Multiple joint inversion of seismic, magnetotelluric and potential field data in Santos basin

Luis A. Gallardo, The University of Western Australia, Crawley, Australia
Sergio L. Fontes, Observatorio Nacional-MCT, Rio de Janeiro, Brazil
Max Meju, Petronas, Kuala Lumpur - Malaysia
Patricia de Lugao, Strataimage Ltda, Rio de Janeiro, Brazil
Vinicius R. Pinto, Observatorio Nacional-MCT, Rio de Janeiro, Brazil

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Abstract

Accurate mapping of subterranean fluid reservoirs and their confining structures may strongly benefit from a multi-geophysical surveying approach and an integrated interpretation of the survey data. Seismic reflection, gravity, magnetic and electromagnetic methods are deployed in routine marine exploration for hydrocarbons. However, multidimensional joint inversion of seismic reflection, marine EM and potential field data is still not common, and remains a very relevant task. We have applied the cross-gradient inversion method to data sets acquired over a petroliferous region in Santos basin of southeast Brazil. The main exploration targets are the top of the fractured Precambrian crystalline basement and any concealed basement grabens, the overlying Pre-salt sediments and the salt/carbonate deposits. The results of joint inversion represent a significant improvement over models derived from separate 2D seismic reflection processing, 2D magnetotelluric imaging as well as potential field models. Basement structures and those of the overlying formations are well defined. We suggest that joint inversion is the way forward for prospect mapping.

Introduction

Offshore seismic reflection, MT, gravity and magnetic measurements are made at different spatial scales. Such multi-dimensional, multi-spectral and often incomplete heterogeneous data sets are used to infer the structure and physical state of subsurface targets. In many cases, detecting and monitoring the presence or movement of fluids within such systems from multi-modal signal sensing and imaging are a primary objective for several reasons, and require accurate knowledge of the structure holding or confining the fluids. In the case of Santos basin in southeast Brazil, accurate characterisation of the Precambrian crystalline basement heterogeneity and overlying pre-Salt sediments were of crucial importance for prospect evaluation. Seismic reflection, MT, gravity and magnetic data are available for this basin for three parallel survey lines across the Mexilhão Gas Field. There are limitations in the way that these data from the two-dimensional (2D) imaging surveys were interpreted, and a unique non-invasive definition of subsurface structure has so far remained a difficult and uncertain proposition. The previous seismic reflection image did not convincingly map the top of the basement especially landward and recent MT interpretations (Fontes *et al.*, 2009, de Lugão et al. 2008) detected grabens in the basement below the resistive salt layer. The carbonate deposits and clastic sediments above the salt layer were not resolved by the MT imaging. The research question is whether an integrated interpretation of the available seismic, MT, gravity and magnetic data may lead to an improved understanding of the subsurface structure.

Intensity and directional gradients in the subsurface hold the key to effective coupling of uncorrelated as well as correlated physical models of the subsurface (Gallardo and Meju, 2010). The mathematical concept of gradients-based data combination in multi-physical imaging was introduced in 2003 (Gallardo and Meju, 2003) and is now finding rapid acceptance in several fields of geophysical, geological, hydrological, biogeophysical and medical imaging. Notably, this concept has permitted the fusion or joint inversion of seismic and electromagnetic data, medical images, biogeophysical and hydrogeophysical data, among others, which have hitherto been considered disparate information or impossible to fuse (Gallardo and Meju, 2007, Haber and Modersitzki, 2007, Linde *et al.*, 2006, Linde *et al.*, 2008, Tryggvason and Linde, 2006, Hu *et al.*, 2009, Fregoso and Gallardo, 2009). The method has also been extended to a generalized 2D joint geophysical image reconstruction of multiple data sets (Gallardo, 2007). We have applied this generalised 2D cross-gradient algorithm in our present study to jointly invert the available MT, seismic reflection, gravity and magnetic data.

Geophysical Data Analysis

The process started by analyzing and selecting the relevant geophysical data that were available to ensure their suitability for the joint inversion experiments and to design a common model grid in terms of horizontal and vertical coverage.

Gravity and Magnetic Data

The provided potential field data correspond to a profile comprising 189 Bouguer anomaly data and 189 Total Magnetic Intensity data. The data are equally spaced at 1 km and are sampled coincidently to a seismic line where Two-way time (TWT) data were also provided. The data were revised for outliers and systematic trends, but no further correction or reduction was applied to them. In theory, both data contain the gravity and magnetic responses from the ocean up to the upper crust heterogeneities.

However, the length of the profile may be inappropriate to determine lower crust/ upper mantle heterogeneities and the sampling rate won't accurately resolve very shallow features.

Seismic Reflection Data

The seismic data provided correspond to 6463 zero-offset two-way reflected travel times picked for five reflectors selected from a seismic (time) section. These reflectors were preliminarily associated to geological interfaces, named: Top of Cretaceous, Sentonian, Top of Aptian, Base of Aptian and Basement. The travel time data were analyzed and corrected for outliers and for crossing reflectors to ensure their stratigraphic continuity along the section and reduce the amount of diffracting apexes and overlapping. The data were resampled every two common depth points (CDP) for inversion and a 5% error was assumed for each one of them.

Marine Magnetotelluric data

The marine magnetotelluric data were collected on 56 sites placed on the sea bottom along the seismic profile. Sampling rate was 62.5Hz and typical deployment last for 3 days, so that the frequency range spanned from 10 Hz to 10^{-4} Hz depending on depth.

Conventional apparent resistivity and phase data for Transverse Electric (TE) and Transverse Magnetic (TM) modes were provided.

Joint Inversion Results

The gravity and magnetic responses of the models were computed using an aggregate of rectangular prisms following the formulations of Banerjee and Gupta (1977) and Bhattacharyya (1964). The magnetotelluric response was computed using Smith and Booker (1991) approach and the seismic reflected travel times using the methodology proposed by Hole and Zelt (1995). These data were jointly inverted using the algorithm of Gallardo (2007), which searches for the multiple models of the subsurface that are structurally similar to each other as measured by the cross-gradient function (Gallardo and Meju, 2003). The process of joint inversion gradually fitted the data at the level of the target misfit for the four data sets and converged to the models illustrated in Figure 2. As expected, the models are structurally concordant and depict a common underlying geological structure. The models clearly imaged two distinctive crystalline units that furnish the basement in the area and their major graben-like structures, features that were unresolved by the individually analyzed MT and seismic data (cf. Figure 1). Immediately above the basement, there is a syn-rift sequence whose architecture seems to be controlled by the main basement structure. In a third group, several layers of post-rift sequences are found deposited as controlled by the mayor basement highs.

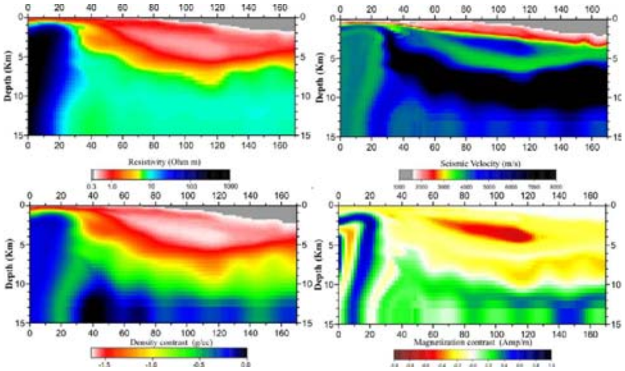
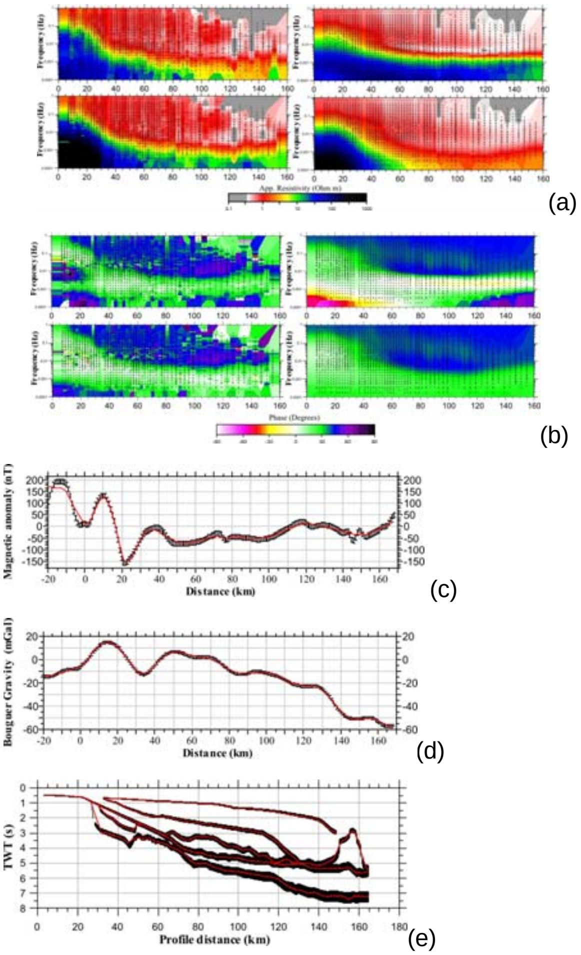


Figure 1: Results of joint cross-gradient inversion of seismic reflection, MT, gravity and magnetic profiles in Santos basin, Brazil.



(a)

(b)

(c)

(d)

(e)

Figure 2: Data fit between observed and inverted data. (a) app. resistivity (b) phase ; (c) mag data; (d) gravity and (e) seismics.

Figure 2 displays the observed fit after joint nversion for all data available. Figure 3 presents a geospectral image after joint inversion. It allows interpreting all models on an integrated manner.

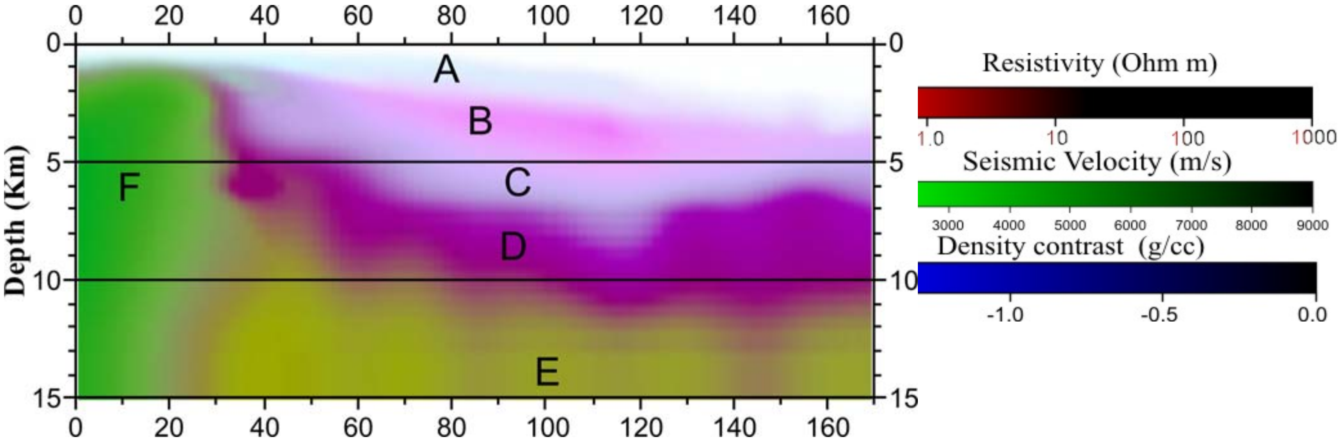


Figure 3: Integrated geospectral joint inversion model.

The geospectral image after joint inversion shows six clear zones A,B, C and D, at levels that correspond in disposition and depth to sedimentary units and E, F that correspond to basement levels.

Basement units are characterized by semi-homogeneous units, whereas sedimentary units show a coupled decay of property values that gives evidence of compactation or porous controlled variations.

Major magnetic units occur in the basement and particularly unit F shows a clear banding as comparable to banded formations that are common in Precambrian belts and metamorfism rings in intrusive materials.

A clear zone of differentiation occurs in between units E and F that is exposed at the sedimentary levels as a major graben structure filled with unit-D sediments

Undulation of top of Unit F may be the clue for plastic deposits which are still smoothed because of the associated smoothness constraints in both objective function and the adopted MT approach.

Major undulation is still noticeable in the units at about 155 km position which may be the evidence of the salt dome located in this place.

Most remarkable, this display bears no underlying geological assumption as it is just a joint display of the obtained images, yet it permits a direct mapping and interpretation as if it may represent a true geological section with the added value that actual physical properties support any given unit and deductions derived for it.

Acknowledgments

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