Mapping basement and Moho along the Equatorial Margin of Brazil using potential field data to assist petroleum exploration

Irena Kivior[1], Patricia de Lugão[2], *Stephen Markham[1], Jacqueline Button[1], Siân Beavers[1], Tom Wise[1] and Stephanie Senderowitz[2]

[1]Archimedes Consulting Pty Ltd, 31 Stirling Street, Adelaide, Australia
[2]Strataimage Consultoria Ltda, Praça Floriano 55, sl. 909 Rio de Janeiro, Brasil

This paper was prepared for presentation during the 13th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 26-29, 2013.

Abstract

Low resolution regional magnetic and satellite gravity datasets were used to conduct an interpretation of the crustal structure along the Equatorial Margin of Brazil. Unique potential field interpretation techniques were used to map basement and Moho. The crustal structure, including major faults, troughs and crustal highs were mapped along the 2000km long Equatorial Margin. The depth to basement derived from the potential field data shows good correspondence to the available well and seismic data. The basement map and the map of the Moho discontinuity will add value to petroleum exploration in offshore basins along the Brazilian Equatorial Margin.

Introduction

A basement and Moho discontinuity study has been undertaken using potential field data covering areas of 700,000km^2 for basement and 900,000km^2 for Moho, across the Equatorial Margin of Brazil. The main aim of this study was mapping depth to the basement and Moho. These objectives were achieved by the application of the spectral analysis technique to the publically available aeromagnetic and satellite gravity data. The primary tools employed in this project were Archimedes' proprietary horizon mapping techniques that were used in two stages: Energy Spectral Analysis 'Multi Window Test' (ESA-MWT) to detect basement and Moho surfaces and the 'Moving Window' (ESA-MW) to refine the horizon mapping in greater detail.

First, to identify magnetic or density interfaces, ESA-MWT was conducted at stations located on a regular mesh of ~28km by 28km over the whole project area. Magnetic data was restricted to surveyed areas concentrated along the coastline, whilst satellite gravity data had a greater offshore coverage. MWT was used to compute the approximate depths to the targeted horizons and to construct the regional horizon skeleton maps. MWT was instrumental in overcoming commonly known limitations of the spectral method. This was done by detecting, at every MWT station, the optimal window size required for spectra computation to determine the correct depths in the second stage of the project; the detailed mapping.

The second stage, the detailed horizon mapping, involved an application of the ESA-MW technique. The spectra were computed and interpreted using the optimal window size determined from the MWT *'depth-plateaus'* over a dense 10 by 10km mesh for the basement.

The Automatic Curve Matching technique (ACM) was applied to magnetic data to define major faults and magnetic lineaments at depth over the study area. 2.5D forward modelling of selected magnetic and gravity profiles was undertaken to QC and validate the interpreted basement configuration.

Geological Setting

The tectonic evolution of the Brazilian Equatorial Margin is dominated by the break-up of Gondwana and the opening of the equatorial Atlantic Ocean between modern day South America and Africa. The rifting period began in the Aptian (Matos & Waick, 1998) and continued until the Albian. In the early stages the rifting showed a strong dextral shear sense that led to the creation of basins filled with thick sedimentary sequences (Trostdorf et al., 2007). Rifting was initiated earlier in the east (Potiguar Basin) see Figure 1, and progressed northwestward towards the Foz do Amazonas Basin.

At the end of the Lower Cretaceous the extension was concentrated in the Foz do Amazonas, Pará-Maranhão and Barreirinhas basins, and evolved to continental rupture of northern South America and western Africa and the opening of the Equatorial Atlantic Ocean. Along transform faults in the Equatorial Margin, linear chains of volcanic plugs and igneous intrusions formed, associated magmatism is recorded in the Norte Brasileira and Fernando do Noronha Ridges.

The margin has a shelf, slope and rise morphology consistent with a passive continental margin (Watts et al., 2009). Following the inception of oceanic crust (whose limit with the continental crust is characterized by an abrupt segmentation by transform faults), the thermal subsidence sedimentation is affected by relatively few fault zones, the exception being gravitational collapse faults that occur in the depocenters near the shelf edge. This process resulted in extensional and compressional features in the slope and in the deep water region of several basins, for example Foz do Amazonas, Pará–Maranhão, Barreirinhas (Bizzi et al., 2003).

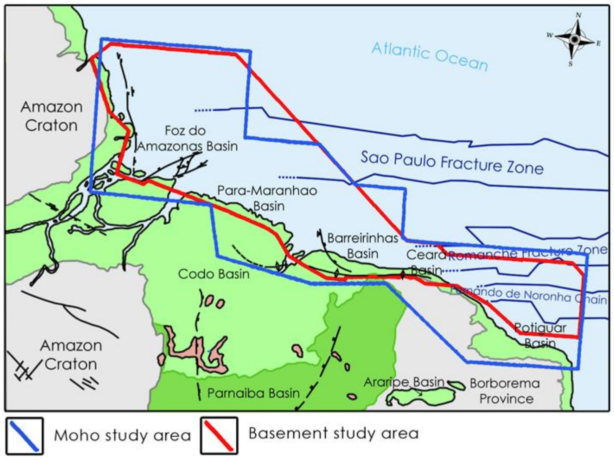

Figure 1. Location map of the study area: basement outlined in red and Moho in blue. The Equatorial Margin of Brazil Map after de Oliveira, C. et al. (2006) Evolução tectônica e arcabouço estrutural de margem Equatorial Brasileira.

Geophysical Data Sets

The magnetic survey data was acquired over part of the offshore continental shelf, Equatorial Margin of Brazil between 1967 and 1970. The whole area is between 5º 59' 50" North and 7º 59' 56" South, and between 51º 59' 30" and 33º 59' 30" West. The supplied data was derived from 3 surveys: Plataforma Continental Para-Amapa, with a line spacing of 4km and a flight height of 700m (NE-SW), Barreirinhas, with a line spacing of 2.5km and a flight height of 400m (perpendicular to coast), and Plataforma Continental Nordeste, with a line spacing of 5km and a flight height of 700m (NE-SW & EW).

The original recorded data from these surveys was unavailable so the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) supplied data that had been digitised from contour maps. The digitised data was extracted from the databases, and the coordinates converted from latitude and longitude (SAD69 datum) to UTM22S (SAD69) coordinates. This coordinate system was used for all interpretation. The final magnetic data was gridded with a 500x500m mesh (Figures 2a,b&c). The low magnetic inclination of the study area (5.5º) meant that standard processes such as Reduction To Pole might introduce artifacts into the data so it was decided to use the original Total Magnetic Intensity (TMI) data.

The resolution of the magnetic survey data is limited by the line spacing, sample interval and flight height of the surveys but also the spacing of the contours that the data was reconstructed from. This has the greatest effect where the amplitude of the magnetic field is changing slowly because the dominant magnetic sources are deep. The wide contours thus result in data with a greater degree of interpolation.

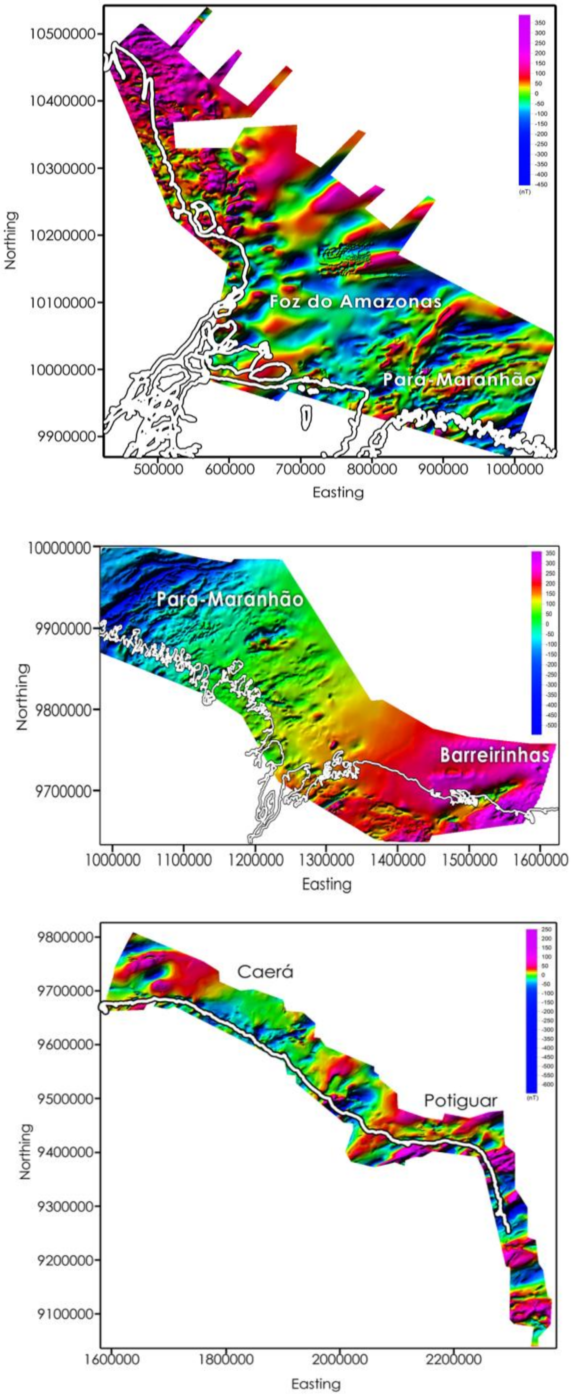

Figure 2a. TMI data across the Foz do Amazonas and Pará-Maranhão basins. **b.** TMI data across the Pará-Maranhão and Barreirihas basins. **c.** TMI data across the Caerá and Potiguar basins.

The gravity and bathymetry data used in this study was supplied by the Scripps Oceanographic Institute, of the United States, as a free download from their web server. This data is version 18.1 (2008) of the Sandwell and Smith satellite marine gravity derived from radar altimeter data. It also includes onshore gravity data of unknown origin and quality. The website does not specify when the onshore gravity data was acquired.

The gravity data was supplied as an ASCII grid in latitude and longitude coordinates and these coordinates were converted to UTM zone 22S coordinates (SAD69 datum) before the data was processed. Bathymetric data was also downloaded from the same location. The downloaded gravity data had a grid spacing of approximately 1 arc-minute so after the locations of the grid points were converted to UTM 22S, easting and northing values, the gravity data was re-gridded to 500x500m (Figure 3). The same processing was applied to the bathymetric data (Figure 4).

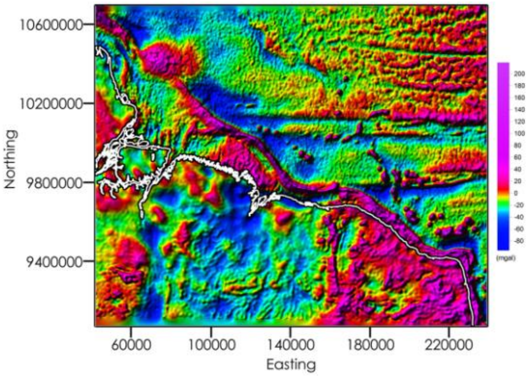

Figure 3. Satellite Gravity data of the Equatorial Margin region.

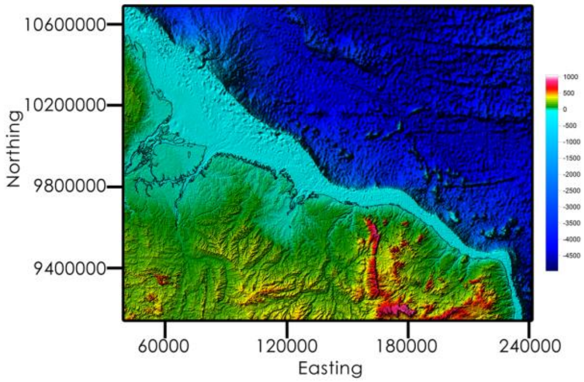

Figure 4. Topographic-bathymetric image of the Equatorial Margin region.

The resolution of the gravity data is limited by the size of the radar beam when it reflects off the sea surface, where it is typically around 7km in diameter. Many observations are used to measure the curvature of the sea surface caused by density variations in the sub-sea geology. Generally, only deeper gravity sources are resolvable with this kind of data.

Method

Energy Spectral Analysis: ESA

ESA is a well established technique for estimating the depth to a sedimentary horizon or crustal interface distinguished by a magnetic susceptibility or density contrast. Such interface is modelled as a statistical ensemble of multi-prisms (Spector and Grant, 1970). An energy spectrum is computed from the gravity or magnetic data and the logarithm of the radial averaged amplitude is plotted versus the radial frequency. This produces a graph of a spectral function with a decay that is proportional to the depth to the top of a mapped sedimentary horizon or crustal interface such as basement or Moho discontinuity. In order to obtain estimates of depths in a localized area, ESA is applied to a windowed sub-region of the potential field data. Applied at multiple locations, depth maps of sedimentary horizons or other crustal interfaces can be produced (Kivior et al. 1993).

Multi-Window-Test: MWT

Determining the correct window size over which spectra are computed is critical for correct depth estimates. If the window is too small, a depth will be too shallow, as it will not cover enough of the anomaly(s) arising from the targeted causative sources; if the window is too large, the low frequency spectral decay will be dominated by the frequencies generated by deeper sources. The Multi Window Test (ESA-MWT) procedure is used to estimate the depth over a span of multiple-window sizes centred over a point of interest (a MWT station, Figure 5). Ranges of window sizes where the derived depth values are nearly constant form depth-plateaus, indicating both an optimal window size for performing detailed mapping in the vicinity of the MWT station, and the approximate depth to the causative interface. The MWT process is applied over a study area on a regular mesh. Multiple depth-plateaus can be detected at each MWT station, and these are correlated with distinct magnetic susceptibility or density interfaces. Plotting all depth-plateaus along a profile can be used to simultaneously image multiple horizons.

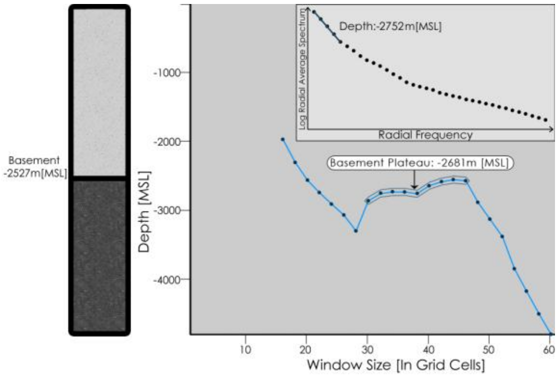

Figure 5. MWT graph showing correlation between depth to basement at the well, and the depth-plateau.

A detailed mapping process is undertaken once a skeletal map for a horizon has been completed. The ESA-MW interpretation process is undertaken over the study area on a denser mesh than that used for initial horizon detection, using the optimal window sizes determined from the depth-plateaus found at nearby ESA-MWT stations. The spectra at the optimal window size are reinterpreted at this denser mesh producing a higher resolution depth map of the detected horizon.

Automatic Curve Matching: ACM

The ACM method is applied to profile data extracted from the TMI grid. The method works by identifying a magnetic anomaly on a profile, splitting it to horizontal and vertical components and each into a representative pair of even and odd functions. These four functions derived from the observed anomaly are compared with the corresponding four functions computed for a theoretical model. The parameters for the causative body are automatically varied and the model which provides the best fit is accepted. The method used in this project is an extension of the curve matching method developed by Shi (1993). This method is applied to profile data in EW, NS, NW-SE and NE-SW directions. The output from ACM processing consists of a depth to the causative body, its geometry, magnetic susceptibility and similarity coefficient (a statistical correlation with the ideal body).

The magnetic sources detected by ACM are imported as a 3D cube into the interpretation software with points representing the centres of causative bodies detected by the automated procedure. Interpretation of magnetic lineaments, with the ACM method, is commonly undertaken on a series of depth slices at various crustal levels. The result of the depth slicing process is a map showing magnetic lineaments interpreted through visual examination. A series of horizontal slices or conformable bands of various thicknesses are interpreted, depending on the targeted depths.

Discussion of the Results

Basement Mapping

ESA-MWT was applied to magnetic and gravity datasets across the study area at stations located on a regular mesh of ~28 x 28km. The MWT procedure was conducted to detect laterally correlatable density and magnetic susceptibility contrasts indicated by depth-plateaus. At each station the MWT depth-plateaus show average depth to the mapped interfaces, and the optimal window size of spectra to be used for more detailed horizon mapping (ESA-MW).

Figure 5 also shows an example of the MWT graph at a well location, where the depth-plateau shows the stability of the depth solution with respect to window-size. Similar procedures have been repeated for each station over the whole area. Depth-plateaus were identified and approximate average depths from the plateaus were used to construct a skeleton map of the basement horizon. This was done for both magnetic and gravity datasets.

Due to a limitation in the magnetic data coverage, the magnetic data was used to detect basement at depths of less than 6km, while basement depths of greater than 6km were derived from the satellite gravity data. The depths from magnetic data were corrected to Mean Sea Level (MSL) before being merged with the gravity results. The juncture between the magnetic and gravity results occurred predominantly where faulting is associated with the continental slope. The exception is an area in the vicinity of the Amazon mouth, where two grabens were mapped from the gravity dataset. An example of the skeleton map of basement is shown in Figure 6.

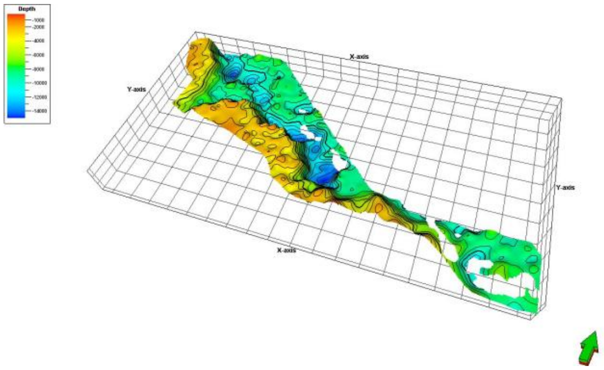

Figure 6. Basement skeleton map; contour interval 1000m. White areas denote where surface has been cropped because of the presence of seamounts.

The detailed mapping was undertaken using the ESA-MW technique. At each single MWT station, for both datasets, the optimal window size was determined from the depth-plateaus and used to construct the combined basement detailed map. For both magnetic and gravity datasets, spectra of different window sizes were interpreted on a regular mesh of 10 by 10km to map basement at a higher resolution than the skeleton map. Figure 7 depicts a comparison between the basement skeleton map and the higher resolution detailed map (over a sample area).

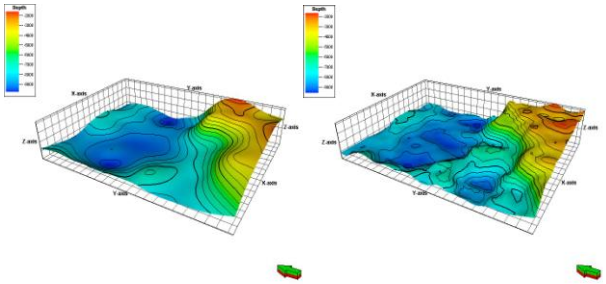

Figure 7. Low-Resolution and Higher-Resolution basement surfaces; contour interval 500m

The depth of the basement ranges from approximately 1 to 6km along the shelf area, with a clearly defined fault pattern following a similar trend to the continental slope. Several of the known basins, Foz do Amazonas, Pará-Maranhão, Barreirinhas, Caerá and Potiguar, are defined on the basement map, with the maximum depth reaching almost 15km.

Moho Mapping

The Moho discontinuity was mapped using the gravity dataset. The MWT depth-plateaus indicating the deepest density contrasts were selected to delineate this interface. The MWT stations were located on a regular mesh of the same density as that used for the basement, ~28 x 28km.

The resultant low-resolution map of the Moho interface is shown in Figure 8.

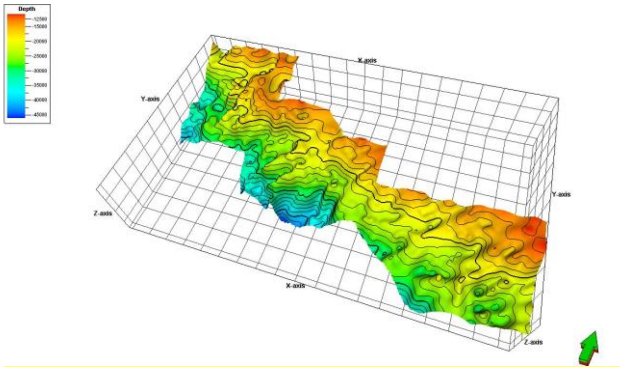

Figure 8. Map of the Moho Discontinuity; contour interval 2000m

The depths depicted in the Moho image range from 10km to 45km. Notably, the depth increases from the north-east to the south–west indicating the transition from oceanic to continental crust.

Magnetic Lineaments

The Automatic Curve Matching (ACM) method was applied along profiles extracted from the TMI grid. The magnetic lineaments were interpreted at different depths throughout the whole Equatorial Margin. The magnetic lineaments often represent fault patterns, shear zones or fault associated structures. Magnetic lineaments were interpreted in horizontal planar view in 2km thick horizontal crustal depth slices (HCDS) within the depth ranges of: (i) HCDS-1 at 2.5km to 4.5km, (ii) HCDS-2 at 4.5km to 6.5km and (iii) HCDS at 6.5km to 8.5km. The magnetic lineaments detected, show the regional structural grain and major structural features of the area.

The shallow crustal slices show complex, numerous and well-defined patterns of linear structural features. Major trends shift from the northern region to the south, but could shed light on the shelf deformation, morphology, and possibly the current distributaries and paleo-channels associated within the delta regions. Magnetic lineaments detected at greater depths are long trending features and are more indicative of the general trend of major structures. The complete set of magnetic lineaments, over all depths, could increase knowledge of shifts in prograding and accretionary trends of the continental shelf.

Magnetic lineaments were also interpreted within a 1km thick Crustal Depth Band (CDB) below the basement surface. These lineaments are directly related to the basement structure alone. Most of the lineaments detected within this CDB show conformity with the interpreted basement surface and highlight fault faces and potential targets. Figure 9 shows an image of a small section of the basement surface with superimposed magnetic lineaments interpreted from ACM.

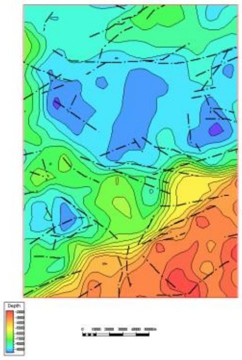

Figure 9. Image of basement surface mapped from magnetic and gravity data with superimposed magnetic lineaments. Sample area; contour interval 500m.

Comparisons

Seismic lines acquired from BDEP were used to indicate major structural trends. Figures 10a and 10b show a comparison of the seismic line FOZ-AMAZONAS-4A.0239-0123 (TWT) with the basement (metres) derived from the potential field data. There is a good correlation between the two.

Geological information obtained from the well data, also acquired from BDEP, assisted in providing control for the determination of basement depths. As mentioned previously, Figure 5 illustrates a MWT graph at Well 1-CES-97-CE. The actual basement depth at this well ties with the plateau depth, with a 6% difference in values.

2.5D Forward Modelling profiles were used as quality control for the depth to basement surface.

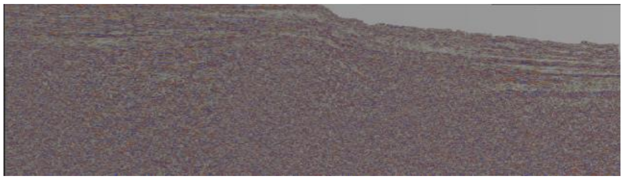

Figure 10a. Seismic line profile (TWT)

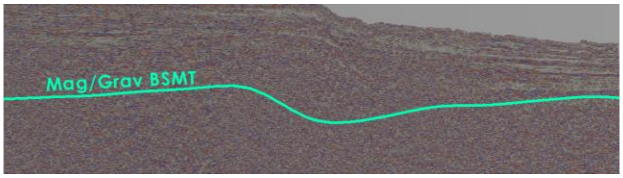

Figure 10b. Seismic line (TWT) with superimposed basement interpreted from magnetic and gravity data (metres)

Conclusions

The basement configuration and Moho discontinuity were successfully mapped from the potential field data across the 2000km long Equatorial Margin of Brazil. The publically available low-resolution magnetic and gravity data was interpreted using the horizon mapping tool based on the spectral technique, ESA-MWT. In addition, magnetic lineaments corresponding to regional structural grain were interpreted from magnetic data using ACM. The results show good correlation with seismic and well data and were also confirmed by forward modelling of the magnetic and gravity field along several profiles.

Higher-resolution basement mapping will provide greater detail, and give more insight into the intricacies of depth variations and the complexity of geological structures. This can be achieved by application of the ESA-MWT and ESA-MW procedure, as well as the ACM method to the high-resolution aeromagnetic data which is available as a spec survey covering a large part of the Equatorial Margin of Brazil. The accuracy and detail would be significantly enhanced using high-resolution survey data, combined with the geological constraints provided by well and seismic data. In addition, high-resolution data would enable interpretation of inter-sedimentary horizons above the basement.

Acknowledgments

We would like to thank ANP and Scripps Oceanographic Institute, for the magnetic and gravity datasets respectively. We are indebted to Archimedes for their input and facilities during interpretation and to Strataimage for their advice and support throughout the project.

References

Bizzi, L. A.; Schobbenhaus C.; Vidotti, R. M. e Gonçalves, J. H. (eds.). Geologia, Tectônica e Recursos Minerais do Brasil CPRM, Brasília, 2003.

de Oliveira, C.H.T., de Gauw, D.S., Vesely, F.F., da Fonseca, J.P.T., Martins, P.S. and Macedo, R.M. (2006) Evolução tectônica e arcabouço estrutural de margem Equatorial Brasileira. XIV, 123 p.29,7cm (Faculdade de Geologia – UERJ, Esp., Curso de Especialização em Projeto de Análise de Bacias: Módulo Geologia do Petróleo).

Kivior, I., Shi, Z., Boyd, D. and McClay, K. R. [1993] Crustal studies of South Australia based on energy spectral analysis of regional magnetic data. *Exploration Geophysics* 24, 603-608.

Krueger A., Murphy M., Gilbert E., and K. Burke, 2012., Deposition and deformation in the deepwater sediment of the offshore Barreirinhas Basin, Brazil. *Geosphere*, 8 (6): 1606-1631.

Matos, R.M.D. & Waick, R.N., 1998. A unique transform margin: the Equatorial Atlantic. *Proceedings of the Rio'98 AAPG International Conference and Exhibition*, pp. 798-799, Rio de Janeiro, Brazil.

Shi, Z**.,** 1993. Automatic interpretation of potential field data applied to the study of overburden thickness and deep crustal structures, South Australia. PhD thesis, Department of Geology and Geophysics, The University of Adelaide.

Soares Junior, Adilson Viana; Costa, João Batista Sena; Hasui, Yociteru. evolução da Margem Atlântica equatorial do Brasil: Três Fases Distensivas. *Geociênc*. (São Paulo), São Paulo, v. 27, n. 4, out. 2008.

Spector, A. and Grant, F. S. 1970, Statistical models for interpreting aeromagnetic data. *Geophysics*, 35, 293‑302.

Trostdorf I., Zalan P.V., Figueiredo J.J.P, and E.F. Soares, 2007., Bacia de Barreirinhas: *Boletim de Geociências da Petrobras*, v. 15, no. 2, p. 331–339.

Watts, A.B., Rodger, M., Peirce, C., Greenroyd, C.J., and R.W. Hobbs. 2009. Seismic structure, gravity anomalies, and flexure of the Amazon continental margin, NE Brazil. *Journal of Geophysical Research*, Vol 114.