Non-seismic methods: RAS, SPI and AS Magnetic Basement Depth Estimation

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Abstract

The development of sedimentary basins is essentially controlled by responses in the crust to tectonically driven forces. The way in which the crust responds to those forces is controlled by the strength, composition and fabric of the crust at the time of the tectonic event. The properties of the basement can be characterized by magnetic and gravity data, as well as with seismic and well log data.

The upper crust is considered as the major source of the magnetic anomalies and has been divided into a number of units characterized by constant densities and magnetization, which show a good correlation with the main structural elements of the Eastern Venezuela's Basins. In E&P prospecting, aeromagnetic information give us evidence from which we can determine depths to basement rocks and thus locate and define the extent of sedimentary basins.

This work seeks to contribute to the study of Espino Graben (associated with Atlantic Ocean opening) through magnetic basement maps with gravity constraints. A combination of *Source Parameter Images* (SPI) and *Analytical Signal* (AS) were employed to evaluate the depth to source magnetic rocks. This research shows the critical role that *non-seismic* methods play for Interpreters, who can use themas tools to appreciate the tectonic features of the basins on geodynamic-scale. The seismic geometric attributes such as gradient and curvature, show the edges of the main geological / geophysical domains, and the depth of such domains were derived from SPI and AS approaches. Besides seismic data, a number of magnetic surveys compilations were used to gain insights into the deep crustal geometries. Furthermore, gravity anomalies were used to focus on the Espino graben crustal structure in a consistent way.

Introduction

The examination of isolated residual and regional magnetic anomalies serves to estimate the shallow and deep structures, respectively. The RAS (*Radial Average Spectrum*; Spector and Grant, 1970; Bhattacharyya and Leu, 1975) gave the first and whole information about the main interfaces in the subsurface in the area of study. Also, *Analytical Signal* (AS; Nabighian, 1972, 1974; Roest *et al*. 1992) and *Source Parameter Images* (SPI; Thurston and Smith, 1997) methods allowed us to estimate the depth of magnetic basement.

Tectonic and Regional Stratigraphy

The Espino Graben represents one of the most important exploration opportunities in Venezuela. As shown in Figure 1, it is a structure of approximately 80 Kms wide, and at least 120 Kms long, with an orientation N50 - 60ºE. The sedimentary thickness is over 22,000 feet, with a fill of Cretaceous – Jurassic - Paleogene rocks. (Salazar, 2006). The sequences include lacustrine deposits that generated good seals and source rocks (Solorzano *et al*., 2001). The graben, produced by the separation of the North and South American plates, was formed during the Jurassic rifting.

Most 2D / 3D seismic interpretations were focused in Cretaceous / Paleogene formations. These studies concluded (Barrios *et al*., 2011) that the structure of the graben is a result of block faulting and inversion, with transfer zones that generated positive structures and depocenters associated with lacustrine deposits which favored the prospectively of the area. The graben has been reactivated several times, producing three types of structures: rotated blocks, transfer zones and roll overs, evidenced by the propagation of faults at different levels during the Cretaceous - Oligocene and Miocene.

The Eastern Venezuela's Basins were affected by four geodynamic phases (Parnaud *et al*. 1995):

- Pre - rift Paleozoic (Continental pre-aperture)
- Rift and drift Jurassic / Early Cretaceous (Continental aperture)
- Passive margin Cretaceous-Paleogene
- Oblique collision Neogene / Quaternary

As a concluding result of these four stages or evolutionary phases, the tangible stratigraphy and structure reflect the change from passive margin into a foreland basin. The key normal faults-system of the Jurassic rift and drift phase that are recognized within the study area (Figure 2) were interpreted by Salazar (2006) and Barrios et al. (2011) using E&P seismic evidence. As per this interpretation, Ruiz Sabán, Guamal Sabán, Tinajones, Aníbal, Altamira, and Anaco, are the external Espino Graben's boundaries, which cover an area of 22,000 square miles (Figure 2).

Aeromagnetic and Gravity Regional RAS Framework

The total magnetic intensity data of EVsB (Eastern Venezuela's basin, Figure 3) were obtained from the aeromagnetic oil company surveys during the 1980s. The merging of different investigations has allowed the recognition of trend geometry and anomaly character, of the geologic features in the total magnetic anomalies such as fault blocks, SW-NE faults, oblique to east-west shear, and

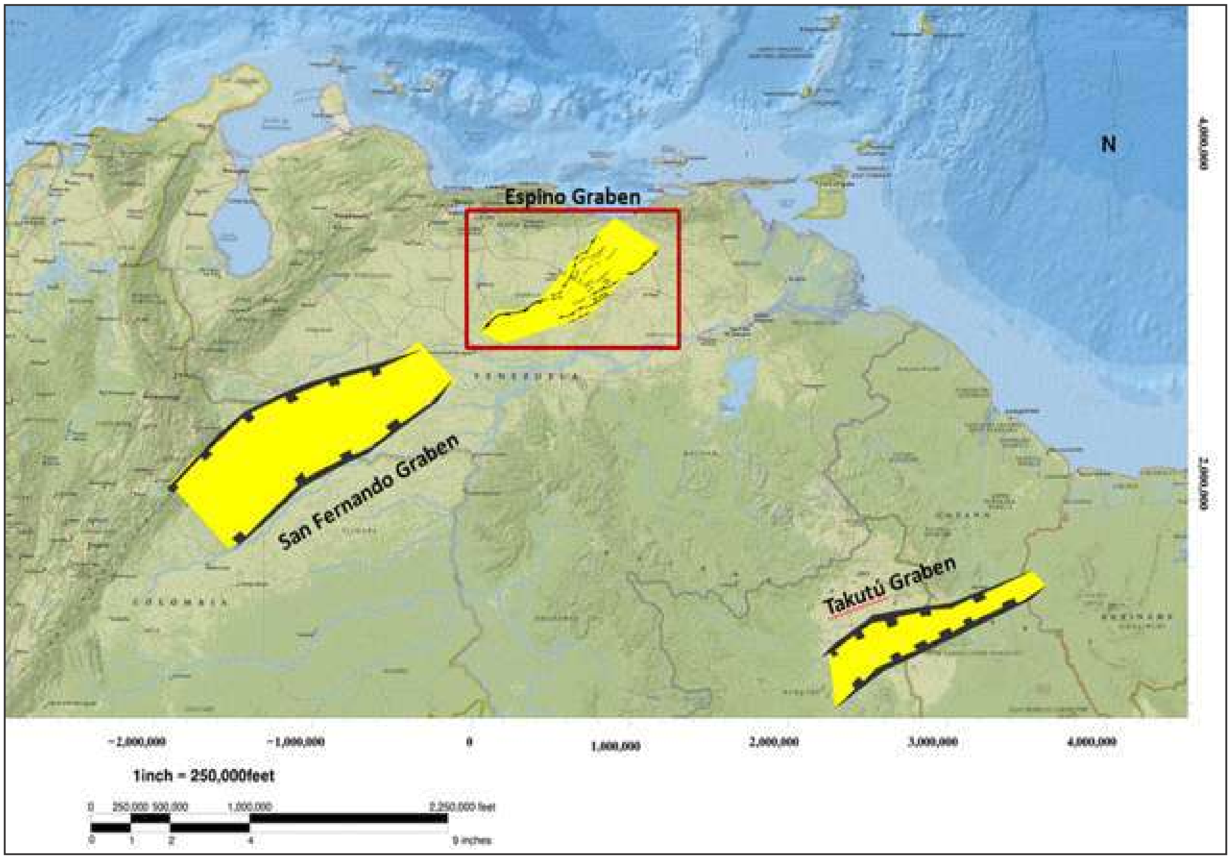

Fig. 1: Regional map of main grabens (Espino, San Fernando and Takutú). Rectangle shows position of Figures 5 to 10.

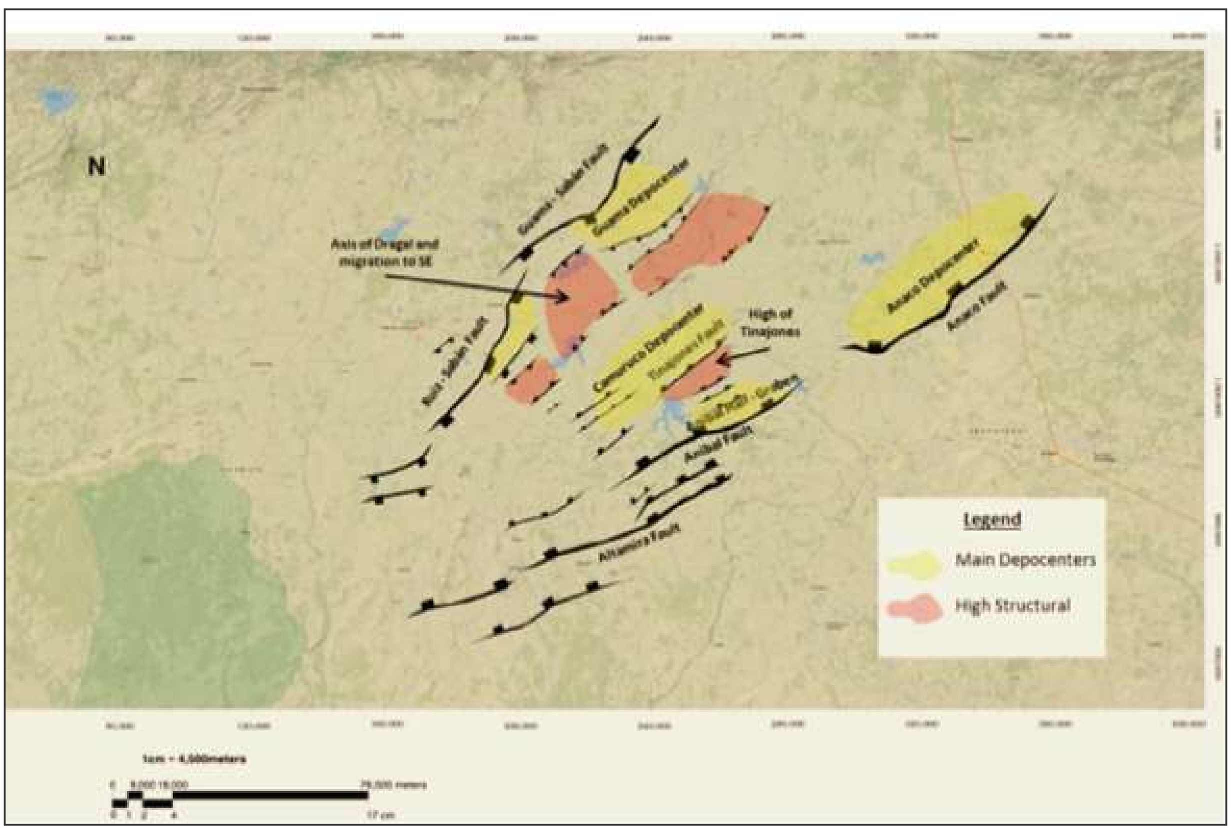

Fig. 2: Espino Graben structural highlights from seismic data (Salazar, 2006; Barrios et al. (2011).

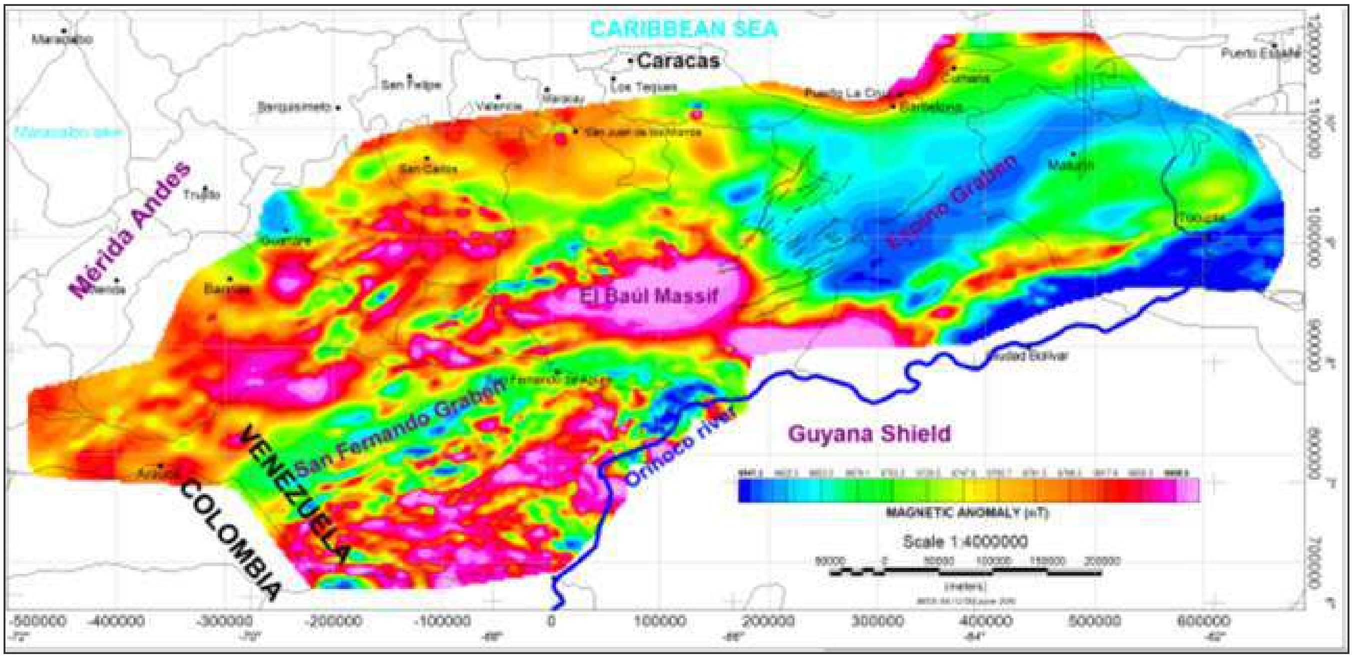

Fig. 3: Magnetic Anomaly map (nT) of EV basin, provide a window to the basement that can cover a huge area than seismic. The focus area is on the Espino Graben, NE zone.

probably intrusions (Fernández, 2002; González et al., 2008; González, 2009).

To verify the depth of the main subsurface interfaces, first of all the Radial Average Spectrum (RAS) of the total magnetic data was used (Figure 5). The depths of three main sources in the subsurface of the EVsB were estimated as follows:

- Deep (27.32 km) with wavelength between 560 km and 80 km come from Moho discontinuity;
- Intermediate (16.69 km) with wavelength between 80 km and 40 km according to Conrad discontinuity;
- Shallow (5.74 km) with wavelength between 40 km and 30 km from basement sources.

Next, the Radial Average Spectrum (RAS) of the Bouguer anomaly (Figure 4) at the Espino Graben and region around it was applied. The depths of three main sources in the subsurface of the EG were estimated as follows:

- Depth (42.47 km) with wavelength between 260 km and 100 km from Moho discontinuity;
- Intermediate (31.87 km) with wavelength between 100 km and 33 km according to Conrad discontinuity;
- Shallow (16.54 km) with wavelength between 33 km and 25 km from basement sources.

As can be appreciated, there is a remarkable difference between the RAS results of the gravimetric and magnetic data. The thin magnetic crust (27.32 km) beneath the EVsB, if 33-35 km is taken as a "*normal*" crust value, could be related to the pull-apart extension occurring in the area, which is believed to be the origin of the basin (Escalona et al., 2011) and furthermore consequences in a passive upwelling (Masy et al., 2015). Another explanation by Hamza and Muñoz (1996) is considered the existence in EVsB of a significant regional geothermal anomaly.

The Espino graben lithosphere is now only 55 –70 km thick, 30 – 40 km less than expected, and thinner than the lithosphere somewhere else to west.

Aeromagnetic SPI and AS Framework

In order to obtain a depth map for the magnetic basement of Espino Graben two methods where used: Analytic Signal (AS) and Source Parameter Images (SPI).

Analytic Signal Amplitude – Map

The Analytic Signal Amplitude (AS) method requires first order horizontal and vertical derivatives of the magnetic data (Figure 7).

Analytical Signal (AS) is sensitive to regional gradients in the data and to overlapping anomalies. The gradients and long wavelengths that are not of interest should be removed before the application of Butterworth / Gaussian filters. This operation can be expressed as follows:

$$as = \sqrt{dz.dz + dx.dx}$$

where: dx and dz are horizontal / vertical derivatives.

Source Parameter Imaging - Map

The Source Parameter Imaging method calculates depth independence of the magnetic inclination, declination, dip, strike and any remnant magnetization (Thurston and Smith, 1997). Thus, it was not necessary to apply the reduction to pole, to remove anomaly asymmetry caused by inclination and locates anomalies above the causative bodies, assuming that the remnant magnetism is small compared to the induced magnetism.

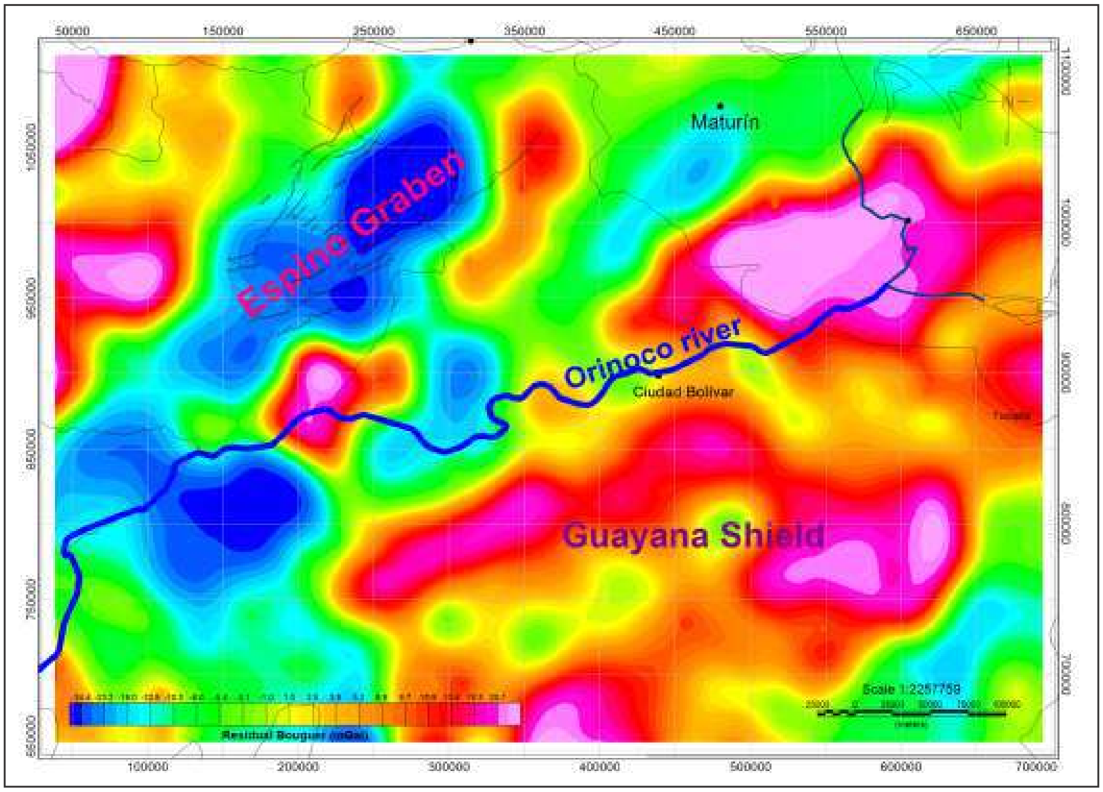

Fig. 4: Residual Bouguer Anomaly map (mGal) of the Espino Graben basin. The negative values are associated with a SW- NE depocenter at least 20,000 feet depth.

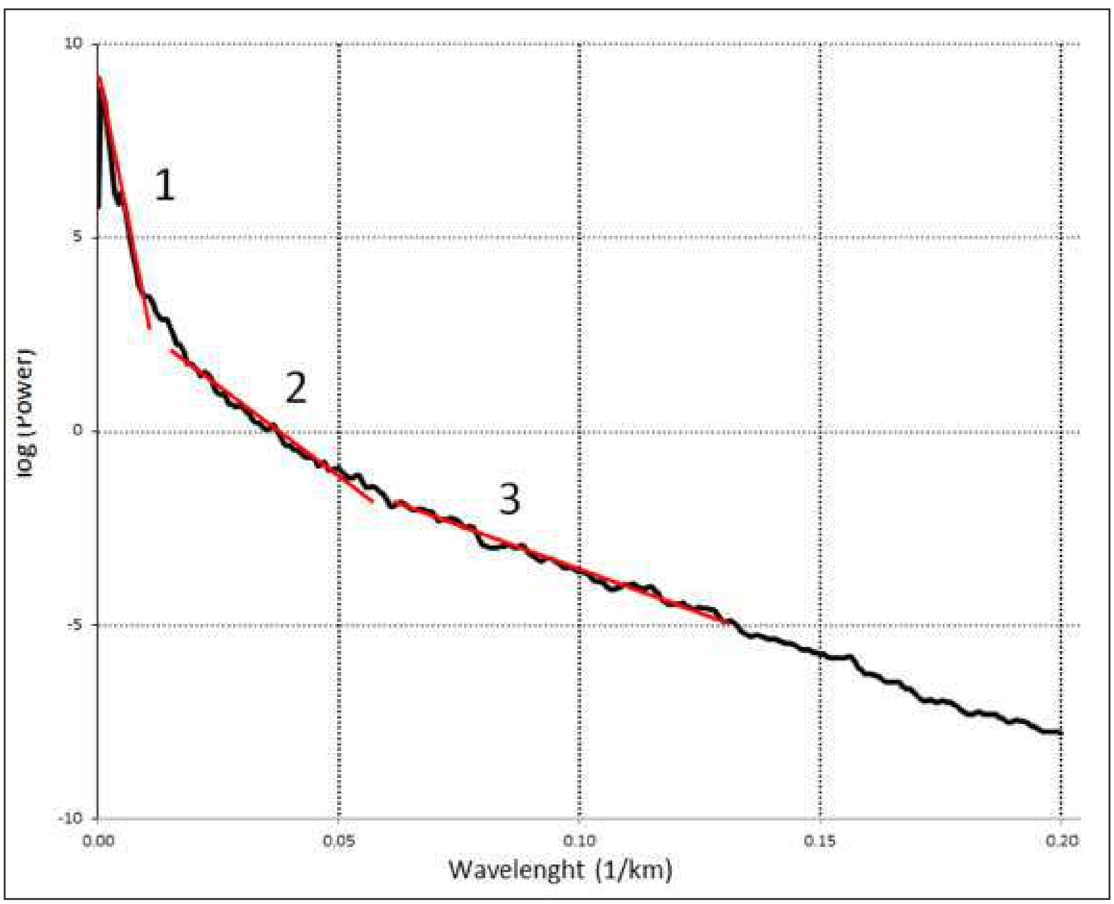

Fig. 5: Radial Average Spectrum Analysis of Total Magnetic Intensity Anomalies of Espino Graben where the depths of the sources are as follows: (1) Deep: 27.32 km, (2) Intermediate: 16.69 km., And (3) Shallow: 5.74 km.

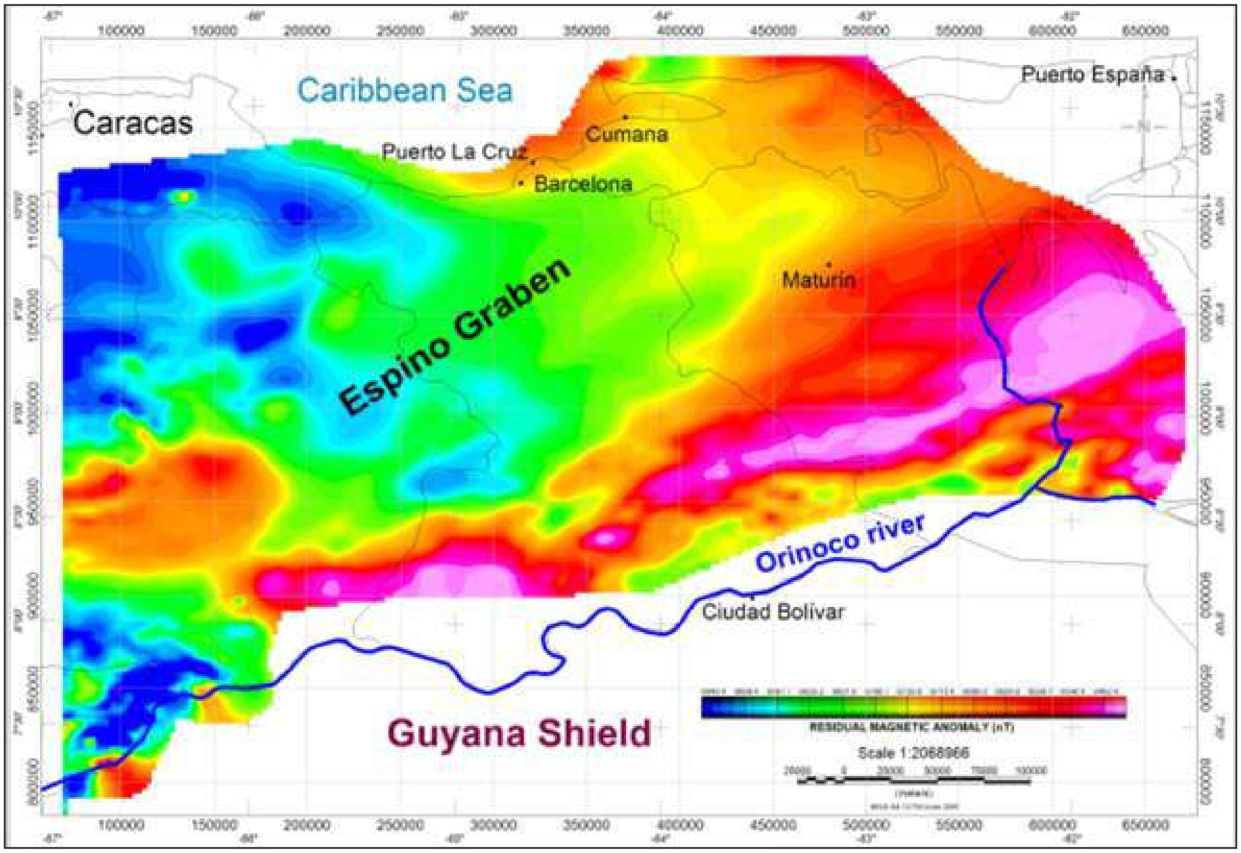

Fig. 6: Map of Residual Magnetic Intensity of Espino Graben.

SPI uses the Blakely and Simpson (1986) method to find localized peaks in a grid. For each grid cell to be considered, it compares its value with the eight surrounding grid cells in four directions (x-direction, y-direction, and both diagonals). These depth results are independent of the magnetic inclination and declination, so it is not necessary to use a pole-reduced input grid.

$$\text{Depth} = \frac{1}{K_{max}}$$

where K_{max} is the peak value of the local value wavenumber K over the step source,

$$K = \sqrt{\left(\left[\frac{dA}{dx}\right]^2 + \left[\frac{dA}{dy}\right]^2\right)}$$

and where tilt average $A = \operatorname{atan}\left\{\frac{\left[\frac{dM}{dz}\right]}{\sqrt{\left(\left[\frac{dA}{dx}\right]^2 + \left[\frac{dA}{dy}\right]^2\right)}}\right\}$

M represents the total magnetic field anomaly grid.

Results and Discussion/ Conclusions

Potential field data provide a window to the basement that covers a wider and continuous (without spatial aliasing) area than the 2D / 3D seismic data. Once calibrated to seismic and well data, magnetic depth estimation provides evidence to development of a predictive structural model. Such interpretation is efficient and cost-effective.

The magnetic basement map obtained through SPI (Figures 7 and 8) defines better the geometry of existing

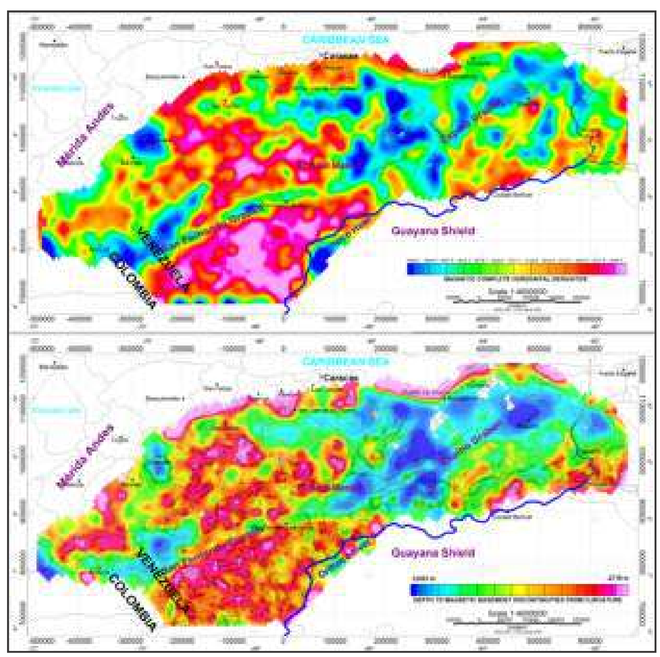

Fig. 7: Magnetic Basement depth (m) of EVsB using AS (above) and SPI methods with structural guidelines interpreted by Salazar (2006) in seismic data.

structures within the Espino Graben compared to the map of magnetic basement top obtained from AS method.

The structural interpretation of the Espino Graben geometry obtained through AS and SPI (Figure 7) coincides with Bouguer gravity anomaly map (Figure 4), especially in the presence of deep depressions in the axis graben. Both methods delineate the geological structures and are consistent with seismic interpreted by Salazar, 2006 and depths of basement perforated for wells from Feo-Codecido *et al*., 1984.

The magnetic basement characterization (Figures 8, 9 and 10) highlighted "transform faults", which proves the suggestion by Salazar (2006) that the graben was generated by pure shear or simple shear related to transfer zones (faults systems that allow the transform of displacement in an extensional regime; Moustafa, 2002).

The modifications in the drift patterns during the separation of Africa generated changes in the stresses within the graben, producing a transition from an orthogonal to an oblique extension.

It is important to note that in oblique extensions, edge faults are not straight but are displaced at some point in the basin, possibly due to discontinuities in the basement or previous faults (Figure 8 and 9). The rift system is characterized by segmented margins and depocenters aligned with these zones (Salazar, 2006).

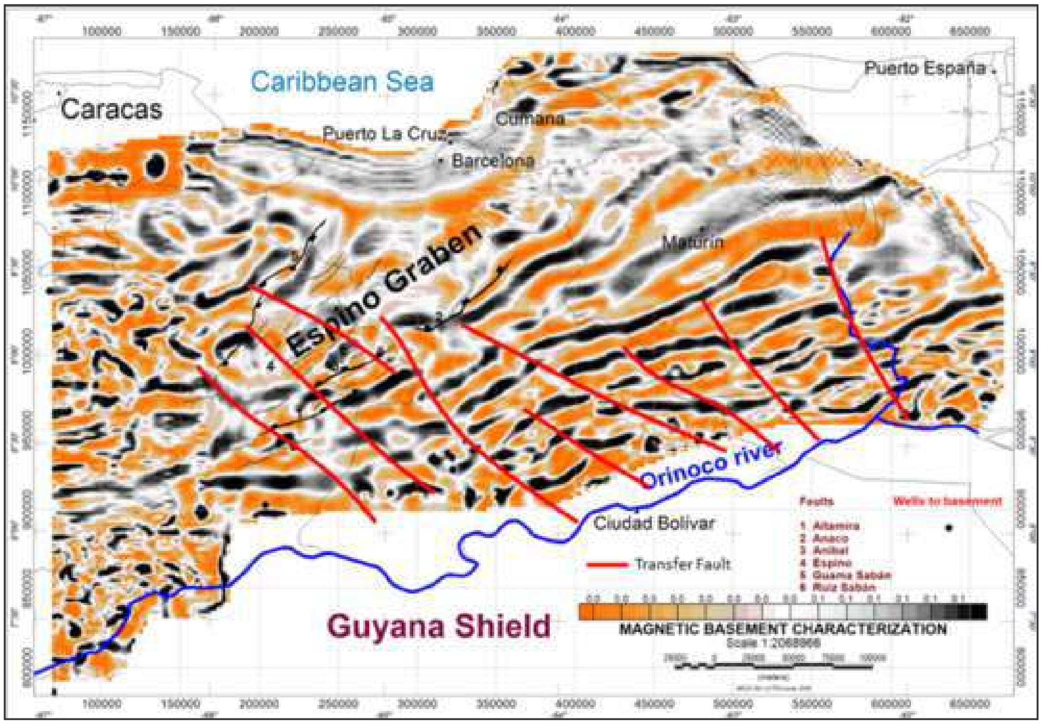

Fig. 8: Espino Graben magnetic basement characterization: the transfer faults due those changes orthogonal to oblique extension.

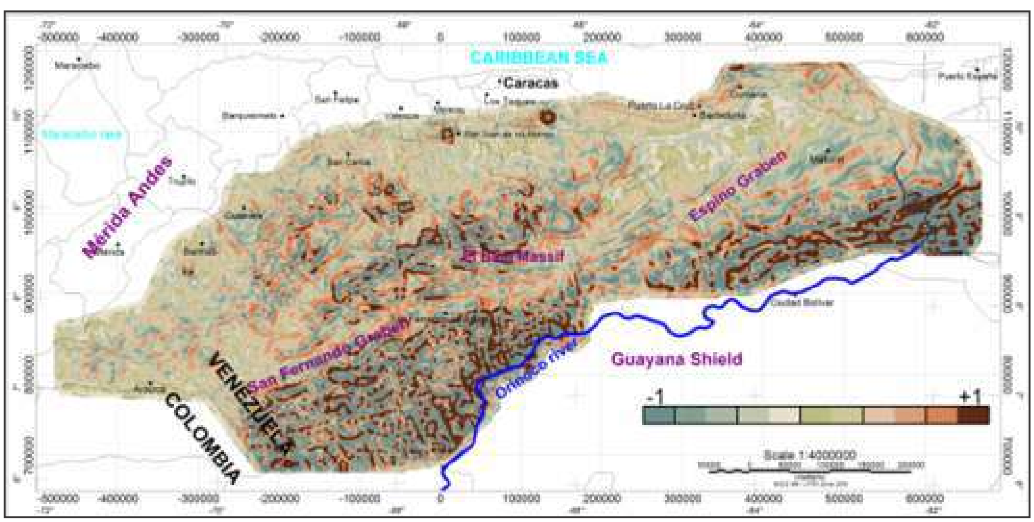

Fig. 9: Fabrics of basement according with the maximum Gaussian curvature attribute of the magnetic anomaly.

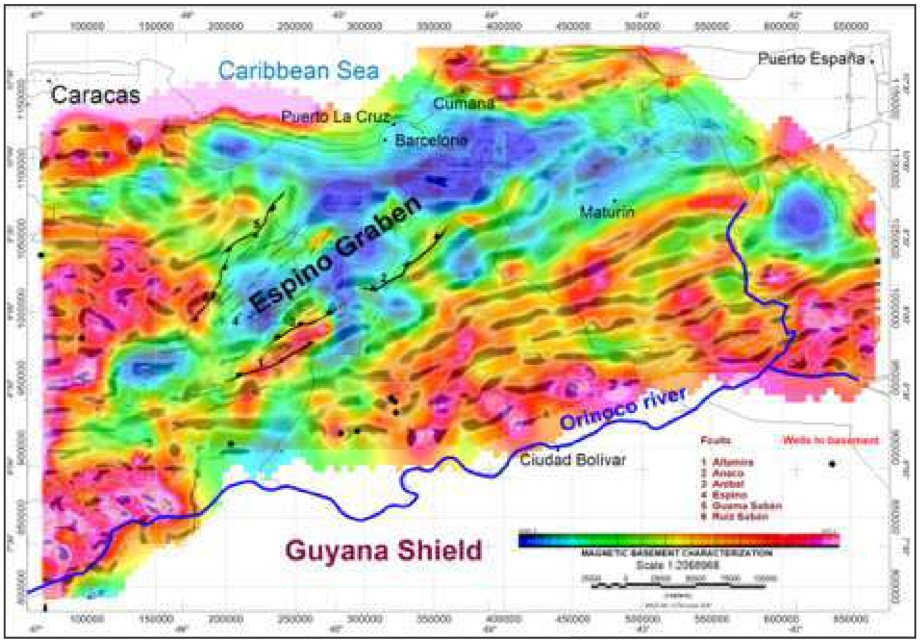

Fig. 10: Magnetic Basement Characterization with interpretations of transfer faults.

The basaltic intrusion of the Jurassic age called "Basaltos de Altamira" drilled for the well NZZ-88X (Feo-Codecido *et al*. 1984) can be observed as a magnetic high between the faults de Altamira and Anibal (Figure 10). The Espino Graben is a medially symmetrical rift with the presence of deep depressions in the west - east direction separated by high intra - basins along its strike.

Estimated depths of magnetic basement using AS and SPI methods are close to the depths of basement perforated by the wells (range from -250 m to -600 m) around Espino Graben (Feo-Codecido *et al*. 1984).

Tectonically, magnetic methods were critical for detecting the geometry of basement and the structures related to new opportunities in frontier areas. The integration of non-seismic and seismic data, are an effective approach for the subsequent studies, and may serve as a driver to create opportunities for E&P in Eastern Venezuela sub-basins, where the models suggest that the sedimentary column is at least 22,000 feet thick in the central portion of the Espino Graben.

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