Tectonic Framework of the Pimenta Bueno Graben

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Abstract

Airborne geophysical surveys are widely used in geological prospecting of hydrocarbon reservoirs. The efficiency and acquisition speed of these methods in covering large areas accredit them as a key tool for any exploration project where there is sparse technical data available to support the exploratory decisions. Among the airborne geophysical methods, potential methods, namely, gravity and magnetics are the most spread in Oil & Gas projects of this nature. Such methods are used to support the generation of regional geological knowledge and detailed approaches to integrate with seismic, geochemical and wells data. Throughout the integration of the Airborne Gravity Gradiometry and magnetic data along a 2D seismic section we inferred the geometry of the Pimenta Bueno Graben. While many works have mapped basement depth about 7,000 m, the current modeling shows basement depth deeper than 10,000 m.

Introduction

The Parecis Basin is still a matter of debate among geoscientists. The scarcity of studies and available data are still a difficulty for the understanding of the genesis and its sedimentary evolution. According to Almeida (1983), the Parecis Basin is one of the largest Brazilian Intracratonic basins, covering approximately 500,000 km^2 in the Brazilian Amazon area (Figure 1 and inset Figure 2). Siqueira & Teixeira (1993) divided this basin, from west to east, in the Rondônia, Juruena and Alto Xingu sub-basins, separated by the Vilhena and Serra Formosa Magmatic Arcs. This division was based on geophysical and geologic data: The extreme west is the Rondônia tectonic depression, the central portion is a gravity low and the eastern part is the Alto Xingu Basin (Figure 1). The main structural trend is oriented E-W and suggests the continuation, under the Mesozoic Sequence, of the Pimenta Bueno and Colorado Grabens (Figure 1).

The area of this study (solid line red polygon in Figure 1) is located in the extreme southeastern portion of the Pimenta Bueno Graben. This is the major feature of the Parecis Basin located between the “Alto de Braznorte” (Braznorte High) and the “Alto do Rio Branco” (Rio Branco High).

Bahia (2007) considers that the sedimentary evolution of the Parecis Basin is associated to extensional events that occurred in the Ordovician, followed by sedimentation lasting up to the Permian (Cacoal, Furnas, Ponta Grossa and Fazenda da Casa Branca formations). Throughout the Mesozoic other sedimentary events were responsible for the deposition of the Anari, Rio Ávila, Salto das Nuvens and Utiariti formations. Braga & Siqueira (1995) concluded that the sedimentary infill of the Pimenta Bueno Graben is the thickest one in the entire Parecis Basin. The well “Salto Magessi” (2-SM-1-MT), drilled by Petrobras in 1995, reveals 5.779m of sediments without any presence of volcanic rocks.

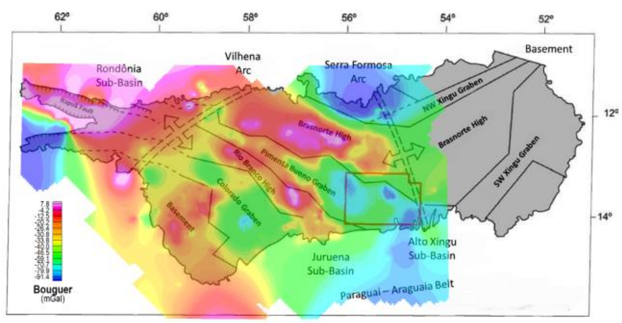

Figure 1 – Location of the study area (red polygon) in the tectonic and Bouguer gravity anomaly map of the Parecis Basin (modified from Bahia, 2007).

According to Zalán (2013 – Oral communication), the Parecis Basin should be classified as a Proterozoic Basin. This was corroborated by the interpretation of the last seismic lines acquired by ANP published in technical seminar of the 12th Bid Round (Haeser, 2013). In this seminar, ANP presented a new stratigraphic chart for the basin that shows wide Proterozoic sequences, sparsely and discordantly covered by very thin Paleozoic and Mesozoic sequences.

The seismic surveys showed a thick sedimentary sequence filling deep grabens oriented along NW-SE. The geometry of these grabens shows compressional structures that could have been generated by the collision of the Paraguay-Araguaia Belt in its southern flank. This suggest a collisional event younger than the supposed E-W-trending taphrogenic event, during which the Paraguay belt was thrust over the Proterozoic sedimentary sequences causing the southern flank subsidence due to loading effect, in a classical foreland tectonic scheme.

In this paper we interpreted airborne magnetic and gravity data of the Parecis Basin proposing the basement relief along the seismic line 295-010 (Figure 2), located along the Pimenta Bueno Graben. It was also possible to define at least four geological provinces according to the potential field data. A 2D Seismic line and a well log (Salto Magessi well) were also used as constrains for all the results.

FALCON™ gravity gradiometry and Magnetic data

In standard ground gravity surveys, the component measured is "gD", which is the vertical component of the acceleration due to gravity. In airborne gravity systems, since the aircraft is itself accelerating, measurement of "gD" cannot be made to the same precision and accuracy as on the ground (Boggs & Dransfield, 2004). Airborne gravity gradiometry uses a differential measurement to remove the aircraft motion effects and delivers gravity data of a spatial resolution and sensitivity comparable with ground gravity data. The FALCON™ gradiometer instrument acquires two curvature components of the gravity gradient tensor namely GNE and GUV where GUV = (GEE – GNN)/2 (Lee, 2001).

Since these curvature components cannot easily and intuitively be related to the causative geology, they are transformed into the vertical gravity gradient (GDD), and integrated to derive the vertical component of gravity (gD). Interpreters display, interpret and model both GDD and gD. The directly measured GNE and GUV data are appropriate for use in inversion software to generate density models of the earth. The vertical gravity gradient, GDD, is more sensitive to small or shallow sources and has greater spatial resolution than gD (similar to the way that the vertical magnetic gradient provides greater spatial resolution and increased sensitivity to shallow sources of the magnetic field). In the integration of GDD to give gD, the very long wavelength component, (wavelengths comparable to or greater than the size of the survey area), cannot be fully recovered. Long wavelength gravity was therefore incorporated in the gD data from other sources that was is meant by conformed Gravity in the literature (Dransfiled, 2010). The Danish National Space Centre global gravity data of 2008 (DNSC08) was used as to produce the gD Conformed grid.

In 2012, CGG Multi-Physics performed an airborne FALCON™ survey in the southern portion of the Parecis Basin (Figure 2), being the first time that this basin was covered with a high-resolution geophysical survey. The surveyed block has approximately 17,000 km^2 flown by 37,577.6 kilometers of gravity gradiometry and magnetic profiles. Actually, any FALCON™ gravity gradiometry survey has both data content, magnetic and gravity gradiometry data.

The survey was designed with 500 meters spacing for flight lines and 10,000 meters spacing for tie lines acquired at 700 meters barometric altitude. The interpretation workflow used in this study considers the use of various filters applied to the basic datasets: total magnetic intensity corrected from IGRF and reduced to pole (Figure 3), conformed gD terrain corrected (Figure 4), aiming to base the qualitative interpretation of tectonic structures and igneous features within the area of interest.

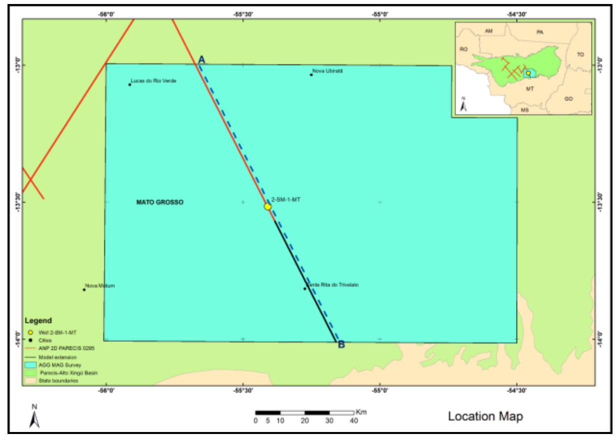

Figure 2 – Location map of the survey, the seismic line 295-010 and the location of the Salto Magessi well.

Qualitative Interpretation

The filters formerly applied over the gravity (not shown in this work) does not seem to contribute significantly to the problem of enhancing the gravity response of igneous rocks. However, these filters when applied over the total field magnetic data showed to be effective to map zones of high frequency content that were associated to the spatial distribution of the igneous rocks. The most effective filters was the first vertical derivative (Figure 4), that enhanced many isolated anomalies and groups of anomalies, addressing a possible area of occurrence of the igneous rock in the surveyed block. The real existence of igneous rocks depends on ground checking. Ideally, this checking shall be done with well drilling located in the mapped zones. It is worth to highlight the nonexistence of igneous rocks in the well SM-1-MT (Figure 2), located in the area.

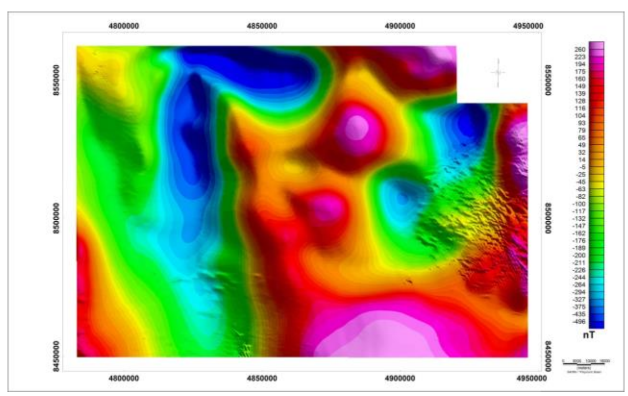

Figure 3 – Total Magnetic Intensity, IGRF removed and reduced to pole.

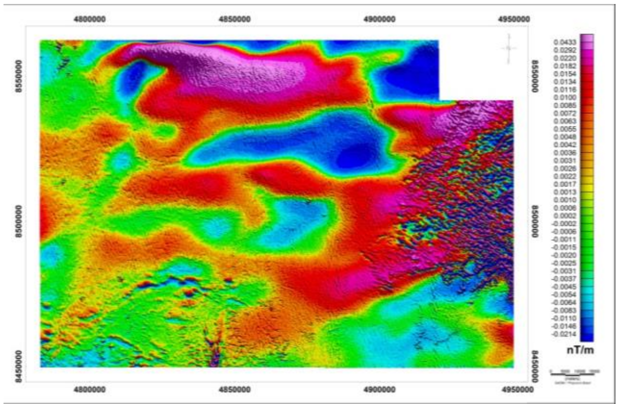

Figure 4 – First Vertical Derivative map of the Total Magnetic Intensity.

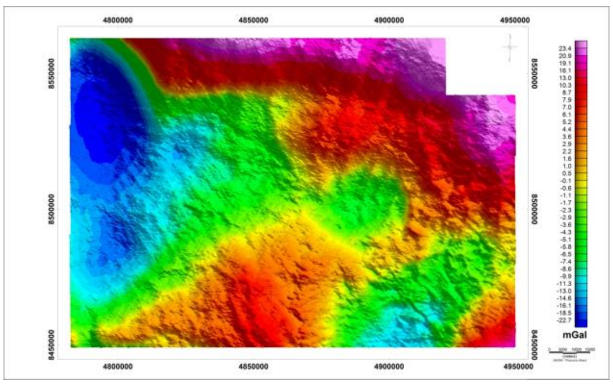

Figure 5 – Conformed gD - Terrain correction used: 2.5 g/cm^3

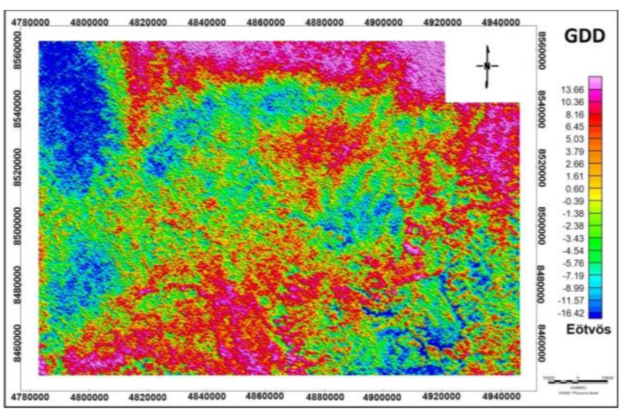

Figure 6 – GDD – Vertical tensor.

In order to organize the results generated by qualitative interpretation methods we uploaded it in a GIS software, aiming to proceed a qualitative zonation for “igneous rock occurrence” and generate a map of likelihood of a “well drilling intersecting igneous rocks”. This map is showed in the Figure 7. We also generated a structural map of the area, addressing all linear features and internal structural highs and lows (Figure 8). The final structural map proposed in Figure 8 is an integrated interpretation over the magnetic, gravity, seismic and well data available.

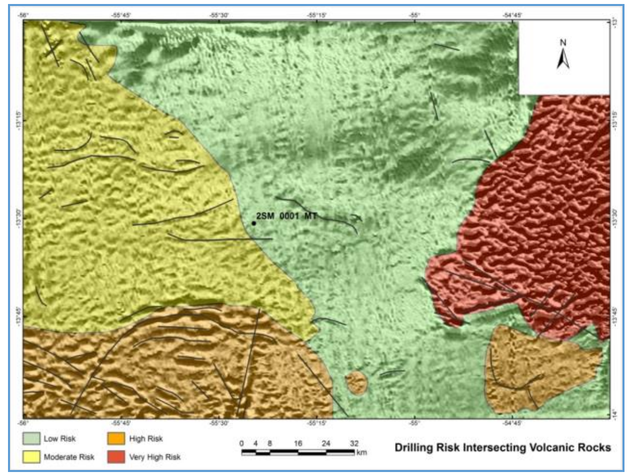

Figure 7 – Mached filter at 425 m of the Total magnetic intensity. The polygons represent the likelihood of wells intersecting igneous rocks in the area of study. The black lines represent mapped linear features in the filter.

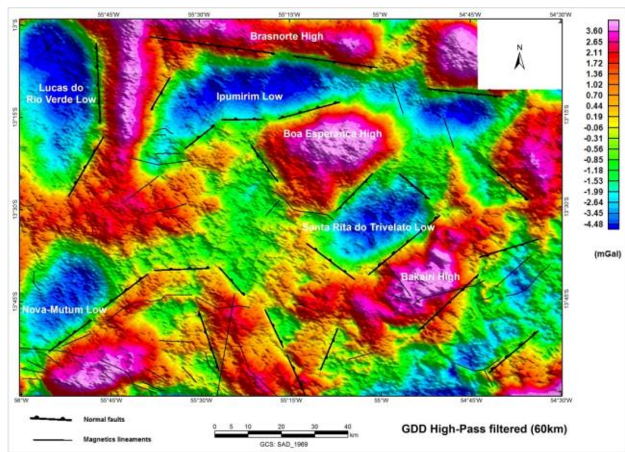

Figure 8 – Structural map of the study area over the High Pass filter of the Conformed gD (60 km).

2D Forward modeling

For this work we used the 2D modeling software called 2MOD^{TM} that is proprietary of CGG Multi-Physics. The program uses Talwani-type polygonal bodies to define the model (Talwani et. al., 1960).

The main objective was to develop an earth model that agrees with the observed seismic, gravity, magnetic and well data. Each layer in the model involves geological and geophysical assumptions: As time to depth relationships, density versus depth and density versus velocity functions (Gardner, 1974) and deep sources were incorporated into the model and tested against the geophysical input data.

The proposed methodology to achieve a consistent 2D forward modeling along the Pimenta Bueno Graben was model along the seismic line 295_010 Parecis, mapping the main geological sequences tied by a composite well log available along seismic profile (Figure 9). Since the seismic profile extends just to the middle of the survey area (Figure 2), the idea was to understand the "geologic behavior" of the layers, basement and extend the model until the end of the survey area using the extracted gravity and magnetic profiles.

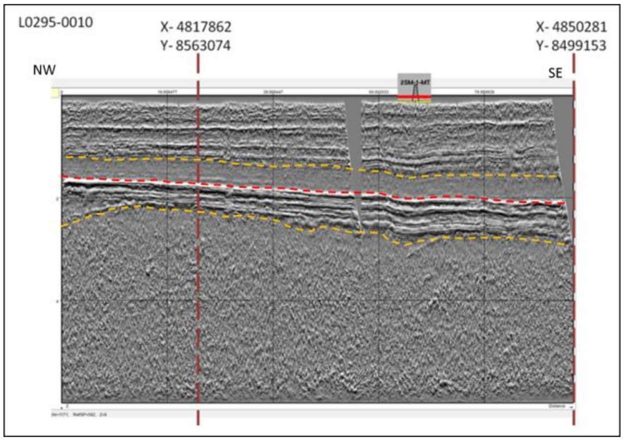

Figure 9 – Seismic Line L0295-0010 with a basic interpretation of the three main sedimentary layers.

The seismic section shows sequences disposed horizontally, plunging softly from west to east in the section and from northwest to southeast in the graben. This preliminary interpretation puts the interpreter of the available data in trouble, since potential fields methods are not an efficient tool to discriminate property contrasts along the vertical direction. Continuing the interpretation, it is possible to discriminate, at least, three main packs of layers (Figure 9), and observe that the signal is lost immediately after the deeper one, around three seconds in the scale.

Assuming the above described framework we produced a 2D model considering this loss of signal represents the interface between sedimentary layers and basement structure. All the parameters used for the modeling are described in Table 1. This first tentative (not shown in this work) showed a strong misfit with the extracted gravity and magnetic profiles. This fact indicated that an important content of the gravity and magnetic signals were not properly mapped, so that we applied some filters over the seismic data, in order to enhance reflectors or structures located bellow this interface, which would indicate the continuation of the sedimentary sequence without a proper mapping from seismic data.

The best result was achieved applying TECVA filter (Bulhões and Amorim, 2005) that enhanced week reflectors in this primary "blind" portion of the section, orienting our work to model deeper basement interfaces. Beyond this, most of the magnetic depth estimations computed along this model, such as, Werner Deconvolution (Werner,1953), Euler Deconvolution (Thompson,1982) and Peters half-slope technic (Peters,1949) generated solutions deeper than this "primary basement". Other indications that Proterozoic basement could be deeper than this interface in the section 295-10 were found in the other lines acquired and processed along the basin by ANP, especially in the Colorado graben, these lines have approximately the same dip of the 295-10. In those lines 295-08, 295-7, the basement was mapped around 4 seconds.

Symbols	Formation	Density (g/cm3)	Susceptibility
	sandstones	2.50	0
	Clastic_siltites	2.54	0
	Clastic_low _energy	2.55	0
	Carbonates	2.56	0
	Rift sediments	2.58	0
	Basement	2.70	1234-6549

Table 1 – Values used for the 2D modeling.

Considering this new context appointed by many different constrains, the final model (Figure 10) was produced deepening the basement interface and ticking the sedimentary Proterozoic section, in consequence, the model showed a clear improvement in the gravity and magnetic profile fitness.

Discussion

The results of the interpretation of this gravity gradiometry and magnetic survey brought many new insights about the geometry of Pimenta Bueno Graben, and mapped significant new features not reported in past publications. In fact, the tight line spacing of 500 meters, and resolution of the survey, were decisive to map innovative features in the geology of the graben, however the flight height, leveled in 760 m (Barometric Flight Height), damaged the final resolution of the data, even considering the advantages of recovering data from a low turbulence operations. The geometry of the FALCON™ Gravity Gradiometry Instrument, measuring the horizontal tensors, allows more aggressive flights, as close to the terrain, as the legislation and safety issue, ideally, from a hundred meters from terrain, that would have improved the high frequency content for both AGG and Magnetic datasets.

For the interpretation process, a conventional workflow was applied generating many enhancements from basic products: conformed gD and total magnetic intensity grid. The 2D model created also adjusted to these extracted profiles along the seismic section. These results mapped many structural features, defining internal compartments inside the Pimenta Bueno graben clearly showed in the high pass filter applied over conformed gD in Figure 8 (<60 km full wavelength).

For the modeling, other approaches using the measured tensors would be more appropriate but their geologic meanings are very complex to evaluate. Other important rule is that the models built did not follow the potential field data along the survey profiles because the available constraints did not coincide with any flight line.

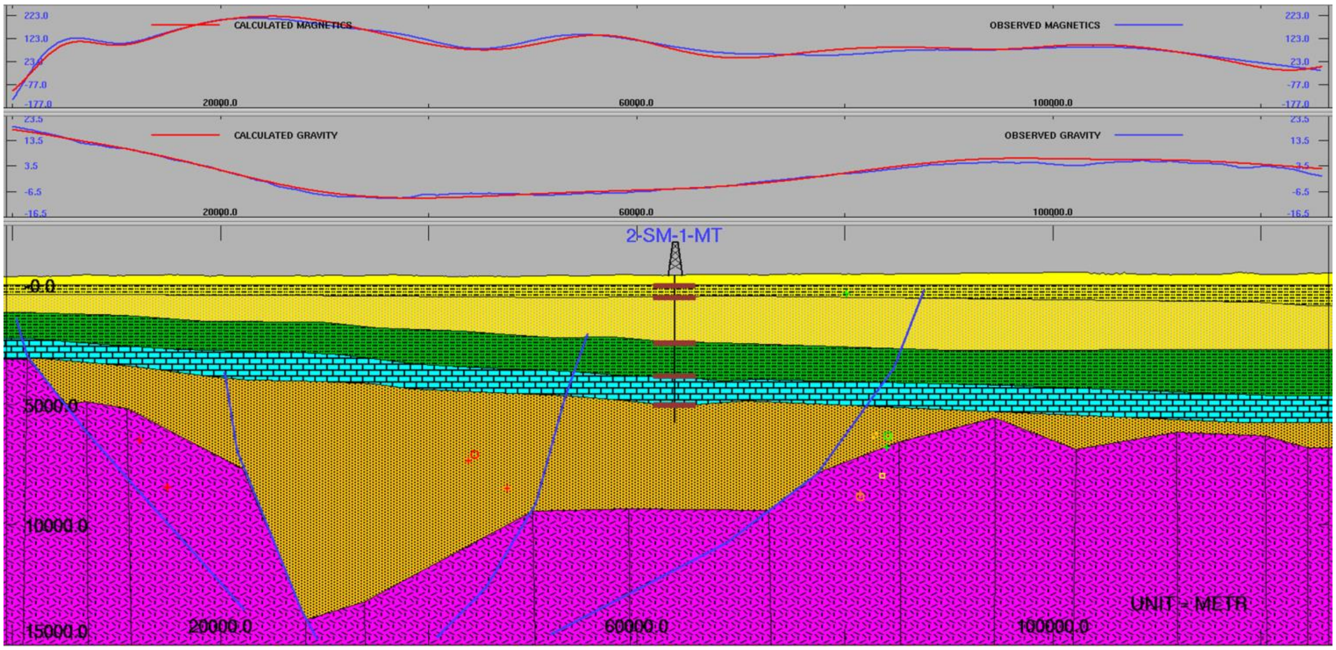

Figure 10 – Final model assuming basement interface locally reaches 13.000 meters of depth and using the density and susceptibility appointed in Table 1.

The option to focus the work in the 2D modeling, despite of the availability of many tools for 3D inversion of gravity data aims to restrict the analyses along the location where constrained data are available: seismic section and well data. Obviously, future works can take advantage of this constrained 2D model to interpolate results for the whole area of the survey, but it also depends on exploratory evolution of the current works being carried by Petrobras in the remaining concessions enclosed by the survey area.

The basement depth estimations from magnetic data were not so fruitful for this scale of investigation, generating few solutions along tested profiles since the gradients related to the low frequency content are small and the magnetic field varies softly in the area of study. This fact would indicate low contrast of magnetite content between basement rocks and the base of the sedimentary Proterozoic sequence. Despite of this, a clear high frequency content may map the spatial igneous rock location. The eastern portion of the magnetic grid shows continuous and extensive group of anomalies that seems to be a “magnetic behavior” of shallow basalt layer. In the southern and southwestern portion of the survey, the magnetic anomalies may be related to linear folded features like extensive dikes, and in the western portion shows located anomalies that could represents small dikes or even kimberlite bodies in the project area.

The basement depth along a representative profile in the survey area and structural compartments mapped inside the Pimenta Bueno Graben are the main results of this work, generating new insights about the maximum depth of basin, tectonic framework, compared with the possible location of igneous rock in the project area.

Conclusions

The technical specifications applied for the airborne gravity gradiometry and magnetic survey over the southern portion of the Parecis basin allowed the achievement of many new insights about the structural framework of the Pimenta Bueno graben. Beyond the 2D geologic model created, many other geologic features were mapped. Other reliable models along the area of the survey depend on the availability of new seismic surveys and new wells that certainly will happen because the evolution of the exploratory activity in the conceded blocks and future foment surveys sponsored by Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP).

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References

ALMEIDA, F. F. M., 1983. Relações Tectônicas das Rochas Alcalinas Mesozóicas da Região Meridional da Plataforma Sul-Americana. *Revista Brasileira de Geociências,* São Paulo, **13(3)**: 139-158.

BAHIA, R. B. C.; 2007. Ouro Preto, Minas Gerais, Brasil: Universidade Federal de Ouro Preto, Phd Thesis, 149pp.

Boggs, D. B. and Dransfield, M. H., 2004, Analysis of errors in gravity derived from the Falcon® airborne gravity gradiometer, Lane, R. (ed.), *Airborne Gravity 2004 - Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop,* Geoscience Australia Record 2004/18, 135-141. CD-ROM.

BRAGA, L.F.S., SIQUEIRA, L.P., 1995. Three-Dimensional Gravity Modelling of the Basement Topography Beneath Parecis Basin, Brazil, Constrained by Espectral Estimates of Depth to Magnetic Sources. *Latin American Petroleum Congress*, 5. Rio de Janeiro, outubro 1995, 8p.

Gardner, G. H. F., L. W. Gardner, and A. R. Gregory (1974). Formation velocity and density—the diagnostic basics for stratigraphic traps, Geophysics **39**, 770-–780.

Haeser, B. 2013, *Brazil 12th Round*: *Oil & Gas Bidding Rounds – Parecis Basin patterns*, ANP webpage, Brazil, viewed 15 December 2013, <http://www.brasil-rounds.gov.br/arquivos/Seminarios_R12/apresentacao/Parecis_R12_English.pdf>.

Lee, J. B., 2001, FALCON Gravity Gradiometer Technology, *Exploration Geophysics*, **32**, 75-79.

Lee, J. B.; Liu, G.; Rose, M.; Dransfield, M.; Mahanta, A.; Christensen, A. and Stone, P., 2001. High resolution gravity surveys from a fixed wing aircraft, *Geoscience and Remote Sensing Symposium, 2001. IGARSS '01. IEEE 2001 International*, **3**, 1327-1331.

Peters, L. J., 1949. The direct approach to magnetic interpretation and its practical application. Geophysics, **14**:290-320.

Siqueira L.P. & Teixeira L.B. 1993. Bacia dos Parecis: novafronteira exploratória da Petrobras. *In*: SBGeof., Congr. Intern. Soc. Bras. Geof., 3, *Resumos Expandidos*, p.168-170.

Talwani, M., Worzel, J. L. & Landisman, M., 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. Jour. Geophys. Res. **64(1):**49-59.

Thompson, D.T., 1982, EULDPH: A new technique for making computer-assisted depth estimates from magnetic data: Geophysics, v. **47**, p. 31-37.

Werner H, Wapner S, Bruell J (1953) Experiments on sensory-tonic field theory of perception: VI. The effect of position of head, eyes, and of object on the position of the apparent median plane. J Exp Psychol **46**: 293–299.