Magnetometry Applied in the Alto Xingu Sub-Basin, Mato Grosso, Brazil

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Abstract

This paper presents an application of aerial magnetometry in the Alto Xingu Sub-Basin, Brazil. This large area of around 200,000 km^2 is covered by large forests hampering terrestrial acquisitions. The aeromagnetic data acquired allow the study of a little explored region which is located in a sedimentary basin possible carrier of natural gas and also unconventional gas (shale gas). The aeromagnetic data received initial treatment by leveling and microleveling techniques. After this, the subtraction of the diurnal variation and IGRF field was performed to isolate the magnetic anomaly. Finally, we calculated the horizontal and vertical derivatives, analytic signal and reduction to magnetic equator of the magnetic anomaly that helped to identify the location of the main magnetic bodies. The maps obtained by magnetometry are compared with a Bouguer anomaly map and they are correlated to tectonic domains in the region.

Keywords: Magnetometry, Sedimentary Basin, Aeromagnetic Survey

1   Introduction

The aim of a magnetic survey is to investigate subsurface geology on the basis of anomalies in the geomagnetic field resulting from the magnetic properties of the underlying rocks [1]. The magnetic anomaly comes from the contrast in magnetization when rocks with different magnetic properties are adjacent to each other, as, for example, when a strongly magnetic basaltic dike intrudes a less magnetic host rock. The stray magnetic fields surrounding the dike disturb the geomagnetic field locally and can be measured with instruments called magnetometers [2]. Magnetic survey is a widely employed technique in large areas like the Alto Xingu Sub-Basin. The region has active petroleum systems with many points of gas exudation as found for over 800 meters along the Teles Pires River. In this region, six blocks have been auctioned in the 10th Oil & Gas Bidding Round. In this context, a mesh of nearly 200,000 km^2 treatable magnetic data is available. By processing these data it is intended to locate the main magnetic bodies and

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to correlate these magnetic bodies found with the regional tectonic.

2   Study Area

The Alto Xingu Sub-Basin was classified by Siqueira (1989) [3] and revised by Bahia (2007) [4] as a syneclise type inner basin. It is located in the eastern sector of the Parecis Basin which is one of the largest Brazilian intracratonic basins (Figure 1).
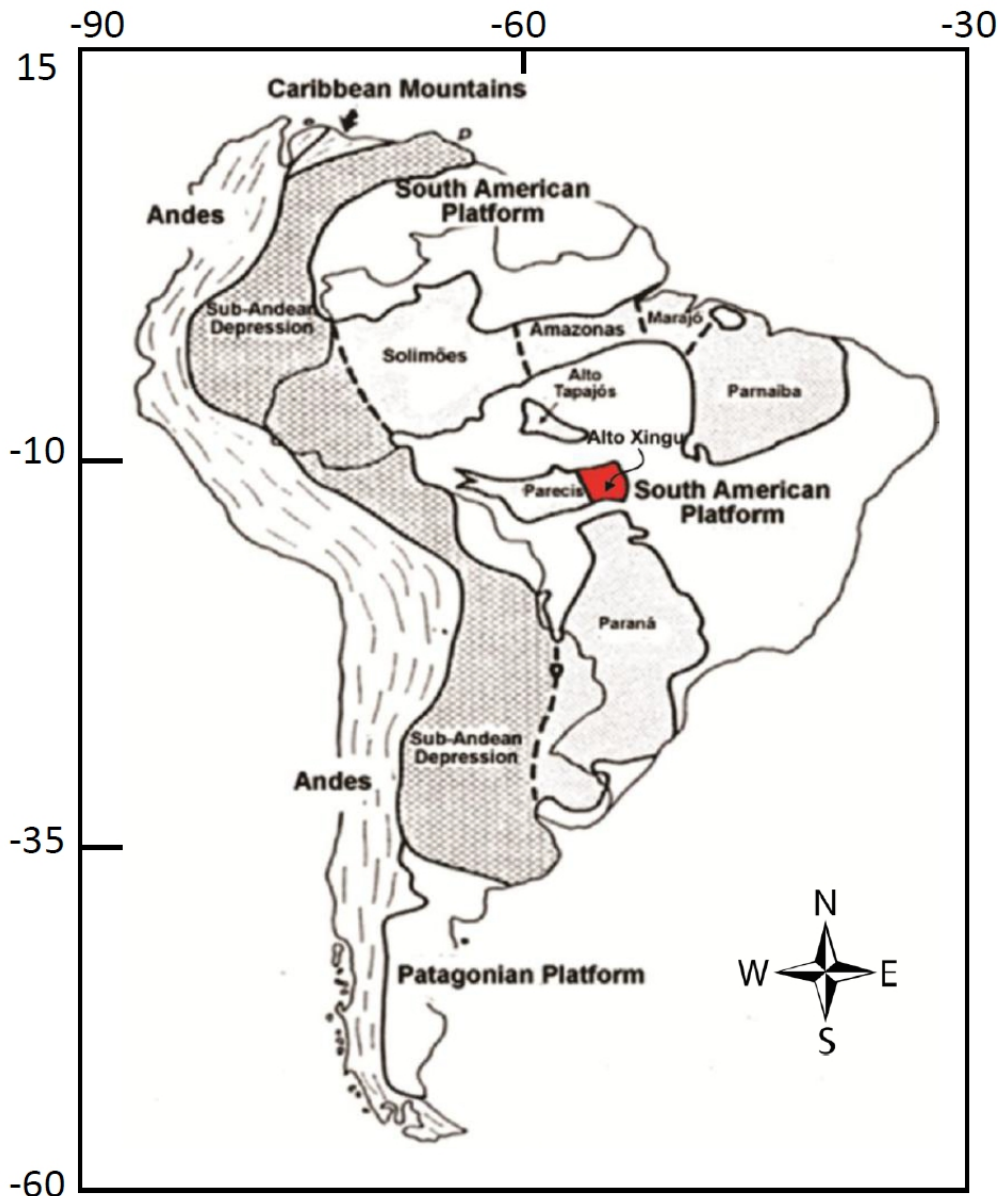

Figure 1: Distribution of sedimentary basins in Brazil (modified from Siqueira, 1989) [3].

The topographic map of the terrain indicates that, in most of the basin, the altitudes range

from around 200 meters (blue portion of Figure 2) up to almost 500 meters in the southern portion of the basin (pink portion of Figure 2).
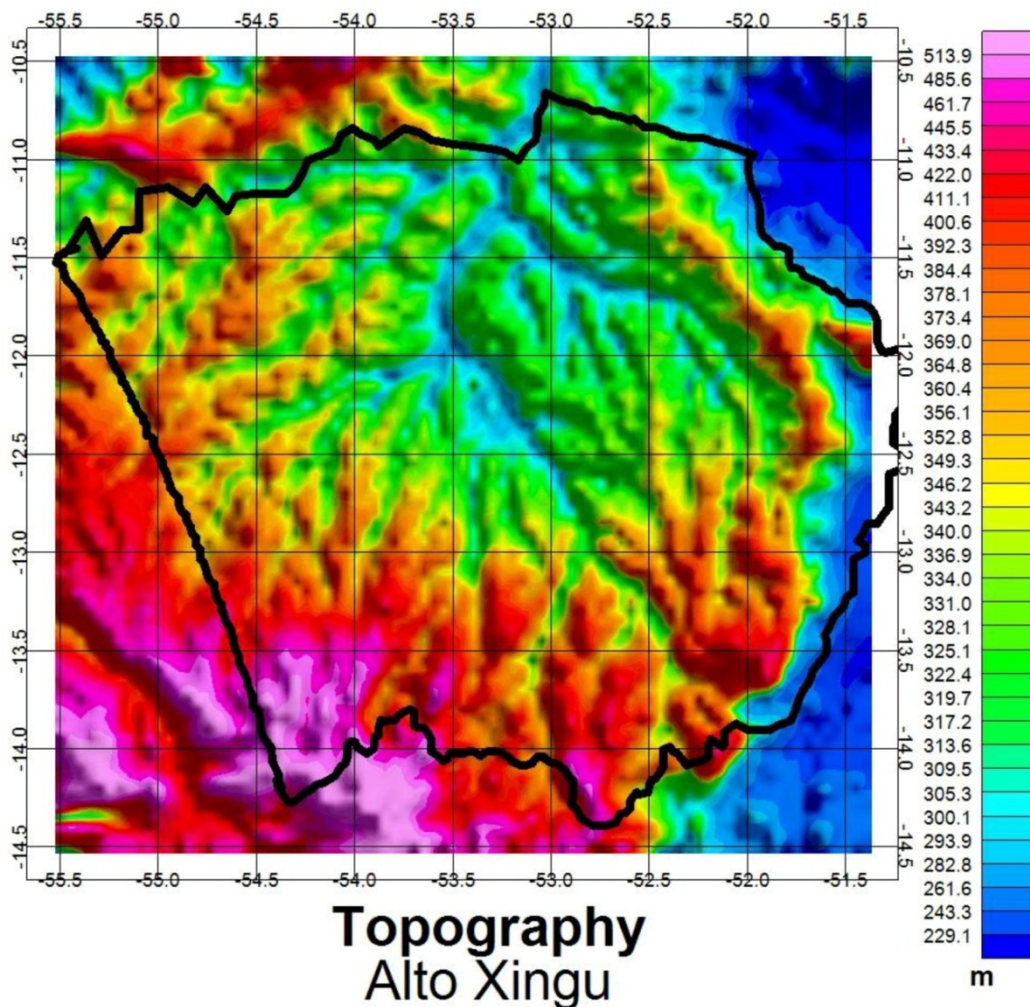

Figure 2: Alto Xingu Sub-Basin topography.

The Basin contains sediments of Paleozoic, Mesozoic and Cenozoic that include volcanic rocks - flows and dikes - from the Cretaceous (Figure 3). Its basement is the Amazon Craton comprising high and low metamorphic, metasedimentary and intrusive rocks.
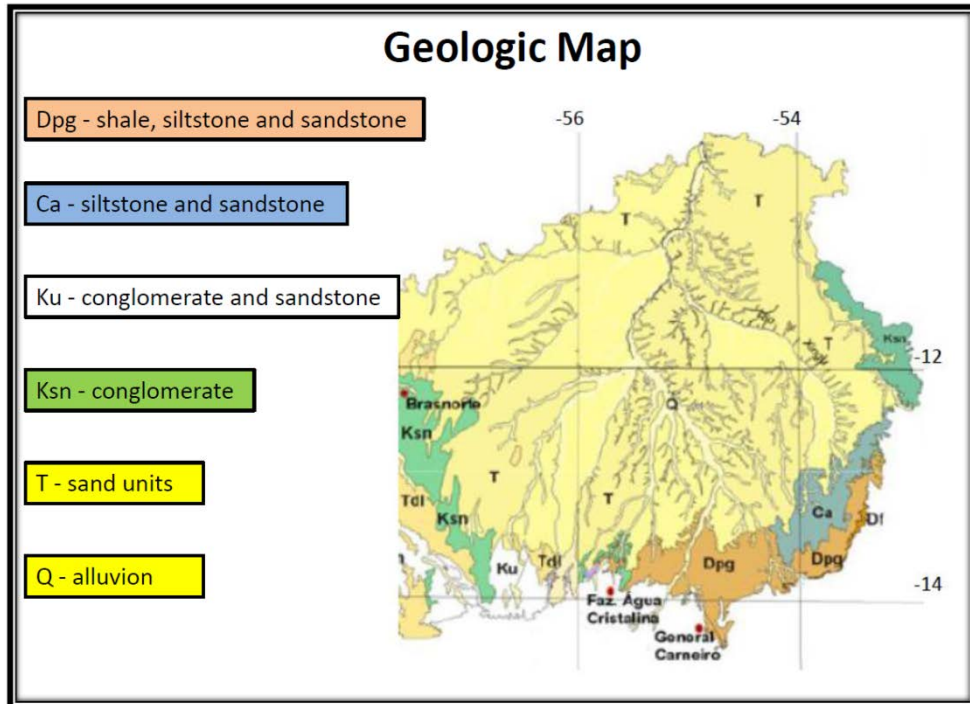
Figure 3: Geologic map of the Alto Xingu Sub-Basin (modified from Bahia, 2007) [4].

The region is separated from the Juruena Sub-Basin by the Serra Formosa Arc and, as southern boundary with Paraná Basin, the Alto Xingu Arc. The Alto Xingu Sub-Basin tectonic domains are shown in Figure 4 [4].
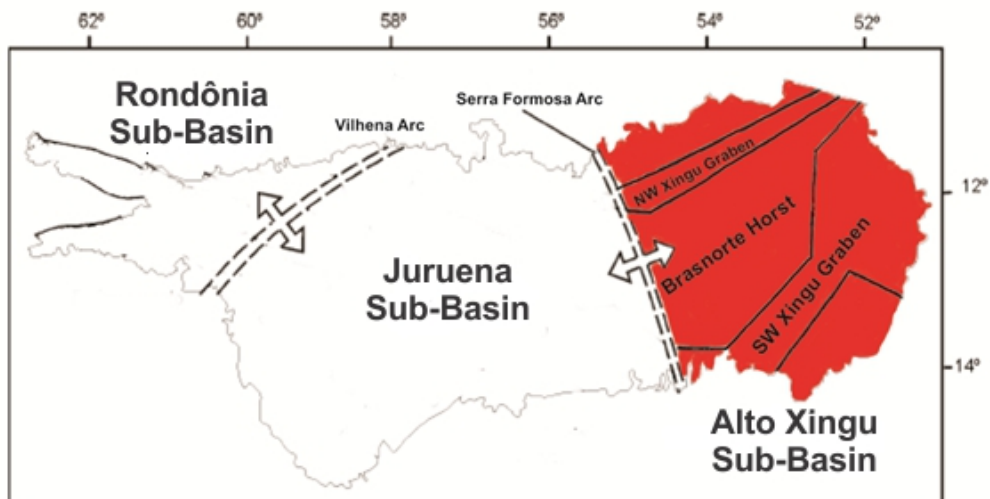

Figure 4: Tectonic domains of the Alto Xingu Sub-Basin (modified from Bahia, 2007) [4].

The graben-horst structures may also be noticed through the Bouguer anomaly map

obtained by Santos (2013) [5] (Figure 5). This map was generated by a method based on rock density and gravitational attraction. It allows the identification of the main structures of the basin.
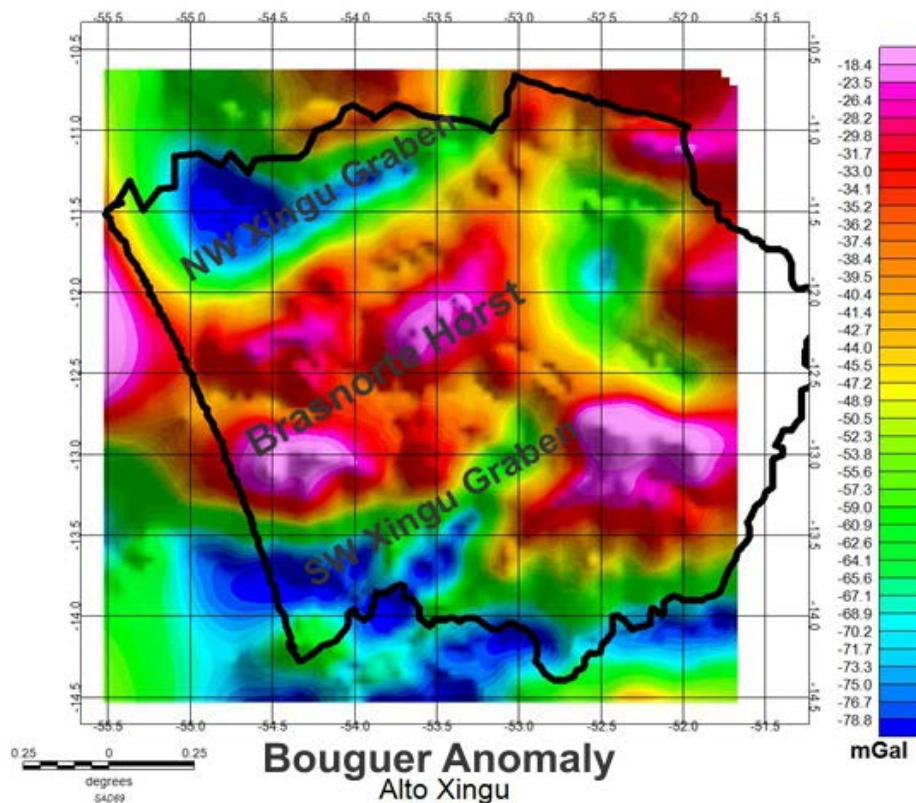

Figure 5: Bouguer anomaly map of Alto Xingu Sub-Basin (modified from Santos, 2013) [5].

3   Available Data

The expectation of natural gas production led PETROBRAS to promote various geophysical surveys in the Alto Xingu Sub-Basin. So it is covered by aeromagnetic surveys (Figure 6 and Figure 7) that generated the data used in this work.

3.1 Project Parecis Basin (Alto Xingu Sub-Basin) / Block 1

The survey covering 94,662 km^2 was executed in constant altitude of 1,000 meters by a Islander aircraft whose average speed was 200 km/h. The sampling interval was 50 m. The flight lines were spaced 3 km at N15W direction and the control lines were spaced 18 km at N75E direction (Figure 6).
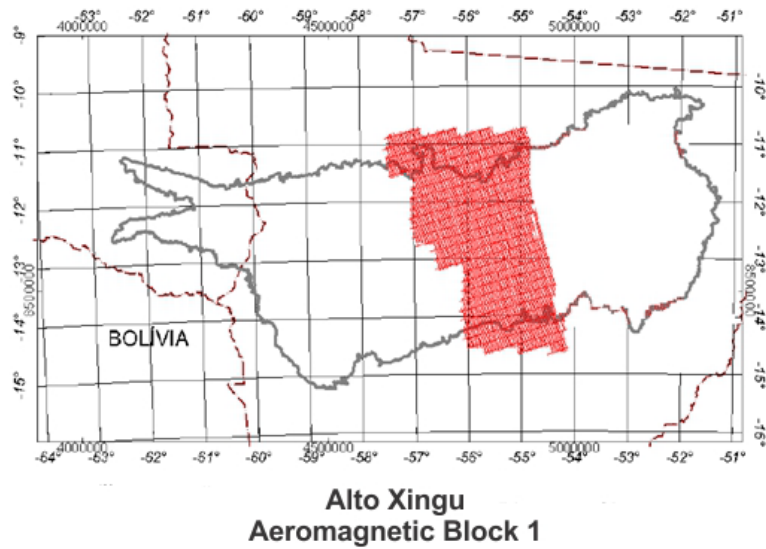
**Alto Xingu
Aeromagnetic Block 1**

Figure 6: Project Parecis Basin (Alto Xingu Sub-Basin) / Block 1.

3.2 Project Parecis Basin (Alto Xingu Sub-Basin) / Block 2

The magnetic survey covering 101,850 km^2 was executed in constant altitude of 1,060 meters by a Dehavilland aircraft whose average speed was 200 km/h. The sampling interval was 50 m. The flight lines were spaced 6 km at N15W direction and control lines were spaced 18 km at N75E direction (Figure 7).
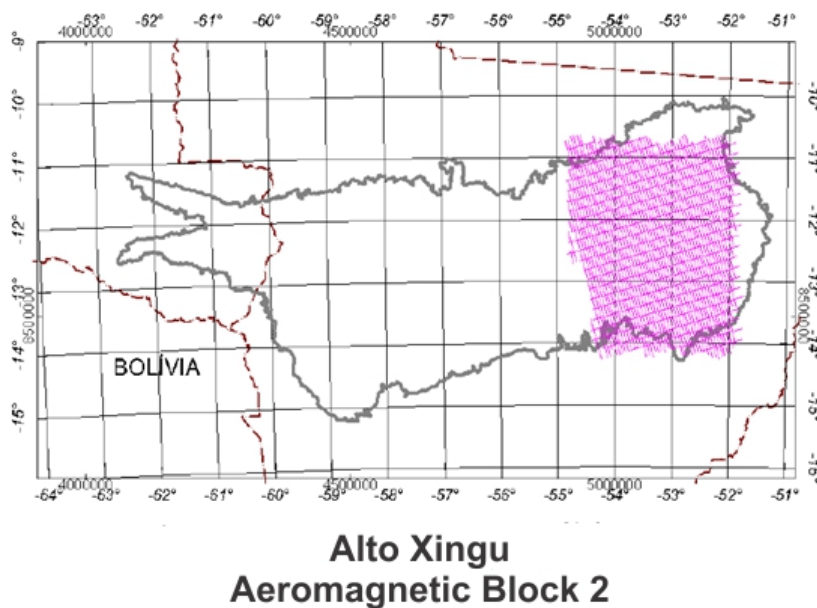

**Alto Xingu
Aeromagnetic Block 2**

Figure 7: Project Parecis Basin (Alto Xingu Sub-Basin) / Block 2.

4 Methods

The magnetometric method is a technique that uses information from the geomagnetic field to investigate subsurface structures. The geomagnetic field induces a secondary magnetic field in rocks and geological structures. These modifications of the magnetic field can be analyzed to investigate the causative sources of the anomalies. It is a quick and efficient method of acquiring and processing information, which can be used effectively in conjunction with other geophysical methods to evaluate of mineral exploration targets.

4.1 Magnetic Anomaly

The magnetometry belongs to the family of potential geophysical methods, not requiring an artificial source. It consists of measuring the total magnetic field and corrections in order to obtain the called magnetic anomalies related to the crust. The magnetic anomalies allow the subsurface investigation. This is done through the following expression:

$$AMF = MF - (EMF + IGRF) \qquad (1)$$

AMF - Anomalous Magnetic Field (<1%)
MF - Measured Field
EMF - External Magnetic Field (Diurnal - sources external to the planet)
IGRF - International Geomagnetic Reference Field - IGRF (99%)

Sedimentary rocks generally have lower magnetic susceptibility than igneous and metamorphic rocks (Figure 8). Thus, the magnetic measurements are directly related to features of the basement or the presence of intrusive rocks.
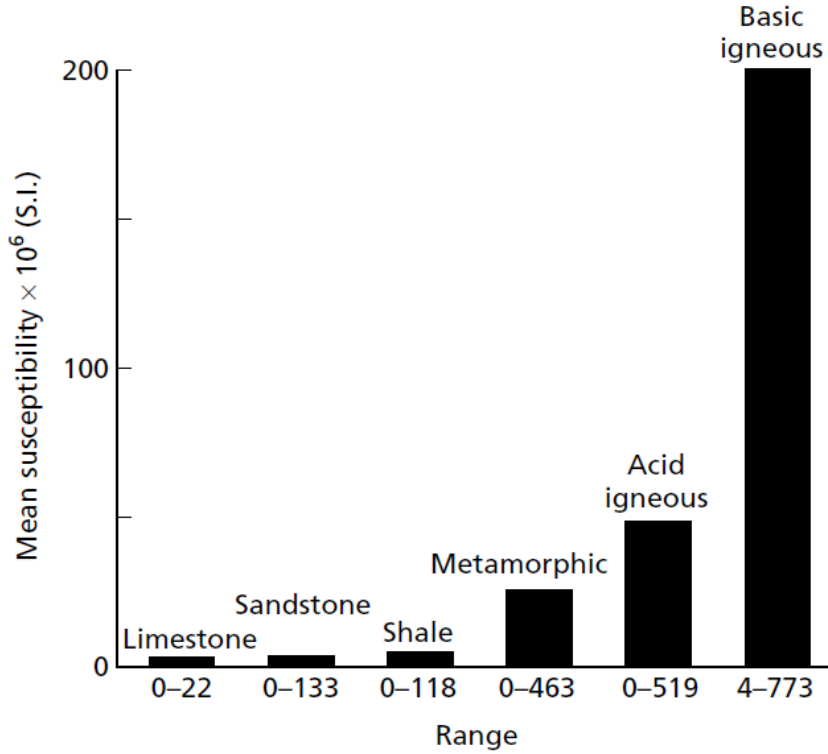
Figure 8: Magnetic susceptibilities of some rocks [1].

When the magnetic anomalies are observed in areas covered by sediment, they are usually caused by an igneous or metamorphic basement, as well as intrusions. Common causes of magnetic anomalies include dykes, sills, intrusions of basic rocks, metamorphic basement and rocks with magnetite ore [1].

4.2 Enhancement Techniques

The magnetic data can be processed through enhancement techniques to provide more subsurface information as estimates of lineaments and location of magnetic bodies [6]. The enhancement techniques used are the horizontal and vertical derivatives, analytic signal and reduction to magnetic equator.

4.2.1 Horizontal and Vertical Derivatives

They are techniques for enhancement of the magnetic signal where the magnetic anomaly (*T*) undergoes a linear transformation through derivative of the horizontal and vertical components of the anomalous magnetic field. In the Fourier domain the horizontal derivatives are given by

$$F\left[\frac{d^n T}{dx^n}\right] = (ik_x)^n F[T] \tag{2}$$

and

$$F\left[\frac{d^n T}{dy^n}\right] = (ik_y)^n F[T] \tag{3}$$

where k_x and k_y are the wave numbers in the x and y directions. These filters transform function on a horizontal surface through nth order derivative with regarding to x and y respectively [6].

The vertical derivative can be obtained through the previous expressions and the Laplace equation. Thus, the vertical derivative of nth order with k_z wavenumber is given by:

$$F\left[\frac{\partial^n T}{\partial z^n}\right] = (k_z)^n F[T] \tag{4}$$

The images of horizontal and vertical derivatives allow to visualize more clearly the contrasts between different magnetic domains identified through the image of the anomalous magnetic field.

4.2.2 Magnitude of Analytical Signal

The amplitude of the analytic signal is a technique that allows locating the magnetic source without the incorporation of remanent magnetization. Besides this advantage, it can be applied at low latitudes where other techniques fail, as in the case of the reduction to the magnetic pole.
The analytic signal is formed by combining the vertical and horizontal gradients of the magnetic anomaly. Its amplitude is given by:

$$\left|A_{(x,y)}\right| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \tag{5}$$

where T is the potential field anomaly, $\left(\frac{\partial T}{\partial x}\right)$, $\left(\frac{\partial T}{\partial y}\right)$ and $\left(\frac{\partial T}{\partial z}\right)$ (horizontal derivatives in x and y directions and vertical derivative in z, respectively).

4.2.3 Reduction to Magnetic Equator

The study area has low latitude, therefore the reduction to pole technique had its use strongly discouraged due to the problems of instability in regions of low magnetic inclination. Thus, we preferred to use the reduction to magnetic equator technique that may facilitate the understanding of the areas that have high and low values of magnetic field.

5   Results and Interpretation

The data collected by the aircraft cover most of the basin, however no data were available in longitudes greater than - 52°. These data contain errors in the direction of flight lines (Figure 9) that must be removed by leveling and microleveling operations. These data are a sum of the magnetic field of the nucleus, the influence of the external magnetic field and the crustal magnetic field that is really what we are interested. Thus, these data need to be processed before interpretation and require some corrections.
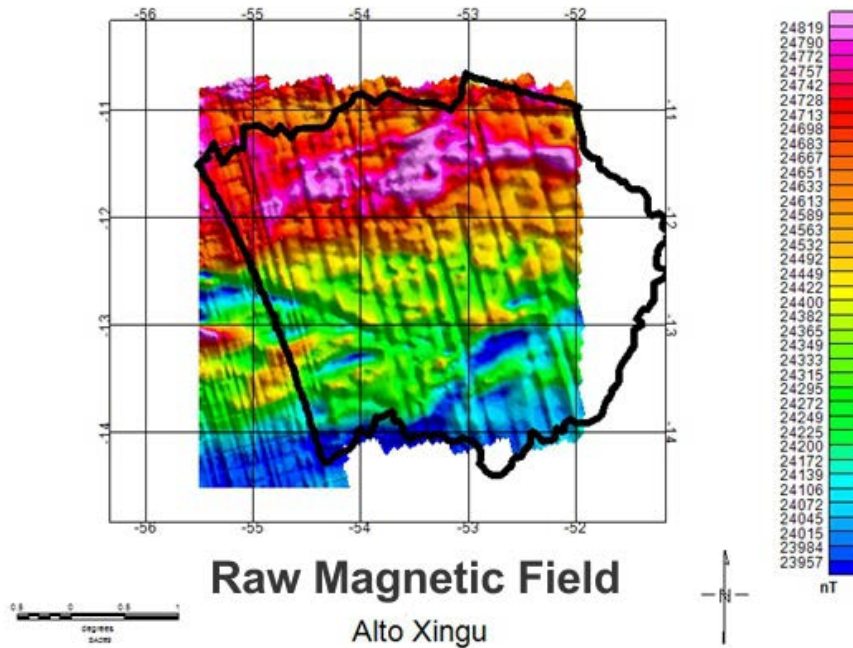
Figure 9: Raw magnetic field map.

The errors in the direction of flight lines can be corrected by leveling techniques and also microleveling (application of the Butterworth filter). The tie-line leveling is based on the differences in the measured field at the intersection of flight lines and tie-lines. If the distance and, hence, the time taken to fly between these intersection points is small enough then it can be assumed that the diurnal varies approximately linearly and can be corrected [7].

The core magnetic field is of the order of thousands of nanotesla. This field can be estimated with close estimate by mathematical models called International Geomagnetic Reference Field (IGRF) (Figure 10).
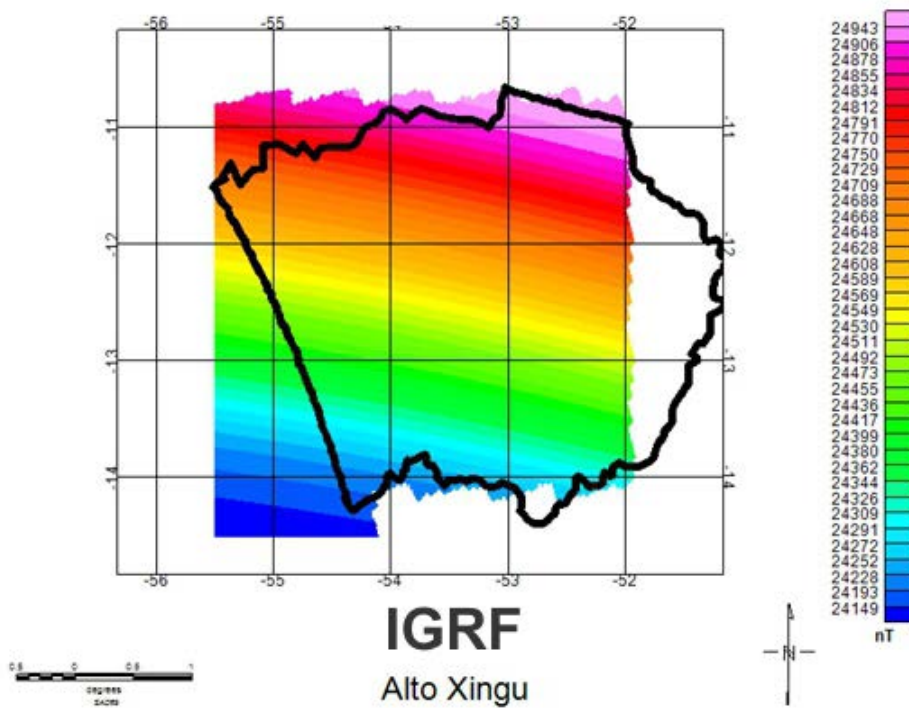
Figure 10: IGRF of 1995 in the Alto Xingu Sub-Basin.

Since the Earth's magnetic field varies temporally as well as spatially, time variations that occur over the period of surveying must be determined and removed from the raw measurements. The dominant effect for airborne surveys is the diurnal variation (Figure 11), which generally has an amplitude of tens of nanotesla. Shorter time-period variations due to magnetic storms can be much larger (hundreds of nanotesla) and severe enough to prevent survey data collection. Data can also be degraded by micropulsations with short periods and amplitudes of several nanotesla [7].
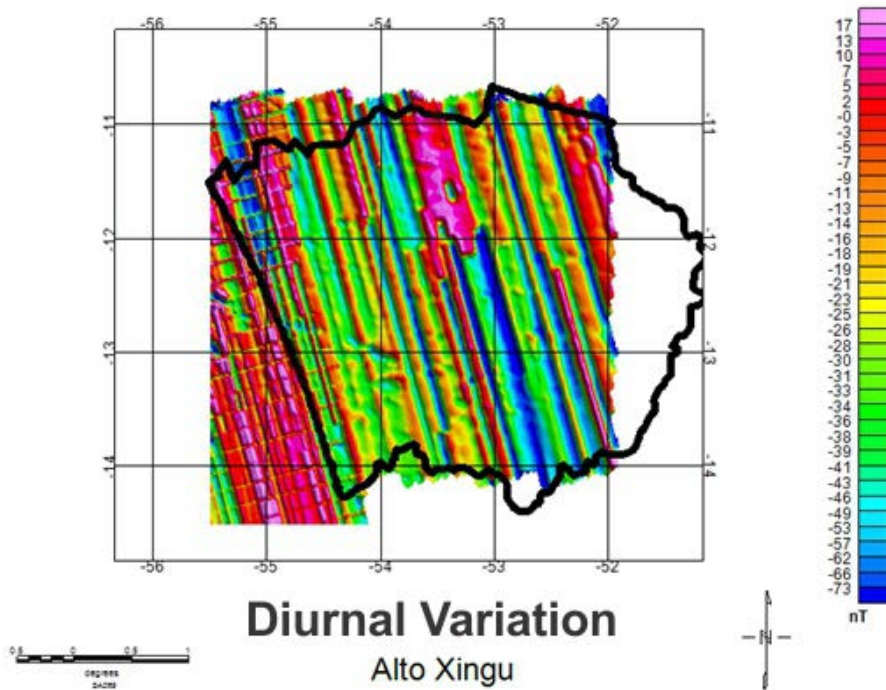
Figure 11: Map of diurnal variation of surveys conducted in the Alto Xingu Sub-Basin.

The Monitoring of the Earth's magnetic field is an essential component of a survey to mitigate these time-varying effects. One or more base stations can be used to track changes in the field during survey operations. The observed differences in the readings of the base are then distributed among the measures according to their time of observation [1].

Thus, with the knowledge of the IGRF and diurnal variation and also the use of Equation 1, we obtained the magnetic anomaly map of the Alto Xingu Sub-Basin (Figure 12).
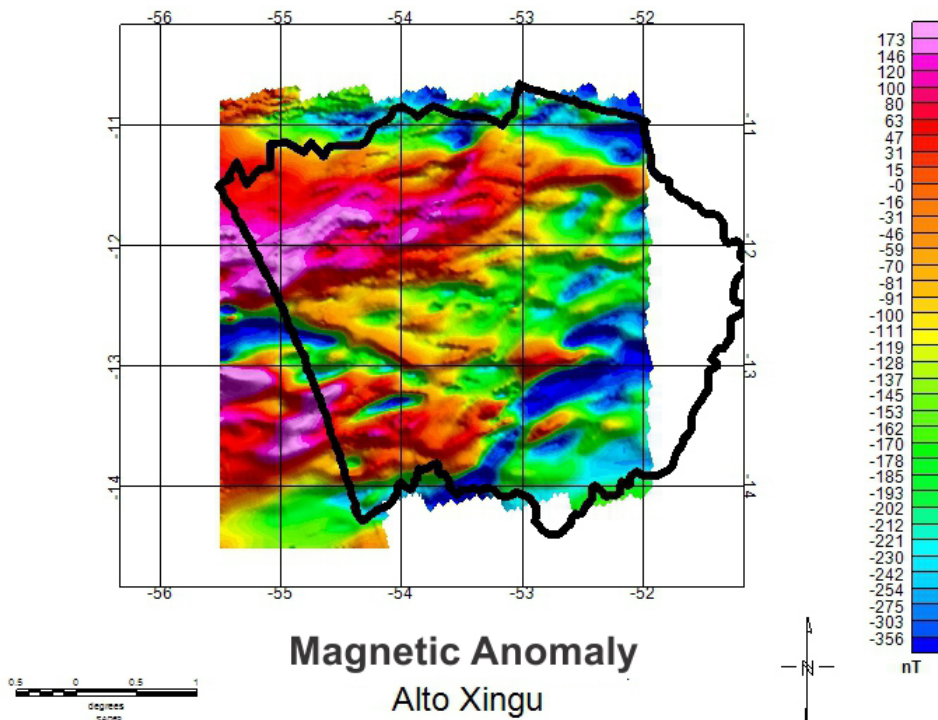
Figure 12: Magnetic anomaly map.

This map reflects the crustal magnetism in the region. It shows strong magnetic anomalies associated with the border regions between the Brasnorte Horst and the adjacent grabens. Therefore, it confirms the tectonic domains defined by Bahia (2007) [4] (Figure 4) and Santos (2013) [5] (Figure 5).

The study area is located near the magnetic equator. It has -7 degrees of magnetic inclination. Therefore, there are no major changes in the magnetic anomaly after applying reduction to magnetic equator technique (Figure 13). However, the anomalies of positive and negative amplitudes were more enhanced through this technique.
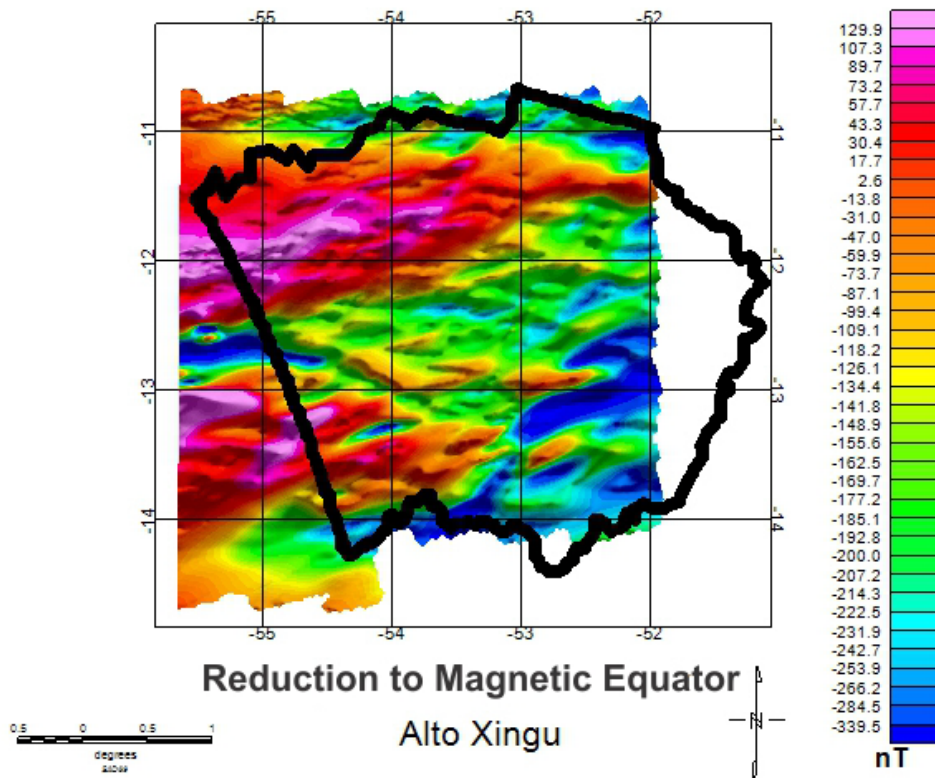
Figure 13: Reduction to magnetic equator map.

The maps of horizontal derivatives in X and Y directions (Figure 14 and Figure 15) and vertical derivative (Figure 16) allow to view a predominance of lineaments in a northeast-southwest directions. They confirm the lineaments obtained by Bahia (2007) [4] (Figure 4) and Santos (2013) [5] (Figure 5) by gravity data.
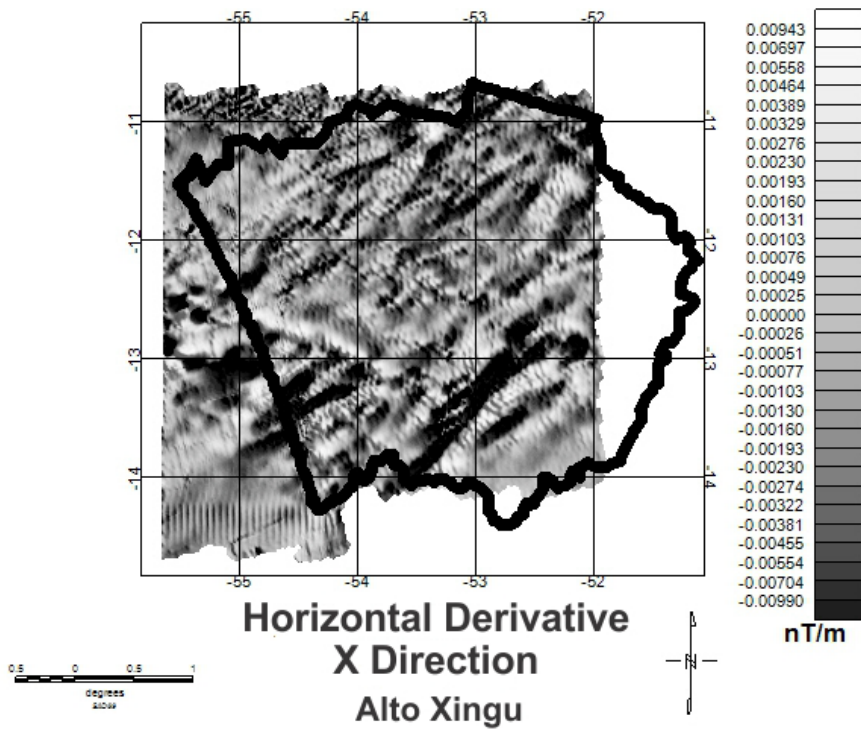
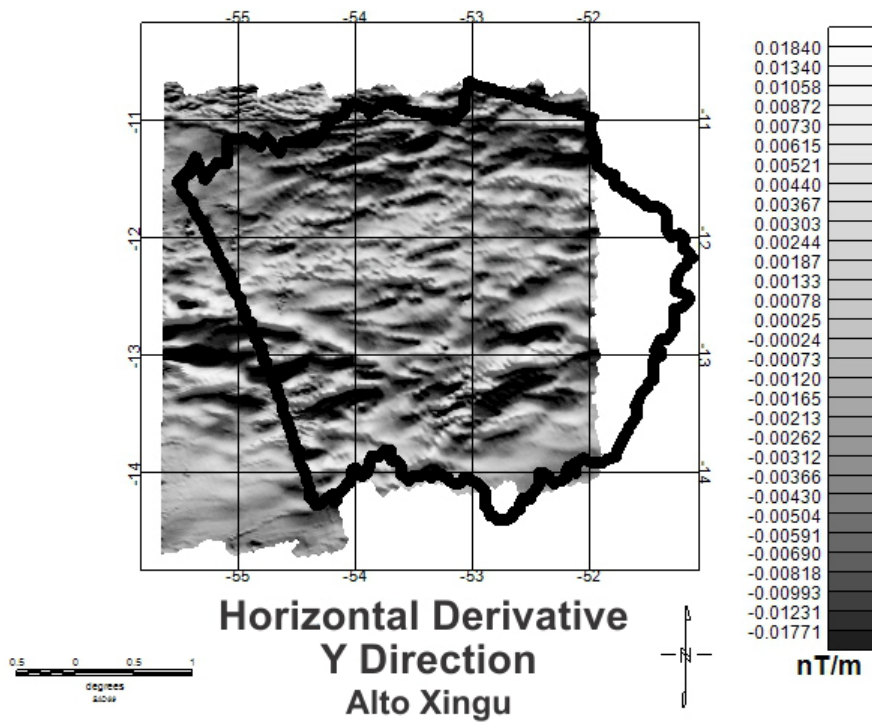Figure 14: Horizontal derivative in the X direction.

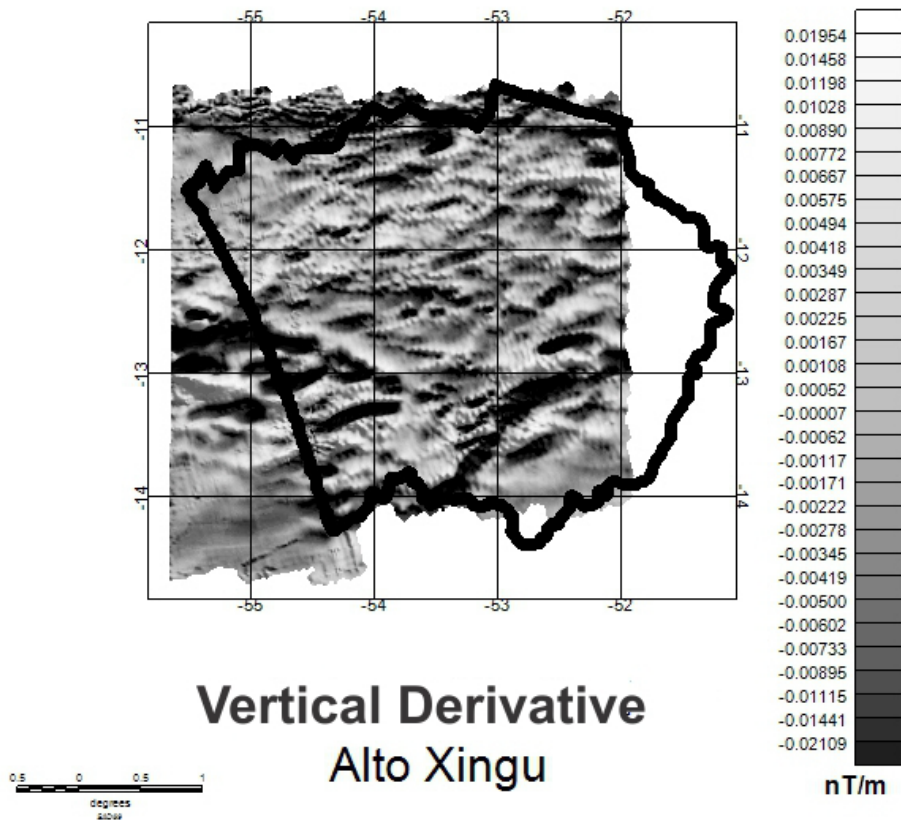Figure 15: Horizontal derivative in the Y direction.

Figure 16: Vertical derivative.

The combination of the three derivatives (Figures 14, 15 and 16) gives the amplitude of the analytic signal according to Equation 5. The location of the larger anomalies is confirmed by the amplitude of the analytic signal map (Figure 17) that produces maximum on the magnetic contacts regardless of the direction of magnetization. It illuminates with efficiency the magnetic bodies associated with the major fault events. These events are observed at the boundaries between the Brasnorte Horst and its adjacent grabens.
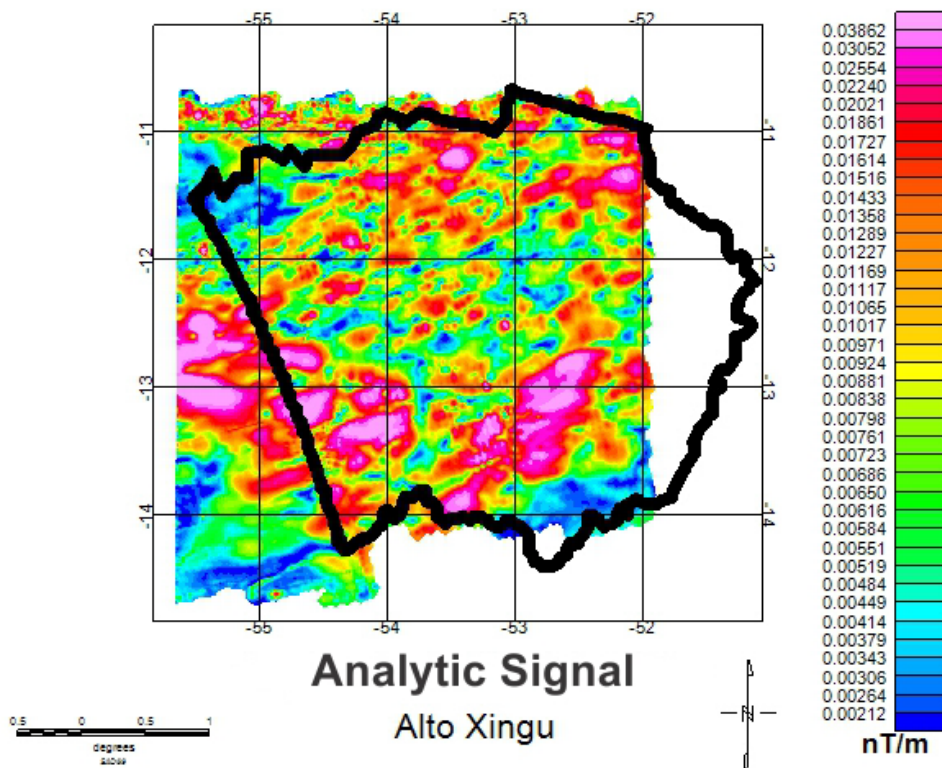
Figure 17: Amplitude of the analytic signal map.

6   Conclusions

The Alto Xingu Sub-Basin is a very little explored region. It is an area covered by forests and Indian reservations that have caused restrictions and lack of interest to research in previous decades. The recent discovery of an active petroleum system and robust gas seeps aroused the interest of the market to promote new research in the region. The magnetometric method allowed locating the main sources of magnetic field and the faulting regions. The data obtained were consistent with the Bouguer anomaly map of the region (Figure 5) locating the key structural features efficiently. We believe that the maps generated in this work could be used as support in further studies. Finally, we suggest the use of the Euler deconvolution technique that can provide estimates of the depths of magnetic sources and also a combined study of magnetometric and seismic methods in the areas of greatest economic interest.

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