Integrated interpretation of the Western Portion of the Pará – Maranhão Basin – Brazilian Equatorial Margin

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Abstract

This work presents part of several results related to integrated interpretation and petroleum evaluation of all sedimentary basins in the Brazilian Equatorial Margin. We interpreted airborne magnetic, satellite gravity and seismic data in order to obtain a new structural and a depth-to-magnetic-basement maps. 2D-forward models were also accomplished using interpreted seismic lines (L0222-0822 and L0222-0831). The airborne magnetic data provided consistent results constrained with seismic and gravity data.

Introduction

The Pará-Maranhão Basin is situated between the Barreirinhas Basin to the Southeast and the Foz do Amazonas Basin to the Northwest. The red polygon represents the studied area (Figure 1). The basin has an area of about 45,500 km^2.

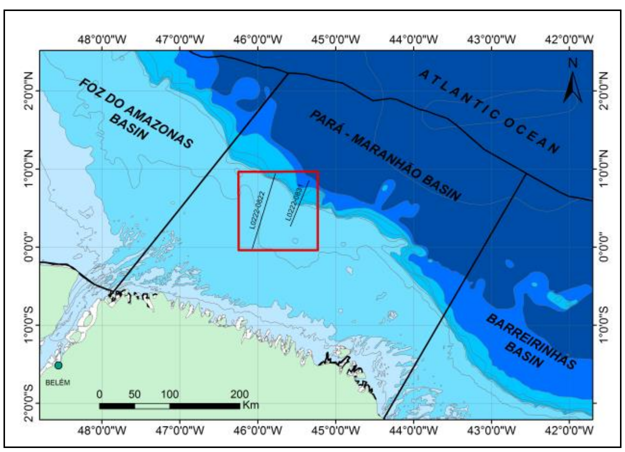

Figure 1: Location map of the Pará-Maranhão Basin. Red Polygon shows the study area.

The basin presents two remarkably different orientations. The NW-SE-trending portion of the basin was established mostly upon the domains of the parted São Luis Craton (Figure 2), an Archean craton which is the remnant Brazilian fragment of the larger West African Craton (Brandão et. al., 1994). In terms of structural geology the most conspicuous feature of the São Luis Craton is its resistant nature to breakage. The continental margin of the Pará-Maranhão and Barreirinhas Basins are relatively narrow when compared to the width of the continental margin of the Foz do Amazonas Basin to the North (established upon a Brasiliano-age foldbelt) and to the Ceará/Potiguar Basin to the South (established upon a Brasiliano-age mobile belt) (Zalán, 2011).

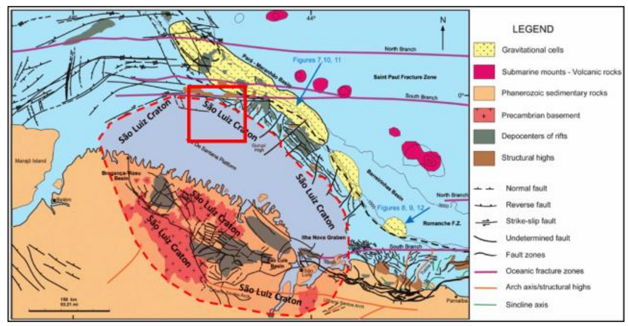

Figure 2: Structural map of the Pará – Maranhão and Barreirinhas map bordering the São Luis Cráton (Oliveira et. al. 2011).

The Pará-Maranhão Basin presents deep, narrow grabens in the shallow water portions representing the crustal stretching and thinning phase of the São Luis Craton, during the Rift Stage of the opening of the Equatorial Atlantic Ocean. These grabens are covered by a relatively thin package of sedimentary sequences developed during the Drift Stage. In the deep and ultra-deep waters of the basin a very thick package of Drift sedimentary sequences occurs resting directly upon oceanic crust.

In this work we present a structural map using potential fields data calibrated with seismic data, two interpreted seismic lines, two 2D-forward models and a depth-to-magnetic-basement map in the studied area.

Geophysical Data Set

The magnetic data herein interpreted (Figure 3) is part of a package of non-exclusive airborne magnetic data acquired in all sedimentary basins of the Brazilian Equatorial Margin, being property of CGG Multi-Physics. This is a high-resolution data, presenting 500m spacing.

The gravity data available for the project is from a satellite-altimetry data (DTU10 - SADG) (Andersen et. al. 2010; Andersen 2010). Much of the free-air gravity anomaly at the continental shelf edge can be explained directly in terms of changing water depth. For this reason, it is customary to apply a Bouguer correction to the free-air data to remove or at least minimize this predictable portion of the anomaly. Implicit in this “removal” of the water bottom density contrast is that there is no similar treatment in the Bouguer reduction step for the positive rise in gravity caused by the shallower mantle. Thus, the Bouguer gravity anomaly (Figure 4) would be expected to have eliminated the sharp negative free-air gravity effect associated with the rapid change in water depth across the shelf edge, but would be anticipated to retain the longer-wavelength, positive rise caused by the shallowing-seaward depth to the Moho. The Bouguer Gravity was calculated by 3D Modelling, using the LCT software, propriety of the CGG Multi-Physics.

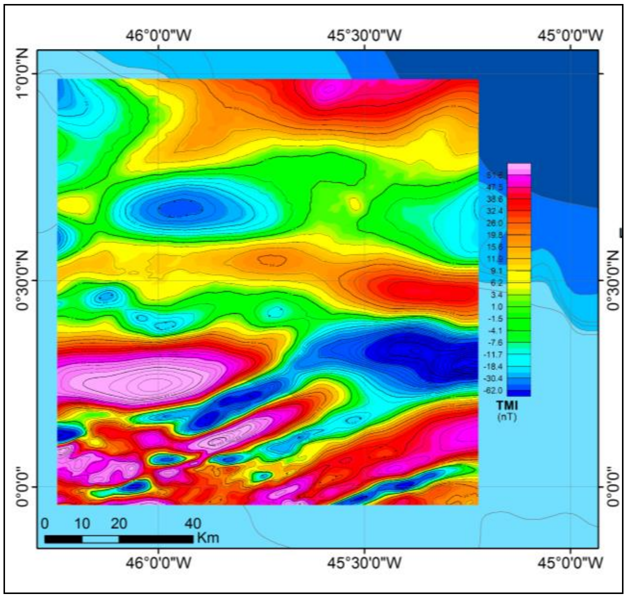

Figure 3: Total Magnetic Intensity Map of the studied area.

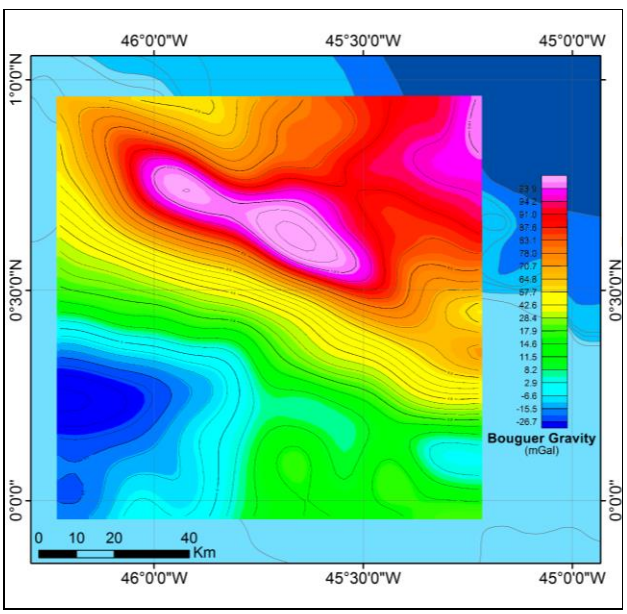

Figure 4 – Satellite Bouguer Gravity Data obtained by 3D Inversion.

Another data used were two seismic lines (TWT) (Figures 1 and 3) interpreted in order to observe the main tectonic features of the studied area. The lines L0222-0822 (Figure 5 (a)) and line L0222-0831 (Figure 5 (b)) present the same structural pattern composed by deep grabens and prominent horsts in the shallow water domain. Another important feature to be mentioned is the mantle behavior. In these two seismic lines, we observed the crustal stretching and mantle uplifts, an important constrain for the 2D forward modeling.

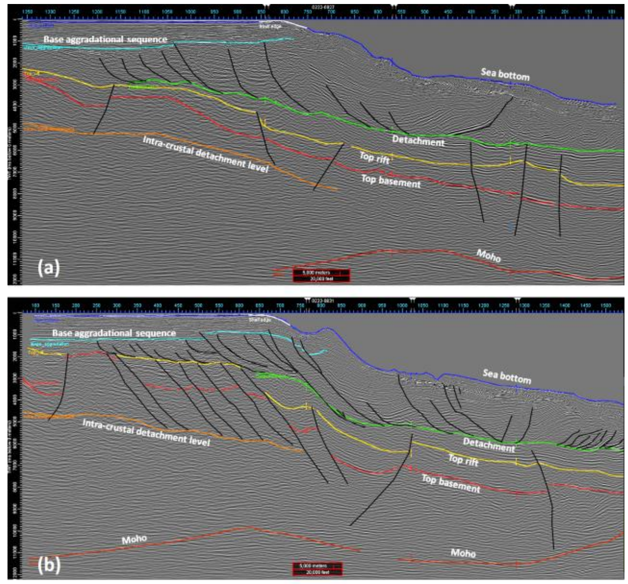

Figure 5: 2D Seismic Lines (TWT). (a) Line L0222-0822. (b) Line L0222-0831.

Structural Mapping

For the confection of the structural map in the western portion of the Pará – Maranhão Basin, all the data available were used. For the magnetic data, the enhancements that provided more effective results were the horizontal gradient (Figure 6 (a)) and the Tilt Derivative (Figure 5(b)) filters (Blakely, 1995). The horizontal gradient map presents a high frequency domain to the south being associated to the shallow basement of the São Luis Craton. Several NE-SW-trending structures can also be observed in this same area. To the north, a low frequency content, analyzed together with the Bouguer Gravity map (Figure 4) was interpreted as an exhumed mantle area.

The Tilt Derivative map (Figure 6(b)) shows very well the NE-SW-trending structures in the shallow water domain (São Luis Craton). Another important feature very well observed in the Tilt Derivative map is the hinge line. The high frequency domain observed in this map can be easily mapped being associated to shallow basement. The normal faults seem to present no correlation to the magnetic data. These faults are not related to tectonic events being associated to mass movements in the sedimentary infill. In the southeastern portion of the area, we observed a continuation of the NE-SW trend in low frequency content due to deeper basement.

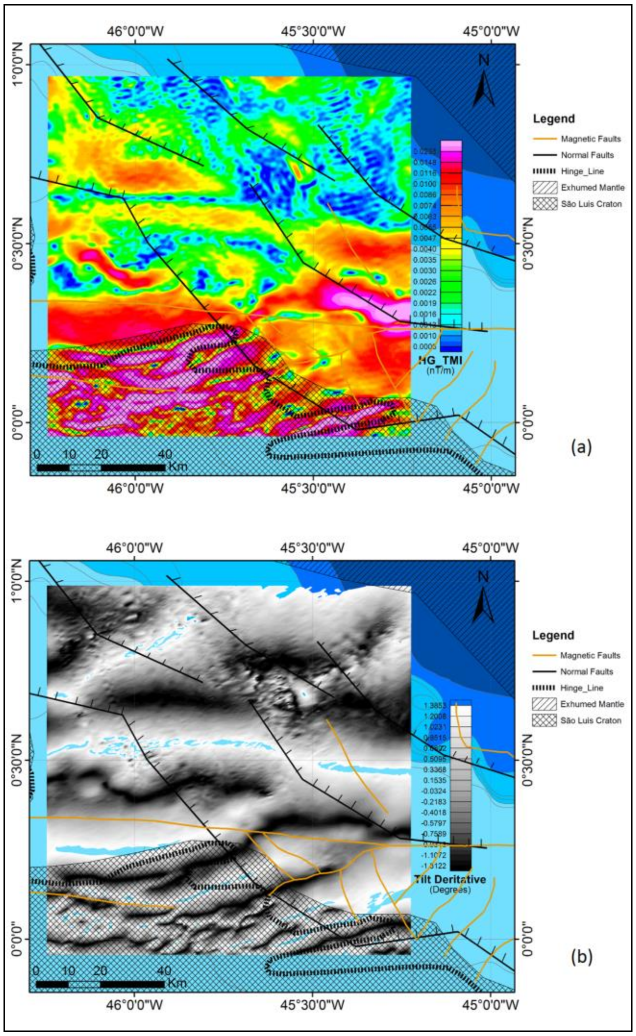

Figure 6: (a) Horizontal Gradient of the Total Magnetic Intensity map. (b) Tilt Derivative filter of the Total Magnetic Intensity map. In both maps, we can observe magnetic faults, normal faults, hinge line, exhumed mantle area and the São Luis Craton area.

The Bouguer Gravity data (Figure 4) and the seismic lines were also used (Figure 5). Considering that the gravity data available for this work are from satellite, only the long wavelength content can be recovered. Most of these anomalies are associated to mantle signature. The positive anomaly observed in the Bouguer Gravity data (Figure 4) is associated to mantle uplifts observed in the seismic lines L0222-0822 and L0222-0831 (Figure 5).

After combining several enhancements techniques in the potential fields data and calibrating these interpretations with seismic, a structural map of the western portion of the Pará – Maranhão Basin was proposed. This map shows a well defined NE-SW structural trend with conjugated SW-NE faults in the shallow water domain. Non-magnetic SW-NE-trending normal faults occur in the whole area. To the south, we defined very well part of the São Luis Craton boundary and to the north we defined a exhumed mantle province. This feature is associated to positive anomalies observed in the Bouguer Gravity data.

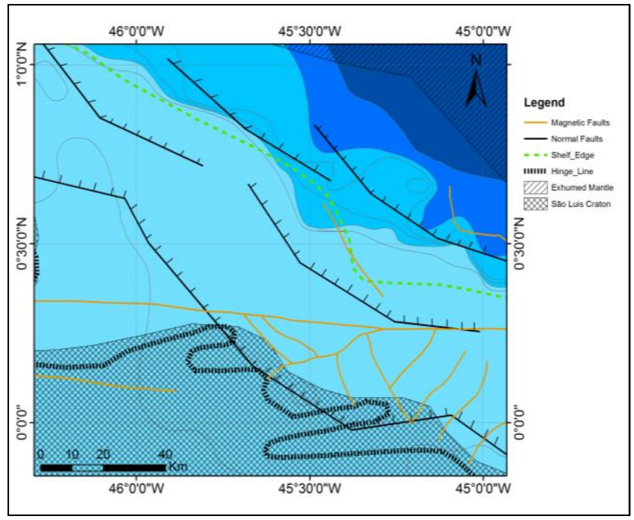

Figure 7: Proposed structural map of the western portion of the Pará-Maranhão Basin.

Depth to Magnetic Basement

Magnetic source depth estimation plays an important role in magnetic data interpretation. For petroleum exploration, the structural surface interpreted from magnetic depth estimates is often the best available approximation to the true crystalline (i.e., metamorphic/igneous) basement configuration. Basement depth, hence sedimentary thickness, is a primary exploration risk parameter. Estimates of basement depth are directly applicable to basin modeling such as source rock volume estimation, and thermal maturity applications such as source rock burial depth.

Magnetic depth estimates, together with enhancements and other data, are now widely applied for the mapping of sedimentary faults, channels, and salt structures. This has been the result of major advancements in magnetic surveying (primarily aeromagnetic) and interpretation technologies.

The average regional magnetic field parameters of these two basins are: Inclination: 7^{o}, declination: -19.6^{o} and Amplitude: 27718 nT.

There are a large number of depth estimate methods. This number keeps growing with continuous development of new algorithms. Some of these methods are listed below:

Peters half-slope technique (Peters, 1949)

Straight-slope technique (Vacquier et al., 1951)

Werner deconvolution (Werner, 1953)

Bean ratio-A technique (Bean, 1966)

Euler deconvolution (Thompson, 1982)

Source parameter imaging™ (SPI™) (Thurston and Smith, 1997)

Continuous wavelet transform (CWT) (Moreau et al., 1997)

For this magnetic basement map herein presented we used three techniques. Euler deconvolution, Werner deconvolution and Peters Half-slope. Combining these three methods, the results will be much more accurate providing a better amount of solution that will compose the magnetic basement surface. The software used for the depth to magnetic basement was the LCT Software, property of CGG Multi-Physics.

The magnetic basement map (Figure 8) was made by applying these three algorithms in all airborne magnetic profiles (Figure 3).

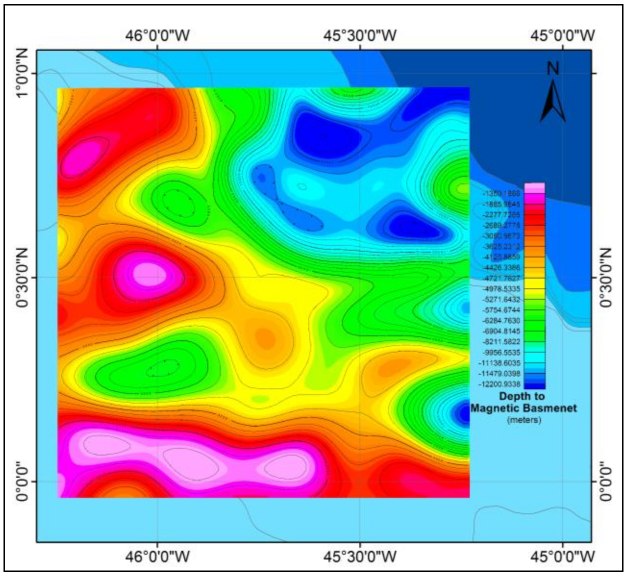

Figure 8:Magnetic basement depth of the studied area.

The result achieved in the depth-to-magnetic-basement is compatible with the structural map already mentioned. The São Luis Craton in the southern portion of the area is very well represented by the shallow basement (around 1500 meters). The NE-SW-trending structures observed to the southeast also present correlation with the basement. In the central portion of the area, we observe some basement highs associated to lows also mapped in the São Luis Craton. Finally, to the northeast, we observed a deeper area (13500 meters) in deep waters domain.

Seismic Interpretation and 2D Modeling

The seismic interpretation is the most popular and accurate method to extract geological information of geophysical data. Depending of the seismic survey, it is possible to observe structures related to basement, the main depositional sequences and the basement behavior. It is also possible to extract information of the deeper portions of the crust, observing the Conrad and Moho's geometry. In this work, the software used for seismic interpretation was the Decision Space software, property of Landmark – Halliburton group.

The seismic lines herein interpreted do not show clearly the Conrad and mantle´s behavior, but it is possible to observe the basement´s geometry and the structural pattern in shallow and deep waters domain.

Line 0222-0822 (Figure 5(a)) present a complex structural pattern composed by grabens and horsts in the São Luis Craton domain. Even in deep waters we also can observe this pattern. A similar structural pattern is also observed in Line L0222-0831 (Figure 5(b)).

These deep narrow grabens in the shallow water portions represent the crustal stretching and thinning phases of the São Luis Craton, during the Rift Stage of the opening of the Equatorial Atlantic Ocean. These structures are covered by a relatively thin package of sedimentary sequences developed during the Drift Stage.

An important method that can help to improve the seismic interpretation reducing uncertainties and providing information about eventual intrusions in the sedimentary infill is to combine seismic data with potential fields methods. One of the most popular methods is the 2D-Forward modeling (Talwani, 1965). For this exercise the LCT – CGG Multi-physics – was used.

The interpreted seismic lines were modeled in order to observe if the magnetic and gravity content are compatible with the pattern interpreted. First, considering that the seismic lines are in time (TWT), it is necessary to convert them to depth for the modeling. The velocity values used were: V = 1500 m/s (water layer), an average velocity value to the sedimentary layer V = 3614 m/s, an average velocity value for the basement layer V = 5962 m/s and for the Moho V = 6961 m/s.

The density value for the water layer was considered constant for all the models D = 2.2g/cm^3 and for the sedimentary infill V= 2.55 g/cm^3. For the Mantle, the density used was D = 3.3 g/cm^3.

Regarding magnetic susceptibility, water, sediments and Moho layers present no susceptibility, hence the variation of densities and magnetic susceptibilities are applied only in the basement layer.

After these steps, the magnetic and gravity data were sampled for the profiles. Using compatible values of magnetic susceptibilities and densities for the geological sequences mapped, the model of the seismic line L0222-0822 (Figure 9 (a)) confirms very well the structural pattern mapped for the basement in seismic line L0222-0822. Narrow grabens and horsts can be very well mapped in seismic and in potential fields. Another important feature is to observe the Moho geometry. In this model we can observe an uplift in deep waters. This phenomenon is also observed in the magnetic data (long wavelengths anomalies) (Figure 3) and a prominent positive high in the Bouguer gravity data (Figure 4).

The situation is similar for the model of the seismic line L0222-0831 (Figure 9 (b)). The pattern of narrow grabens and zoned horst in the Sao Luis Craton domain is also observed presenting in the deep water mantle uplift as well.

Furthermore, the values obtained for the magnetic basement depth (Figure 8) were also compared with the 2D models. Considering the seismic lines are in time (TWT), it is the best way to compare what was mapped in seismic with what was obtained with the potential fields data.

Observing both models (Figure 9), the values related to the magnetic basement are represented by the thick black line.

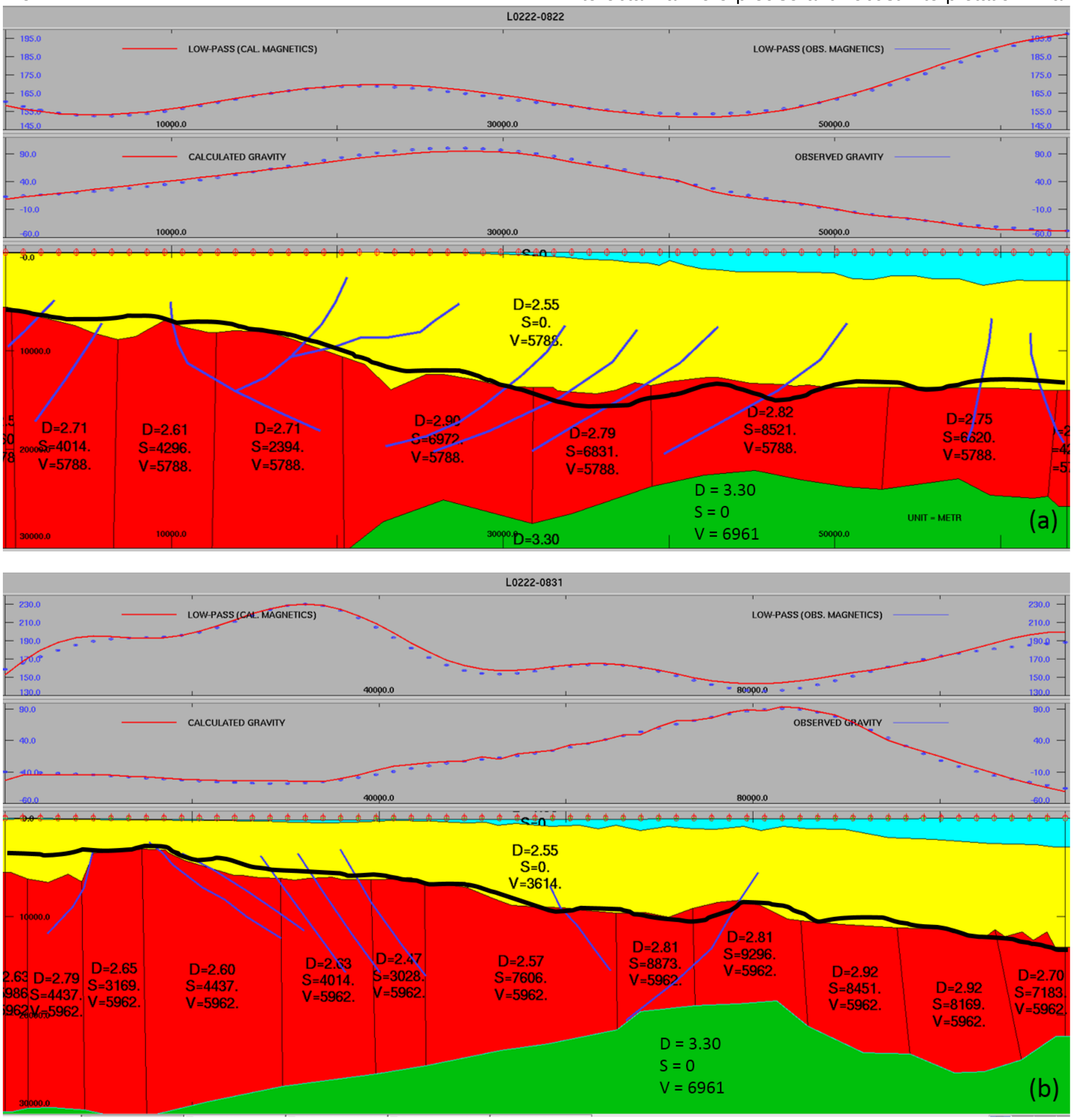

Figure 9: (a) 2D Forward Model for Seismic Line L0222-0822 – (b) 2D Forward Model for Seismic Line L0222-0831.

The compatibility of the interpretation of the different methodologies and geophysical methods is very good. The results achieved in the depth of magnetic sources are very close of what was obtained with seismic interpretation.

This fact emphasizes the importance to combine and integrate different tools and geophysical methods in order to obtain a more precise and robust interpretation in any exploratory campaign. Although the seismic surveys are more precise and recommended for mapping hydrocarbon occurrences, potential fields methods can provide useful information to any kind of exploratory campaign being a powerful tool considering the much lower cost compared to seismic surveys.

Conclusions

In this work we used airborne high resolution magnetic data combined with satellite gravity and seismic data in order to propose a structural map in the western portion of the Pará – Maranhão Basin.

Observing the results obtained for the basement depth, the shallow portion of the São Luis craton present depths around 2000 meters. In deep water domain, the values can be around 13.500 meters. This result was constrained with seismic interpretation and converted to 2D-Forward models providing an integrated interpretation result.

The airborne high resolution magnetic data provided consistent and reliable results contributing for the knowledge of the Brazilian Equatorial Margin.

Considering the lower cost and the constant line spacing of the magnetic profiles, the airborne magnetic data available for all Brazilian Equatorial Margin surely is a powerful tool to any kind of exploratory activity.

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