed.

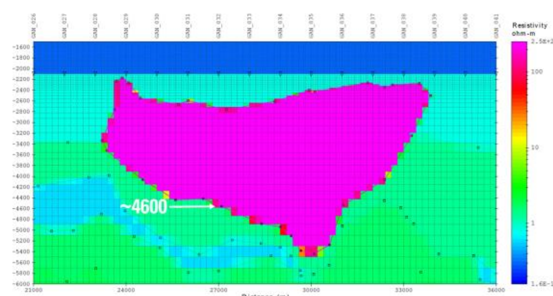

Figure 9. ***Gan*** – salt body B_G inversion sub-domain. Joint seismic-MT inversion. Horizontal resistivity well resolved (400 Ohm-m), base of salt accurately reconstructed.