

Integration of Geophysical Data to Define a Structural Model in the North-Central Coast of the Venezuelan Platform*

Vanessa Villarroel Estaba¹ and Nuris Orihuela¹

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¹Geology, Central University of Venezuela, Caracas, Venezuela (vanessa_ilia@hotmail.com)

Abstract

The study area is located in the La Orchila-La Tortuga region, in the Caribbean Sea, to the north of the central part of the Venezuelan coast, in the La Blanquilla and Tuy-Cariaco basins, between latitudes 10° and 12.5° north and longitudes -66.5° and -64° west. Over the last years the country has been affected by several seismic events; this generates the necessity to define a structural model for the northern offshore area of Venezuela, emphasizing the neotectonic activity. This model will allow a better understanding of the active structures that may be affecting the seismic activity in this area.

The structural model has been created from the integration of geophysical and geological data, allowing the interpretation of six different geological provinces in the area: (1) Leeward Antilles (Orchila zone); (2) Leeward Antilles (Eastern Blanquilla Basin); (3) Western Blanquilla Basin; (4) Margarita-La Tortuga Platform; (5) Margarita-Los Testigos Platform; and (6) Tuy-Cariaco Basin, including the San Sebastian-El Pilar fault system. The cortical thickness shows a general trend to decrease northward, with some exceptions, in the La Tortuga high and the Margarita Platform associated with the volcanic arc of the Leeward Antilles. The cortical thickness is increasing southwards, with an abrupt change to the south of the fault system, the average thickness in the north side is 16 km and in the south is 25 km. The Moho discontinuity is shallower northwards and deepening southwards. The depths range between 27 km and 16 km, with an average of 27 km in the coast and 18 km in the Leeward Antilles area. These results are similar to those obtained from the regional gravimetric anomaly; however, due to the size of the window used to perform the spectral analysis, dividing the area into four blocks, the total component for the mantle spectrum could not be covered. This data cross correlated with GPS vector data to show the possible existence of two different blocks on each side of the fault system, one to the north associated with the Caribbean Plate and one to the south associated with the South American Plate, suggesting that this fault system corresponds to an structural feature which is affecting not only the crust but also the upper mantle, establishing the San Sebastian-El Pilar fault system as a lithospheric element which is part of the plate boundary between the Caribbean and South American Plate.

Introduction

The study area is located in the La Blanquilla and Tuy-Cariaco basins in water depths between 100 and 2000 m; the total area is about 76,000 km² ([Figure 1](#)). The latest studies of the offshore areas of Venezuela have focused on the hydrocarbon potential or to the characterization of the deepest intervals of the crust, disregarding the seismic-genetic features. In the last years the country has been affected by several seismic events, the most important being the in September 2009, with a magnitude of 6.4 Mw, 28 km northeast of Morón City. Due to this important event the necessity of defining a new structural model has been proposed in order to characterize the neo-tectonic activity. This model will allow a better understanding of the active structures that may be affecting the seismic activity of this area.

The structural model has been created from the definition of geomorphological patterns, though the integration and interpretation of geophysical and geological data as: 2D seismic, bathymetric data from the digital model SRTM plus v 6.0 (Maus et al., 2009), gravimetric data from the combined earth gravitational model EGM2008 (Pavlis et al., 2008), and magnetic data from the earth magnetic model EMAG2 (Magnani et al., 2009), correlated with two wells and velocity models (García, 2009; Schmitz et al., 2005) in the area. As the area is a very complex tectonic zone, this interpretation allows the definition of the structures which are interacting to cause the deformation and seismic activity in the area.

Geological Framework

The north-central coast of Venezuela is located on the southern edge of the Caribbean Plate, in an area of complex interaction between the South American and Caribbean plates. The geometric complexity observed along the east limit of the Caribbean Plate is a result of the long interaction between the Caribbean and South America plates which are characterized by different lithospheric thicknesses and compositions of their crust (Ysaccis, 1997; Lallemand and Sisson, 2012).

The east-west dextral simple shear regime affecting the southern edge of the Caribbean has developed strike-slip faults of first-order, such as Oca, San Sebastian, La Victoria, and El Pilar; conjugated synthetic faults such as Tacata, Charallave, and Margarita; and subordinate antithetic faults (Audemard and Singer, 1996). Although it is widely accepted that the Caribbean Plate is moving eastward with respect to South America, this plate boundary is not only dextral, rather it is a broad zone of active deformation, resulting in a process of oblique collision between plates (Audemard, 2000; Audemard et al., 2005).

During the last years different models have been proposed to explain the boundary between the Caribbean and South America plates. Some of these models agree that the El Pilar-San Sebastian Fault system is part of the boundary between them. Blanco and Giraldo (2012) and others suggest that the boundary between the Caribbean and South America plates is a diffuse area of approximately 400 km wide, bounded on the north and south limits by back-thrust faults, folded belts and foreland basins, and bisected by the strike-slip fault system of San Sebastian-El Pilar, 800 km long, which acts as a connector between two subduction zones (Molnar and Sykes, 1969; Dewey and Pindell, 1986; Mann, 1999; Giunta et al., 2003). This work used the analysis of these two described models and the model proposed by Magnani et al. (2009) for a zone westward of the study area which considers the San Sebastián-El Pilar Fault system as a lithospheric element.

The area corresponding to the southern boundary of the Caribbean Plate, specifically between longitudes 63° and 69° west, corresponds to a shear distribution zone (Audemard et al., 2005). Ostos (1990) has divided the northern Venezuela in seven tectono-stratigraphic belts, east-west oriented. Following Ostos (1990) subdivision, Lallemand and Sisson (2005) subdivided this area from north to south into the following belts: (1) Deformation Belt in the southern Caribbean, (2) Leeward Antilles, (3) extensive Tertiary basins belt, and (4) Caribbean Mountain System. For the purpose of this study we will focus on the area corresponding to the Extensive Tertiary basins belt, as the study area is located in the area corresponding to La Blanquilla and Tuy-Cariaco basins within the aforementioned belt.

Methodology and Results

Seismic Interpretation

The seismic interpretation was taken from Villarroel (2012) which was carried out from 1000 km of 2D seismic, describing four mega-sequences: Cretaceous, Paleogene, Miocene, and Plio-Pleistocene, and was revised for the three selected profiles. The Cretaceous basement has been interpreted as the acoustic basement. The seismic reflector which defines the top of this sequence is very strong and it is very well defined in La Blanquilla Basin. Closed to the La Tortuga high, the seismic character is chaotic, probably due to its volcanic origin. Towards the Tuy-Cariaco Basin the basement was interpreted as an unconformity between the Miocene and Cretaceous. In the Margarita-La Tortuga Platform and Tuy-Cariaco Basin the internal seismic reflections are more continuous and slightly folded.

The top of the Paleogene sequence is defined by some onlap reflections. This sequence is characterized by decreasing southward, pinching out against the basement. In the La Blanquilla Basin the sequence shows a thickness of around 400 m, and in the Tuy-Cariaco Basin is absent. The depositional system corresponds to a slope marine environment, with a high content of shale, according to the well data. The contact with the Miocene sequence is erosive, showing an unconformity.

The top of the Miocene sequence is characterized by a regional unconformity. The Miocene seismic facies show continuity, variable amplitudes, and onlap reflections toward the top. In the Tuy-Cariaco Basin a thickening has been observed in the center and in the eastern part.

The Plio-Pleistocene sequence is the thickest one. The internal reflections are sigmoidal (clinoforms), parallels, defining a shallow marine environment (platform). In the Tuy-Cariaco Basin the geometry of the reflectors defines a progradational system. The thickness of this unit shows that the maximum development of the basin occurred during this period. Some convergent reflectors and sedimentary wedges are observed in the La Blanquilla Basin.

Gravimetric Interpretation

The Bouguer anomaly generated for the study area shows values between -111 and 232 mGals ([Figure 2](#)). The maximum values are located in the northern part, ranging from 120 to 232 mGals, belonging to the Leeward Antilles and Venezuelan Basin, and related to the oceanic character of the crust. The average gravimetric values, around 60 mGals, are located in the center of the area, and the minimum values are related to the Cariaco-Tuy Basin, in the southern part of the area, reaching -111 mGals.

Identified from the spectral analysis of the gravimetric data were: a deep or regional source with a wavelength range between 0.0 and 0.013; an intermediate or residual source with a wavelength between 0.013 and 0.06; and a shallow source or noise with a wavelength >0.06 . From this analysis the estimated depth for the regional source was 20 km, and 8 km for the residual source.

Magnetic Interpretation

The magnetic anomaly of total field generated for the study area shows a range of values between -113 and 165 nT ([Figure 3](#)). Towards the north-central part there is evidence of a compound anomaly. This anomaly comprises a sequence of magnetic highs to the south and their corresponding pairs of magnetic lows to the north related to the Leeward Antilles Arch, with maximum and minimum magnetic values of 165 and -113 nT, respectively. In the lower part of the area, within its northern side, an east-west alignment associated with the San Sebastián-El Pilar Fault system can be observed, with anomalies ranging between 33 and 7 nT. Towards the southern extreme and, in spite of its complexity, caused by the compound nature of its magnetic anomalies, a magnetic low zone can be observed associated to Tuy-Curiaco Basin, reaching a minimum value of -113 nT.

Several sources can be identified from the spectral analysis of the magnetic data: A deep or regional source that lies in a range of wavelength of 0.0 and 0.02; an intermediate or residual source with values between 0.02 and 0.76; and shallow sources or noise with a wavelength >0.76 . From the previous analysis an estimated depth for the regional source was around 20 km and for the residual source was around 6 km.

Spectral Analysis of Gravimetric and Magnetic Data (Regional/Residual)

The residual-regional separation was performed through the data obtained from the spectral analysis. A Gaussian filter was applied to the data allowing the processing of the anomalies in the frequency domain.

Three east-west belts were observed in the Bouguer anomaly regional map ([Figure 4](#)), from north to south: (1) Leeward Antilles, showing the highest gravimetric values, with an average of 140 mGals; (2) plates boundary zone including the San Sebastián-El Pilar Fault system with values ranging between 20 and 140 mGals, and (3) a zone attributed to the Tuy-Cariaco Basin and Barcelona Bay showing the maximum negative values in the map of <4 mGals.

In the Bouguer anomaly residual component map two groups of anomalous responses were observed ([Figure 5](#)). One group is located in the northern half, within the Leeward Antilles area, with orientations close to northwest-southeast. The second group is located in the southern half and is oriented east-west. The range of values for the area varies from 28 and -28 mGals.

The map obtained for the regional component of the total field magnetic anomaly shows a range of values between 138 and -91 nT ([Figure 6](#)). In the northern half there is a northwest-southeast alignment which matches with the Leeward Antilles. In the map obtained from the spectral analysis for the residual component of the magnetic anomaly ([Figure 7](#)), the values range between 47 and -29 nT, defining two groups of anomalies: (1) one located in the north part comprising little anomalous highs with their respective pairs of magnetic lows, matching the ones

obtained in the gravimetric residual map, with orientation close to northwest-southeast and attributed to the Leeward Antilles, and (2) a second group located in the southern area, oriented east-west and correlated to the San Sebastian-El Pilar Fault system.

Construction of the Model

The model building was based on the integration of geophysical data obtained from the seismic interpretation, the gravimetric and magnetic interpretations, density data and magnetic susceptibilities. The gravimetric data used for the modeling corresponds to the Bouguer anomaly from the combine Earth gravitational model EGM2008 (Pavlis et al., 2008), with an applied sea correction (García, 2009) and the magnetic data correspond to the total field anomaly from the earth magnetic model EMAG2 (Maus et al., 2009).

The definition and depth estimations of the shallower units (Recent sediments to basement), were obtained from the seismic interpretation. The definition of the deeper units was obtained from the spectral analysis of the gravimetric data (upper-lower crust boundary) and magnetic data (Curie isotherm). Due to the window extension of the study area the total spectral component was not reached and the boundary lower crust-mantle could not be defined. This limit was defined using published data by Paolini (2012), Mann (1999), Schmitz et al. (2005), Giraldo (2002), and Caribbean Moho' Model (2012).

The profile A3 has an average initial depth from west to east, of 24 km. The profile A6 has an initial depth at the south 28 km and 21 km to the north. The profile A7 has a range between 30 km at the south and 21 km at the north. The initial densities were calculated from the equation proposed by Ludwig et al. (1970), using the velocity data from the models published by Giraldo (2002) and Schmitz et al. (2005). The initial densities were defined as follow: quaternary and tertiary sediments 2.39 g/cm^3 , upper crust 2.71 g/cm^3 , lower crust 2.95 g/cm^3 , and mantle 3.33 g/cm^3 .

Gravimetric and Magnetic Modeling

The gravimetric-magnetic model was performed using the program GM-SYS, which is hosted by the interface of Oasis Montaj 6.4.2. Three profiles were modeled, A3, A6 and A7 ([Figure 1](#)). To achieve the models adjustment, the initial depths of the present interphases, as well as their geometries, were controlled through the gravimetric modeling.

Profile A3

The A3 profile shows a west-east direction and a length of 180 km. In the areas of topographic highs, the initial model has a high correlation coefficient between the observed and calculated gravity curves. After the inverse modeling of magnetic densities and susceptibilities, a good adjustment between calculated and observed gravities was obtained reaching a maximum error of 4.4 mGals ([Figure 8](#)). The sedimentary column thickness obtained for the West Blanquilla Basin was approximately 4000 m. The magnetic model was performed through the inverse modeling of the magnetic susceptibilities and the Curie's isotherm adjustment, reaching a maximum error of 5.3 nT ([Figure 8](#)).

Profile A6

The A6 profile has a southwest-northeast orientation and a length of 180 km. The range obtained for the gravimetric anomalies varies between -30 and 120 mGals. The range of magnetic values fluctuates between 21 and 86 nT.

The initial gravimetric model shows a high correlation coefficient between the calculated and observed gravity curves in the central zone of the profile. The discrepancy between both curves in the Tuy-Cariaco and Eastern La Blanquilla basins was adjusted due to the inverse modeling of the limit upper-lower crust and densities. An error of 6.7 mGals was reached ([Figure 9](#)).

Large crustal thickness variations were observed to the north and south of the San Sebastian-El Pilar Fault system, with crust thickness of 15 km in the northern side and 26 km in the southern side. Regarding the magnetic model, the adjustment of Curie's isotherm responds to magnetic highs and lows, associated to the crust, deepening to the south with an average of 23 km, and reaching a minimum depth of 11 km in the northern part. The remnant error of the model was 10.6 nT.

Profile A7

A7 profile presents a northwest-southeast direction and a length of 120 km. The observed gravimetric anomalies ranges between -60 and 98 mGals, while the magnetic varies from 16 and 86 nT. The initial gravimetric model shows low correlation between the observed and calculated gravity curves, although both keep the same trend. The model adjustment was done through the inverse modeling of the bodies' densities and through the adjustment of the present surfaces.

In the San Sebastián-El Pilar Fault system area, a variation in the crustal thickness, similar to the one present in the A6 profile, was observed. To the north and south of the system, the average cortical thicknesses are 12 and 25 km, respectively. These variations reflect the existent of two different blocks, one to the north and one to the south of the fault system. The error reached was 4.8 mGals ([Figure 10](#)).

The magnetic model for this profile allowed a good correlation for the trend related to the bodies behavior similar to the one reflected by the observed gravity curve. The Curie's isotherm shows depths values of 12 km to the north and 14 km to the south. The final magnetic model reached an error of 8.4 nT ([Figure 10](#)).

Discussion

Three cortical models along three profiles A3, A6, and A7 ([Figure 1](#)) were constructed from the integration of the geophysical data and their further interpretation. These models were obtained through inverse modeling of densities derived from velocity data and magnetic susceptibilities, and adjustments of Curie's isotherm.

The densities used for the final adjustment of each unit were: (1) Neogene sediments 2.46 g/cm^3 , (2) Paleogene sediments 2.6 g/cm^3 , (3) upper crust 2.71 g/cm^3 , (4) lower crust 2.93 g/cm^3 , and (5) mantle 3.3 g/cm^3 . The final magnetic susceptibilities for each unit were: (1) Neogene sediments $S=0$, (2) Paleogene sediments $S=0$, (3) upper crust $S=0$, (4) lower crust $S=0.001$, and (5) mantle $S=0$.

The study area was divided in six geological provinces due to the associated behavior of their anomalies ([Figure 11](#)). In the northern part is located the Leeward Antilles province. The gravimetric response of this province corresponds to the northwest-southeast alignment of gravimetric highs related to the islands and basement highs, and their pairs of gravimetric lows related to the depressions between them, like the Eastern La Blanquilla Basin.

In the central part are located the provinces of Western La Blanquilla Basin, Margarita-La Tortuga and Margarita-Los Testigos platforms. The Western La Blanquilla Basin is east-west oriented, projected towards the Eastern La Blanquilla Basin, both being separated by the Margarita Fault. This province is represented in a gravimetric low, which suggests a sediment accumulation zone.

The geological province of the Tuy-Cariaco Basin is located in the southern part of the area. This area shows the lowest gravimetric value, around -111 mGals, with a huge amount of sediment accumulation in the basin. The most important structural element in the study area is located in this province, the San Sebastian-El Pilar Fault.

The cortical thickness obtained from the modeling shows a tendency to increase southward, with an important and abrupt change below the Tuy-Cariaco Basin. The thickness varies from 17 km in the north side of the fault system to 25 km in the south side.

The Mohorovich discontinuity is deepening southward, with an average of 25 km in the Tuy-Cariaco Basin and 17 km in the Blanquilla Basin. These results are similar to previous results obtained by: (1) Paolini (2012), who found a depth of 24 km south at the La Tortuga High westward of the study area; (2) Magnani (2009), in the 69° W meridian, at the San Sebastian-El Pilar Fault, established a depth of 25 km; (3) Schmitz et al. (2005), modeled a north-south profile from Los Roques Basin to Eastern Venezuelan Basin, defining a depth for the Moho at 30 km south of Tuy-Cariaco Basin; (4) Giraldo et al. (2002), who modeled a profile from the La Blanquilla Basin to El Cratón Guayanés, determining 35 km for the depth at Barcelona City; and (5) the Caribbean Moho' map.

The existence of an important variation in the cortical thickness implies that the San Sebastian-El Pilar Fault system is not limited to the crust but to the mantle (Magnani et al., 2009) ([Figure 13](#)). The hypothesis of the existence of two different blocks, one to the north and one to the south of the fault system, is corroborated by GPS vectors which show that in the northern block the velocities and vectors are similar to velocities and vectors of the Caribbean Plate, and in the southern block velocities and vectors are similar to the ones of the South American Plate (Pérez et al., 2001; Weber et al., 2001; Magnani et al., 2009) ([Figure 12](#)).

Conclusions

The integration of the geophysical data allowed us to define a layer cake model, from the crust to the mantle. The interpretation of seismic data was used to define the sediment column to the top of the upper crust, corresponding to the basement top. The gravimetric and magnetic spectral analyses were used to define the upper-lower crust and lower crust-mantle boundaries. This integration shows the benefits of using these kinds of data, especially in structural complex areas, in order to reach the deepest depth where plate boundary structures, such as the San Sebastian-El Pilar Fault, may be active. Seismic data was used to define the shallower surfaces for the structural model, while the gravimetric and magnetic data were used to define the deeper surfaces.

From the interpretation, the study area was divided into six different geological provinces, mainly characterized by the behavior of their gravimetric and magnetic anomalies. These are: (1) Leeward Antilles, La Orchila Island area, (2) Leeward Antilles and Eastern Blanquilla Basin, (3) Western Blanquilla Basin, (4) Margarita-La Tortuga Platform, (5) Margarita-Los Testigos Platform, and (6) Tuy-Cariaco Basin, including the San Sebastián-El Pilar Fault system.

The cortical thickness shows a general trend to decrease northward, with some local exceptions in La Tortuga High and in the Margarita Platform where an increase is reflecting their association with the Leeward Antilles volcanic arc. Southward, the cortical thickness is increasing, with an abrupt change at the San Sebastian-El Pilar Fault. The average thickness at the north side is 16 km and 25 km at the south ([Figure 13](#)).

The Moho decreases northward and is deepening southward. The depths range between 27 km and 16 km, with an average of 27 km in the coastline and 18 km in the Leeward Antilles, confirming the abrupt changes at the San Sebastian-El Pilar Fault area. The map for this surface shows a similar trend to the regional component gravimetric anomaly map, but due to the size of the window for the study area, the mantle spectral component was not covered to perform spectral analysis.

These results correlated to GPS data vectors reflect the possible existence of two different blocks, one north of the San Sebastian-El Pilar Fault related to the Caribbean Plate, and another block to the south related to the South American Plate ([Figure 12](#)), suggesting that this fault system corresponds to a structural element that affects not only the crust but also the mantle ([Figure 13](#)).

The San Sebastian-El Pilar Fault system corresponds to a lithospheric element which belongs to the boundary between the South American and Caribbean plates. This hypothesis is consistent with the results obtained by Magnani et al. (2009) westward of the study area.

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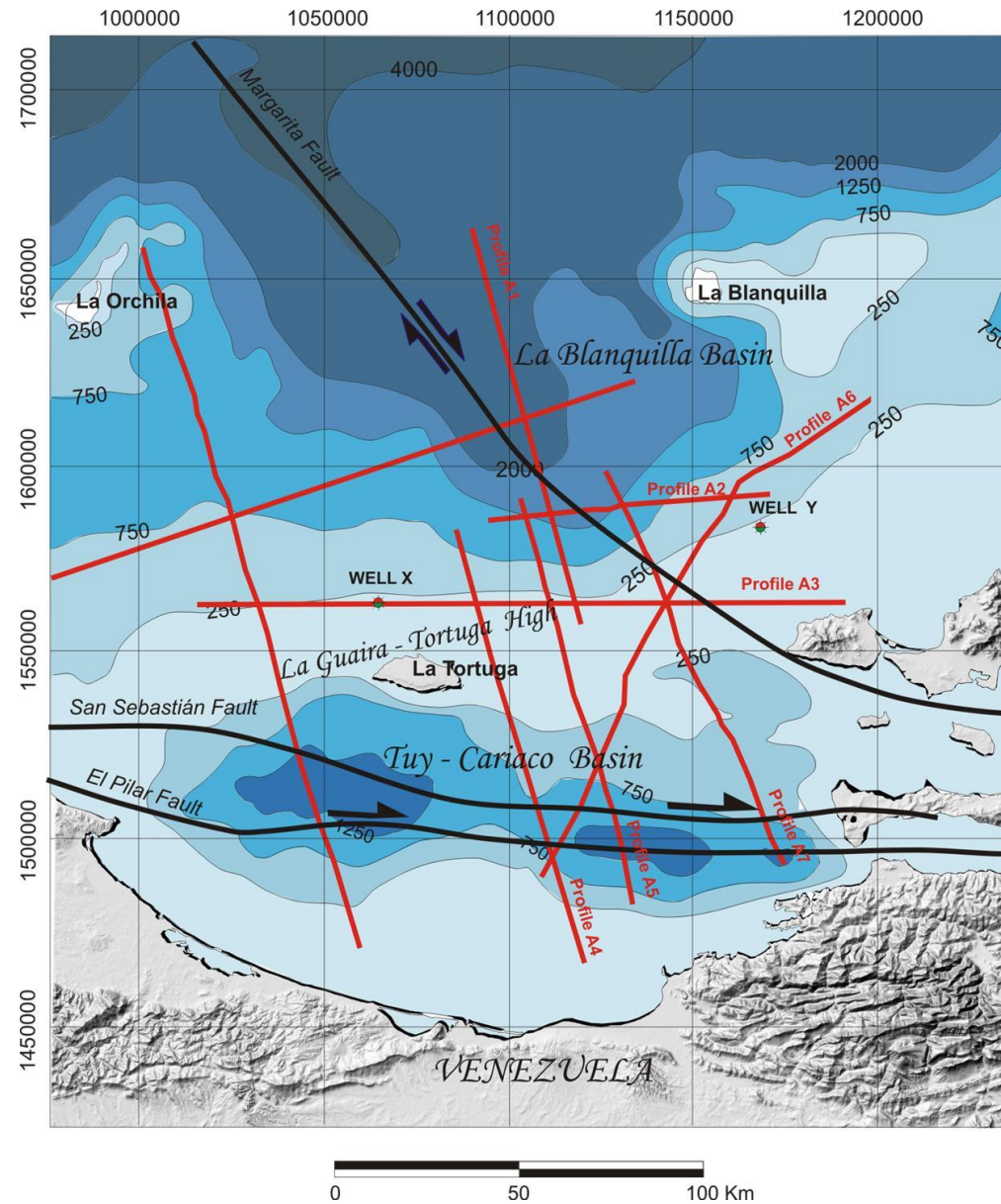


Figure 1. Location map of the study area showing bathymetric data, seismic lines and available wells. The study area is in the La Blanquilla and Tuy-Cariaco basins, located to the north of Miranda, Anzoátegui, Sucre and Nueva Esparta states. The map shows the location of nine 2D seismic lines of the Caribe Central survey, two wells, and the area of gravimetric and magnetic database that corresponds to the window.

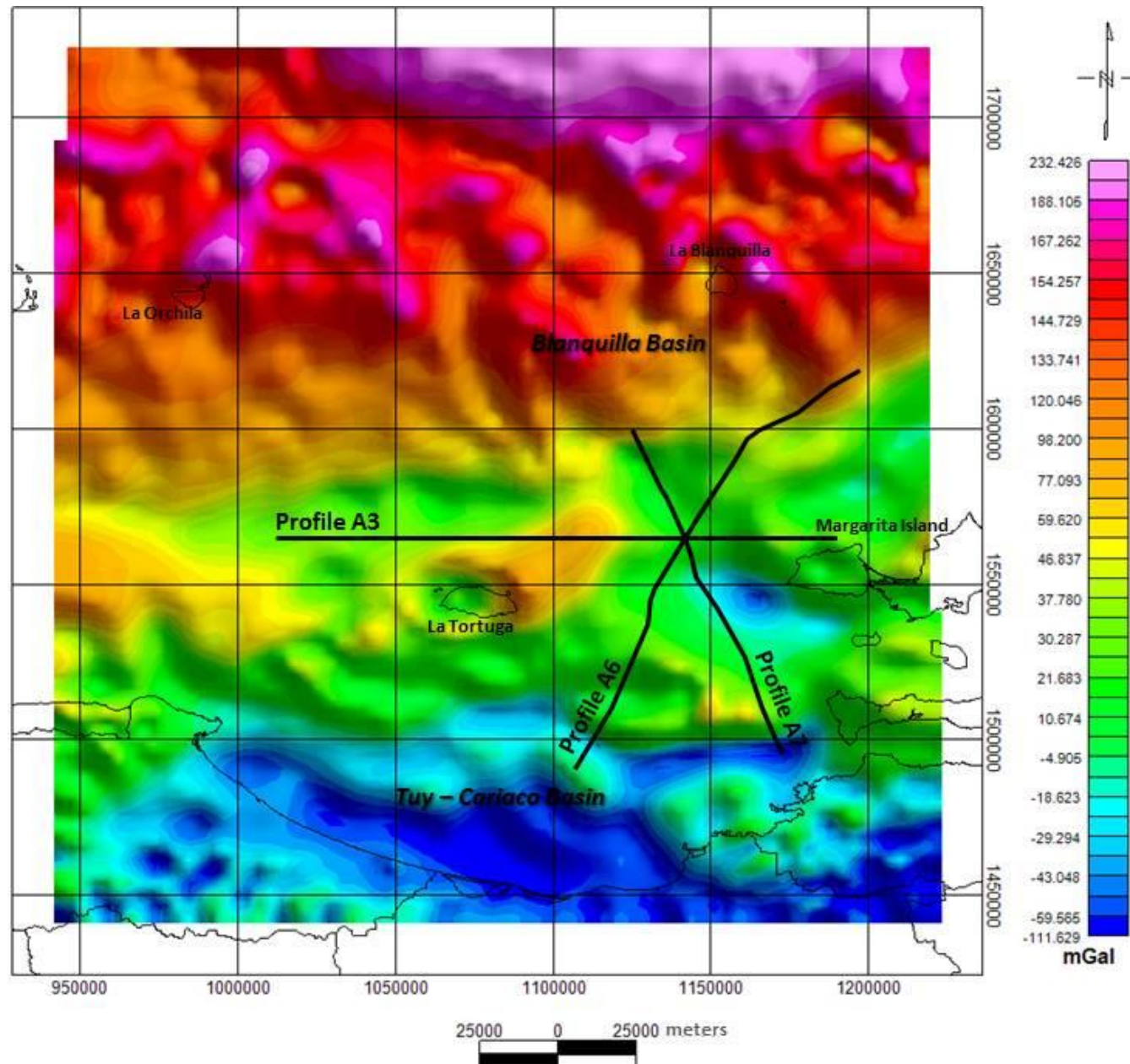


Figure 2. Bouguer anomaly map of La Orchila-La Tortuga, north-central coastal platform of Venezuela.

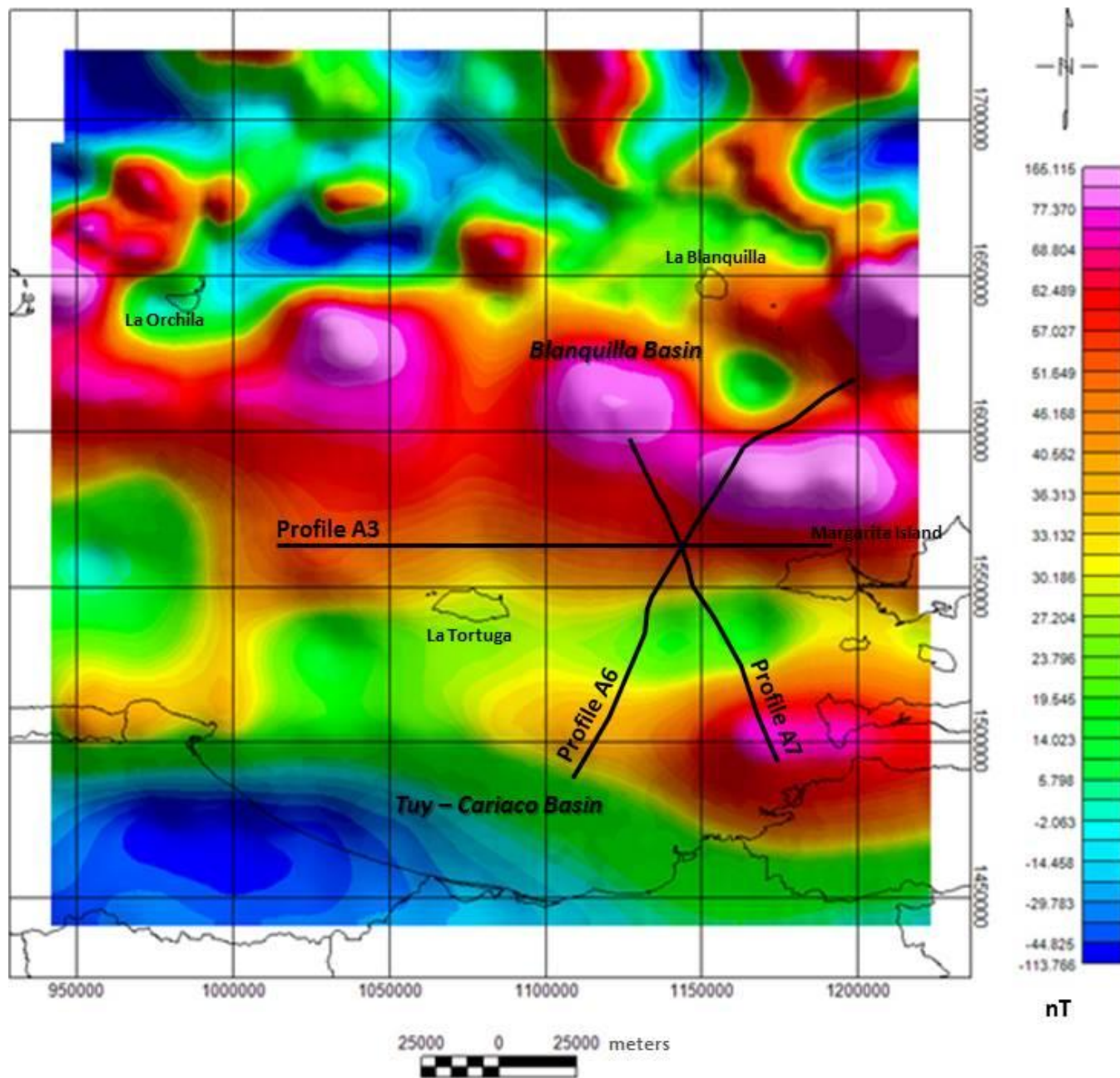


Figure 3. Magnetic anomaly map of total field of La Orchila-La Tortuga, north-central coastal platform.

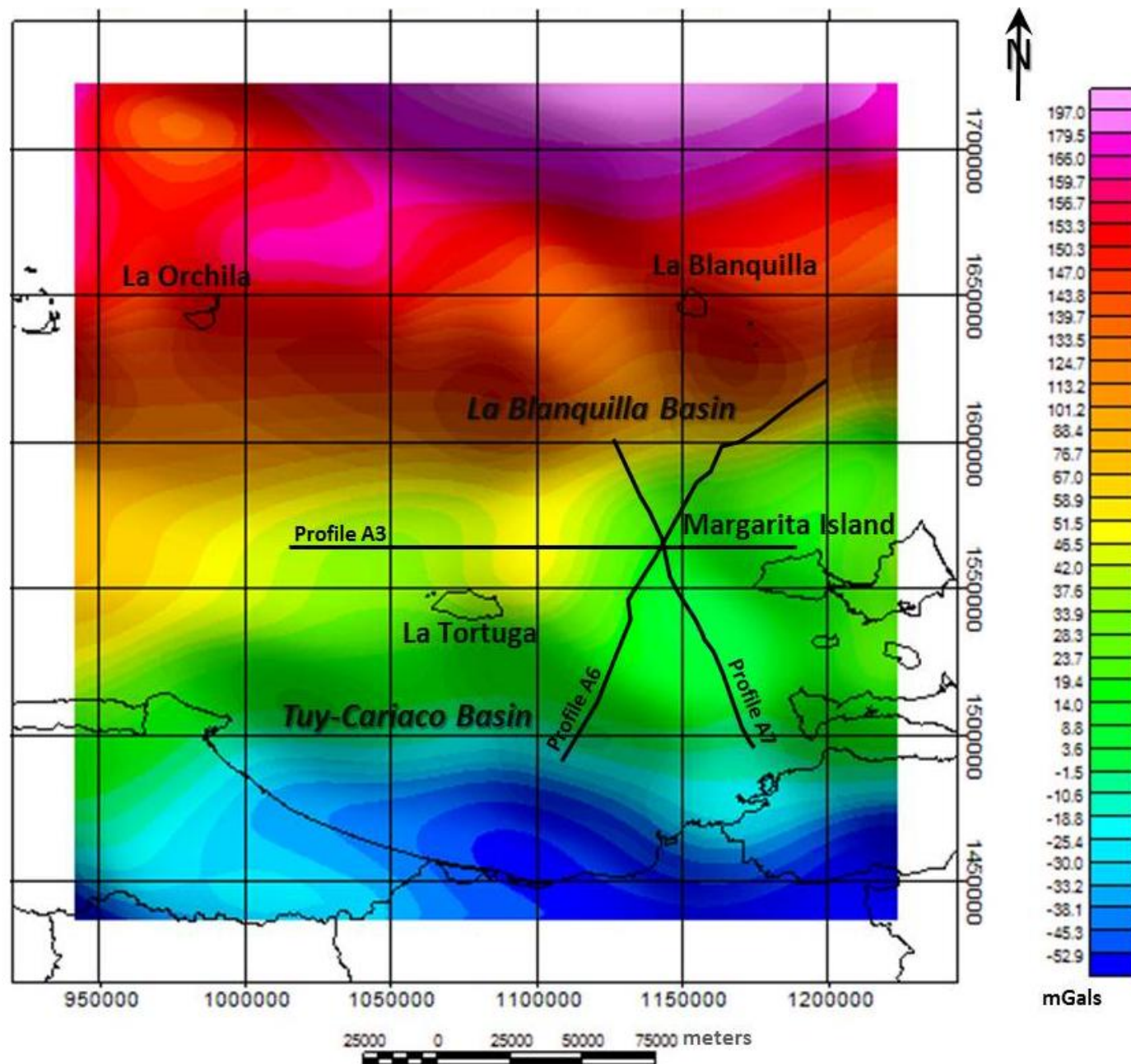


Figure 4. Regional component map of the Bouguer gravimetric anomaly.

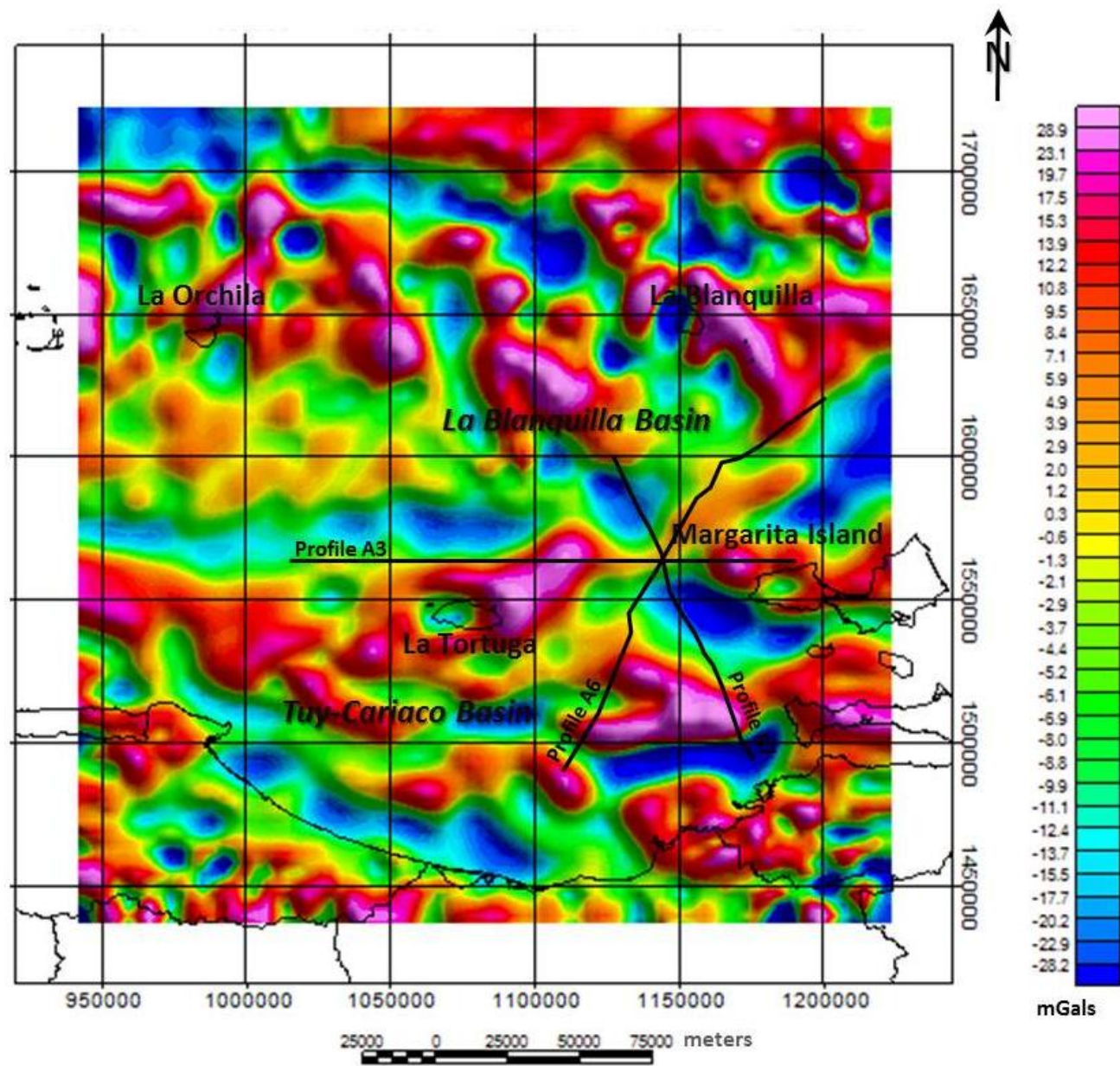


Figure 5. Residual component map of the Bouguer gravimetric anomaly.

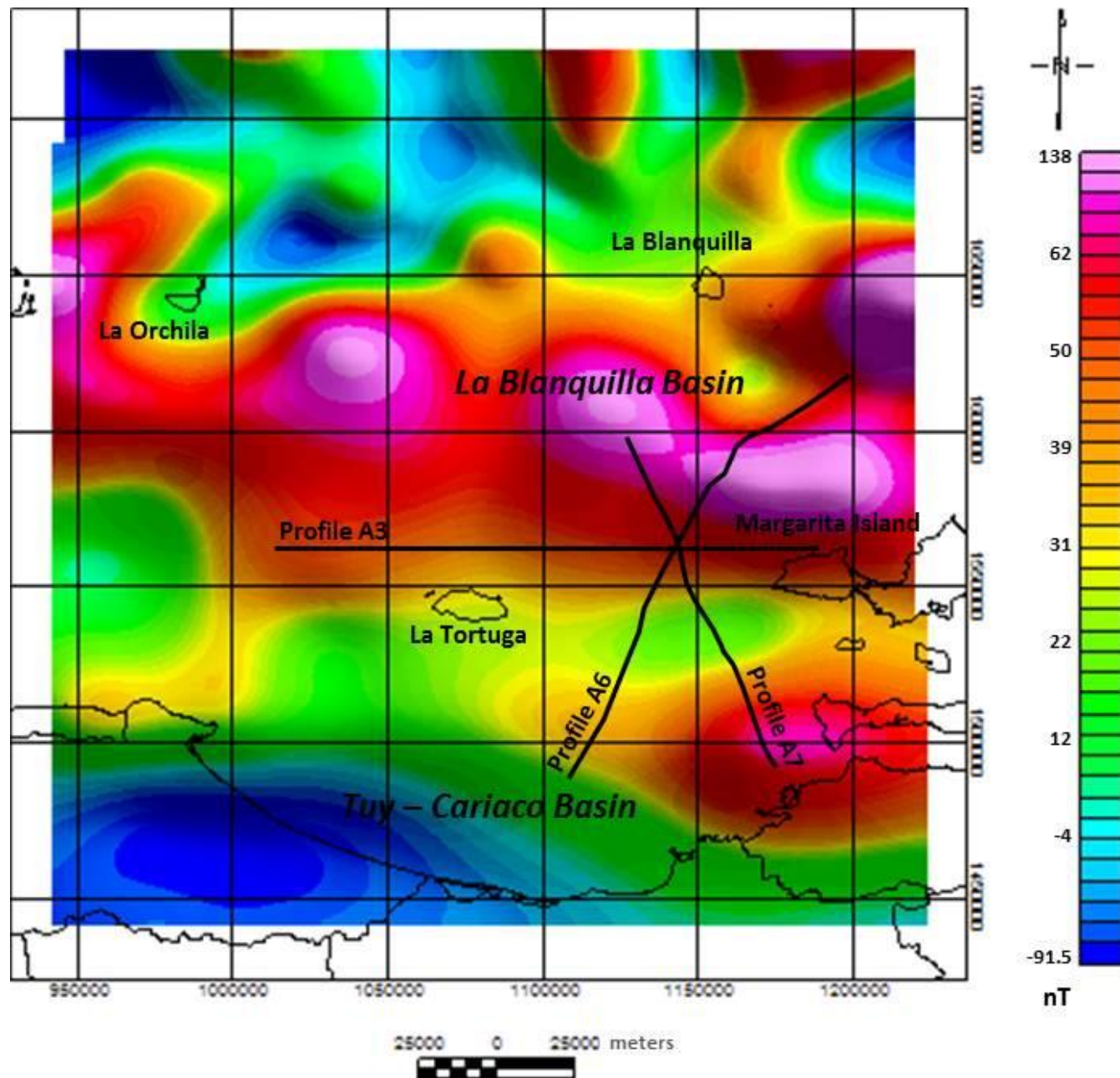


Figure 6. Regional component map of total magnetic field anomaly.

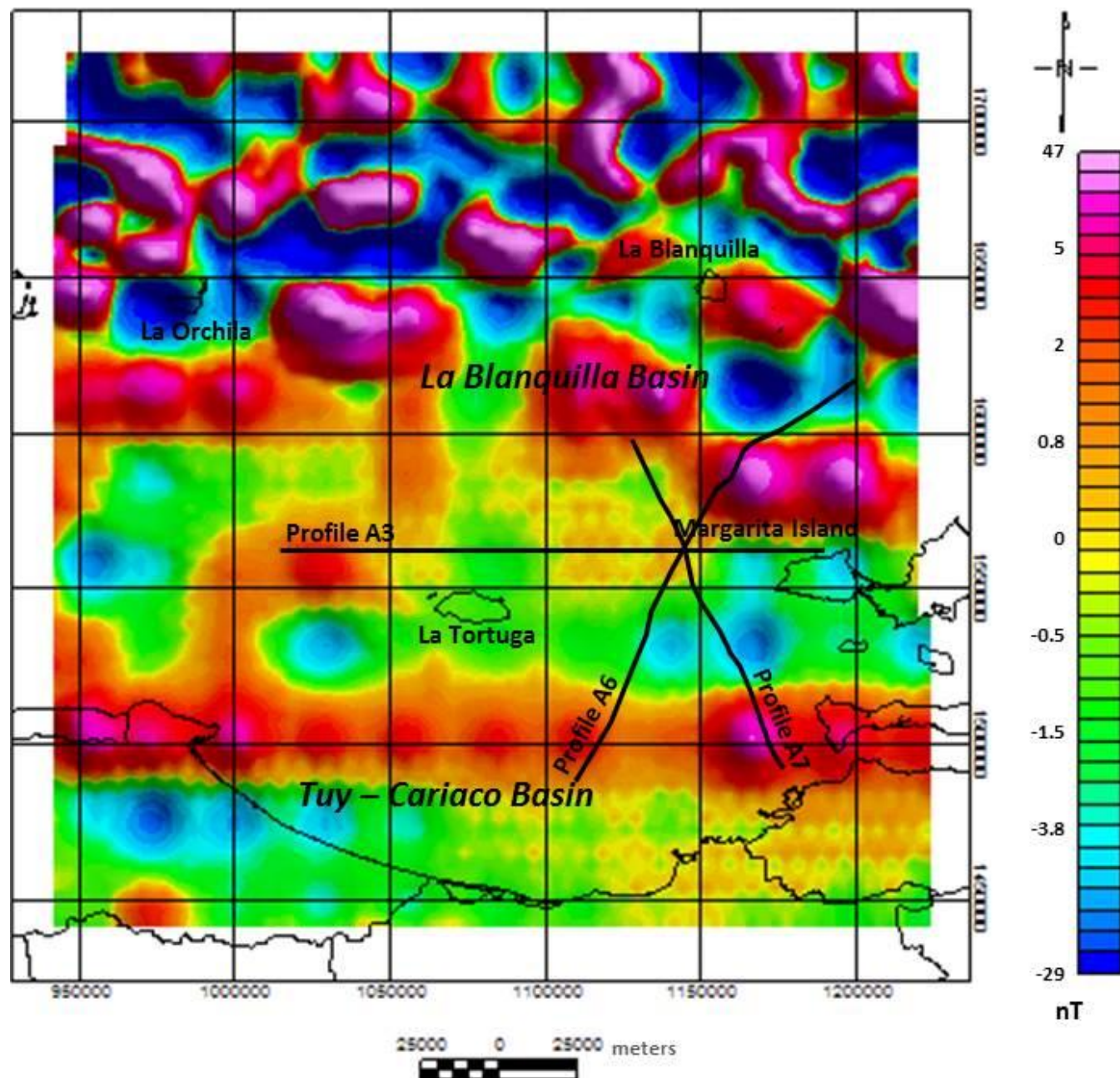


Figure 7. Residual component map of total magnetic field anomaly.

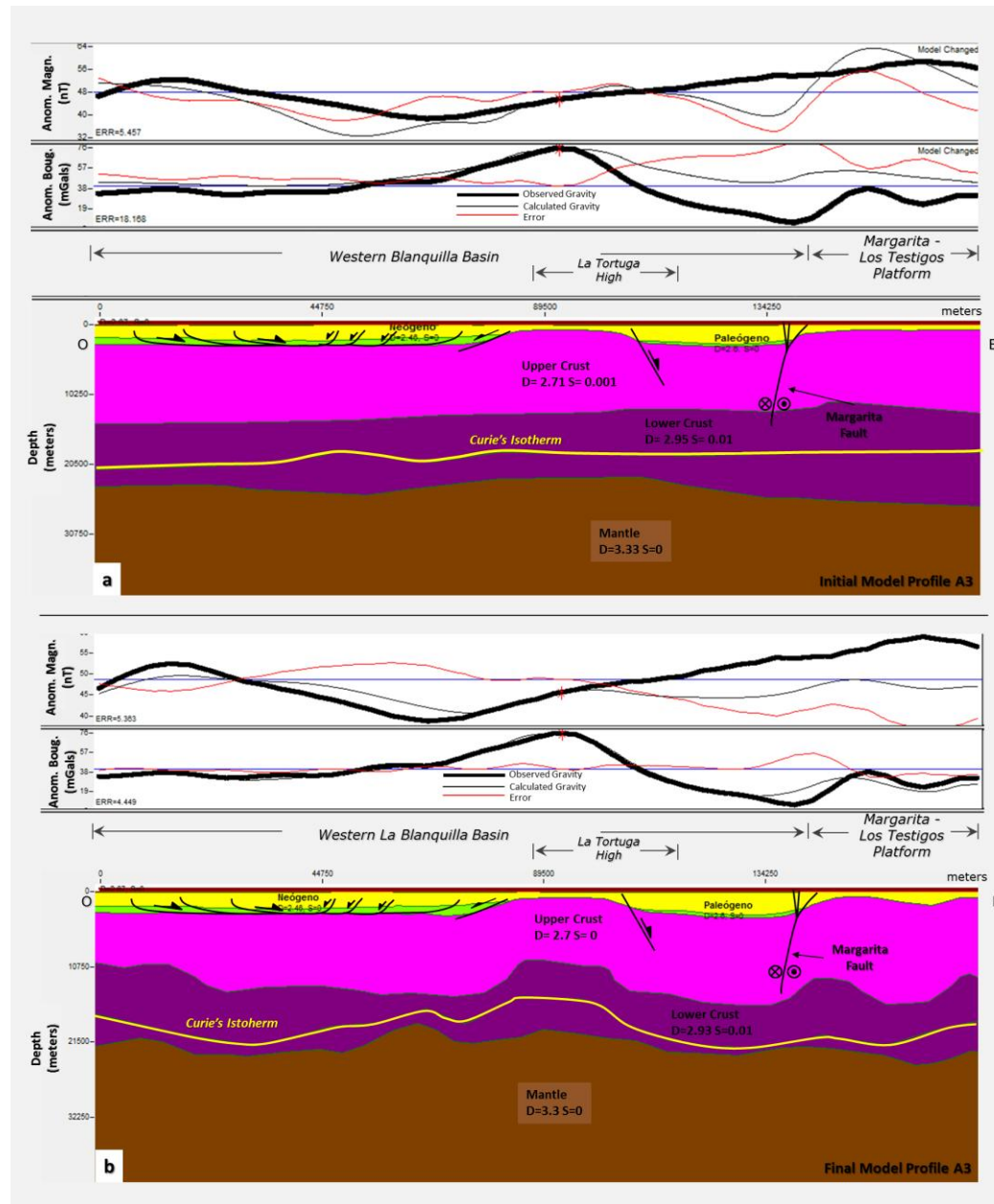


Figure 8. Cortical model of Profile A3. The figure shows (a) the initial model, and (b) the calibrated model from the inverse modeling of density and magnetic susceptibilities.

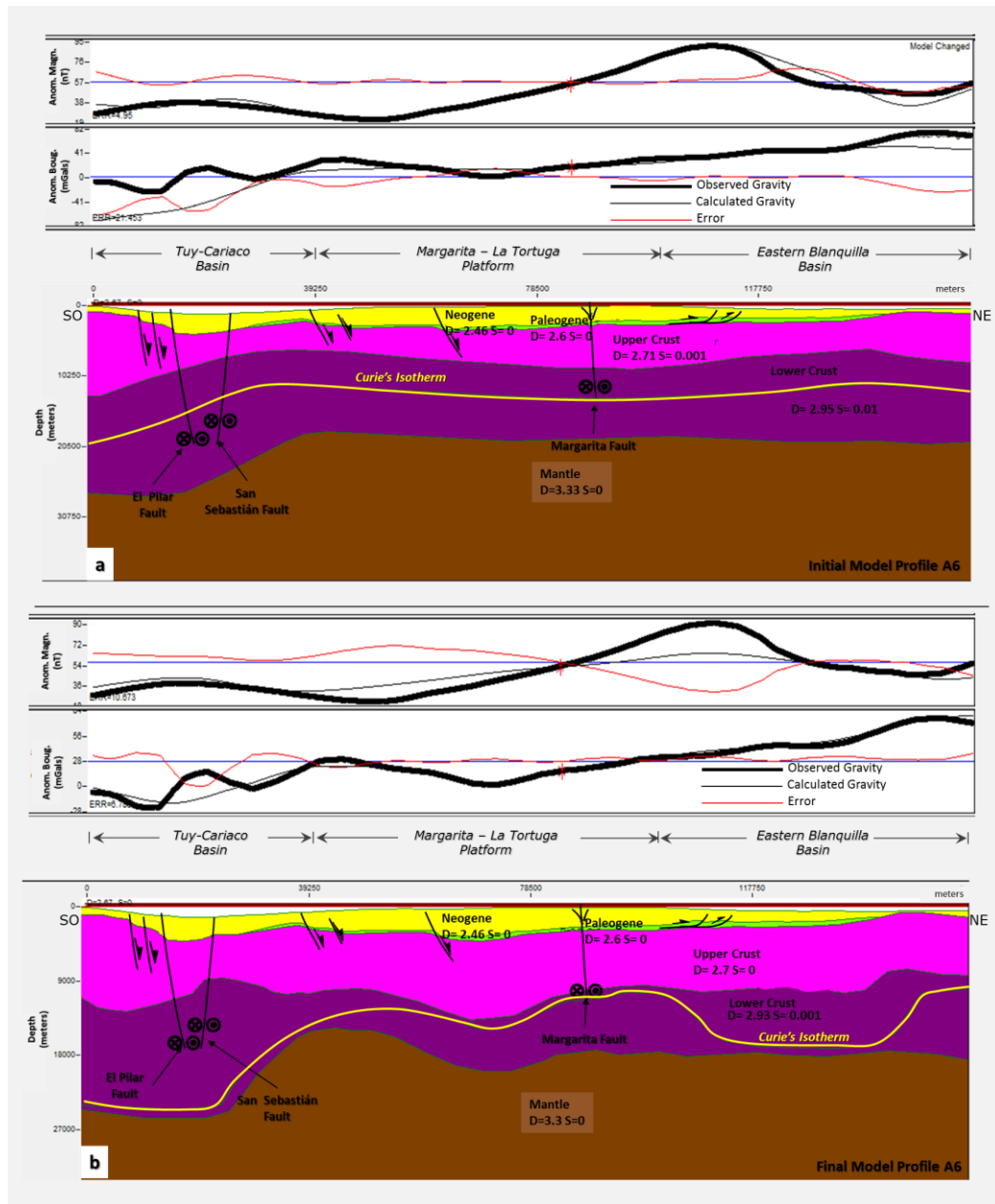


Figure 9. Cortical model of Profile A6. The figure shows the (a) initial model, and (b) the calibrated model from the inverse modeling of density and magnetic susceptibilities.

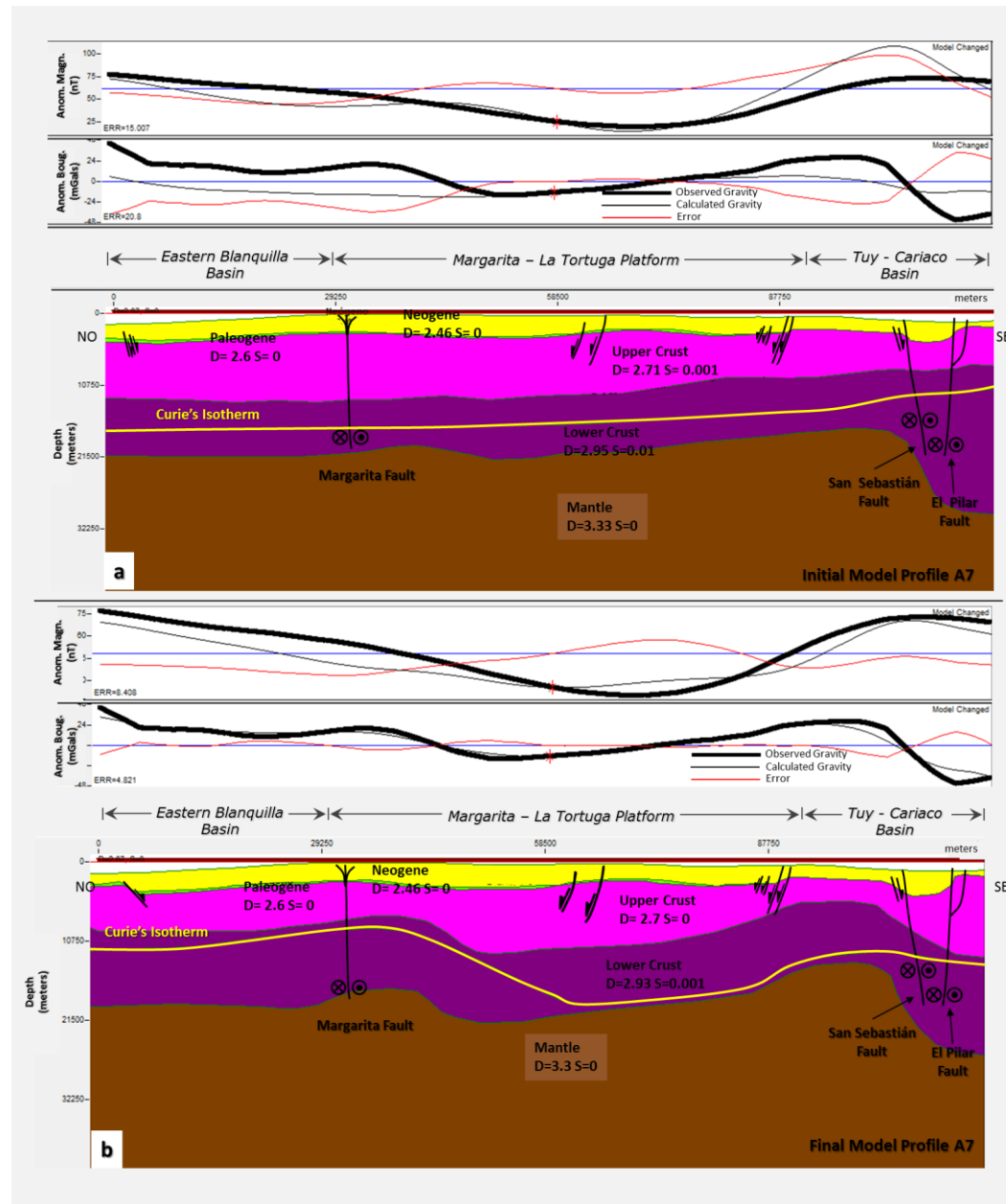


Figure 10. Cortical model of Profile A7. The figure shows the (a) initial model, and (b) the calibrated model from the inverse modeling of density and magnetic susceptibilities.

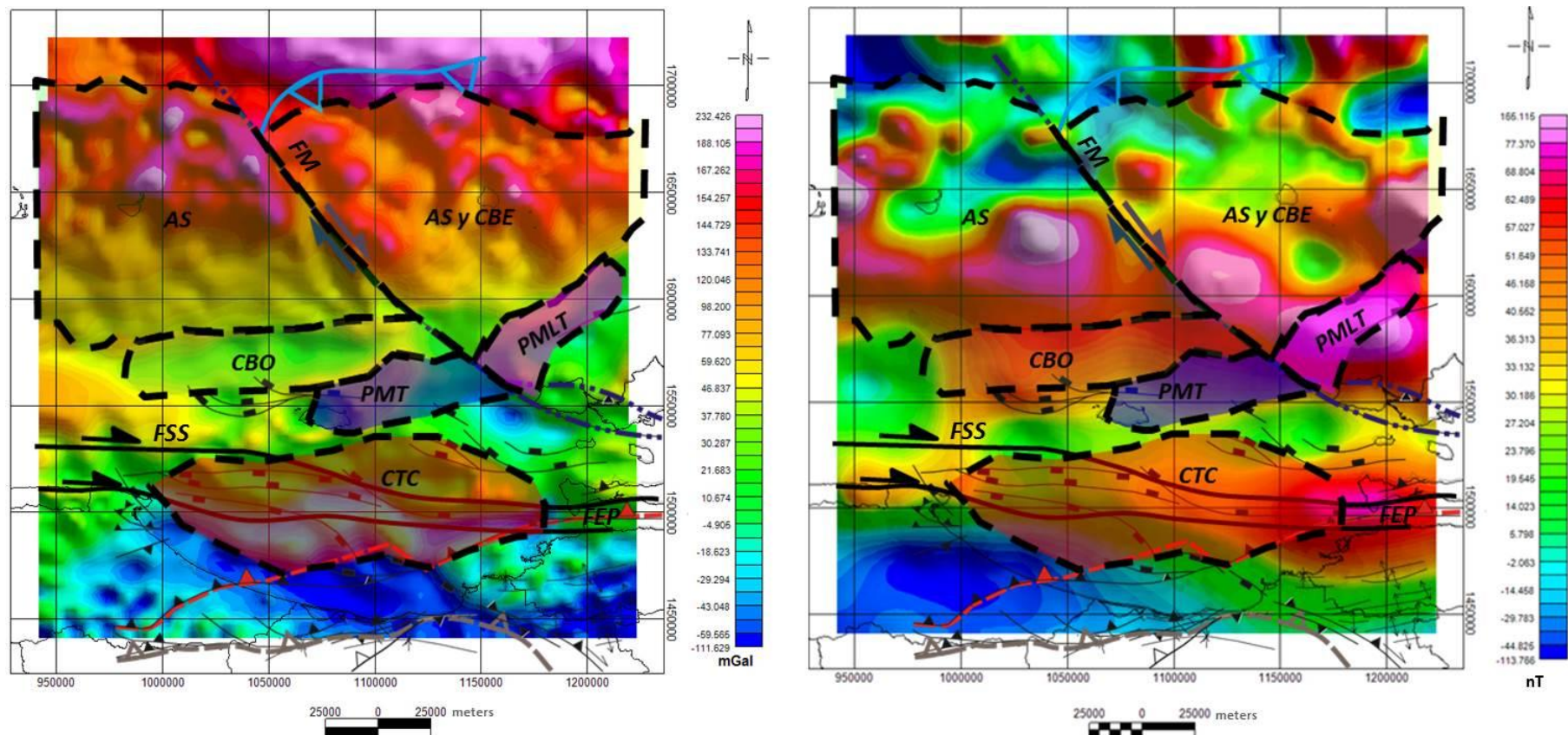


Figure 11. Bouguer Anomaly map (left) and total magnetic field anomaly (right), showing the anomalies' behavior of each geological province. AS = Leeward Antilles; AS y CBE = Leeward Antilles and East Blanquilla Basin; CBO = West Blanquilla Basin; PMT = Margarita-La Tortuga Platform; PMLT = Margarita-Los Testigos Platform; CTC = Tuy-Cariaco Basin; FSS = San Sebastian Fault; FEP = El Pilar Fault; FM = Margarita Fault.

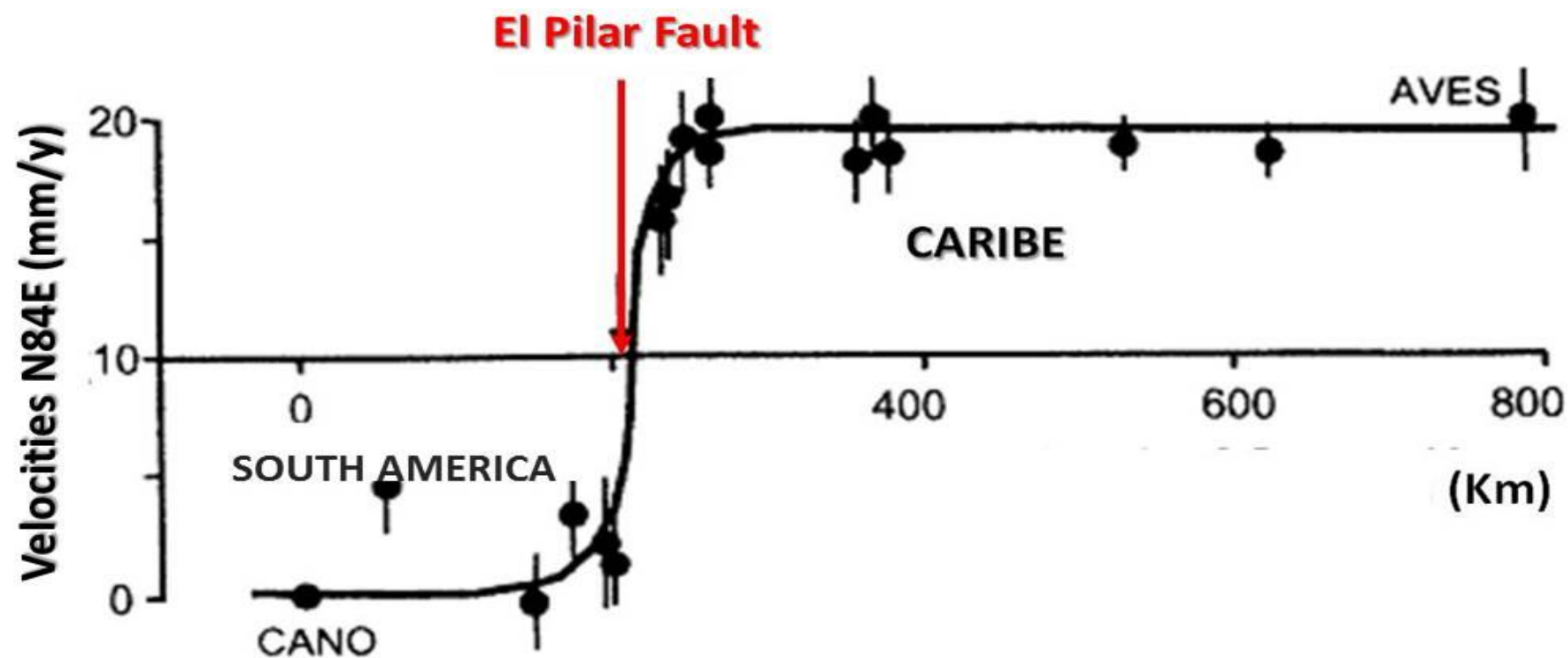


Figure 12. Present velocities at each side of El Pilar Fault in the northeast area of Venezuela. The continuum line corresponds to the velocities modeled surface, related to dextral shear with a displacement of 20 mm/y under the surface to 14 km of depth, fault orientation N84E (Pérez et al., 2001).

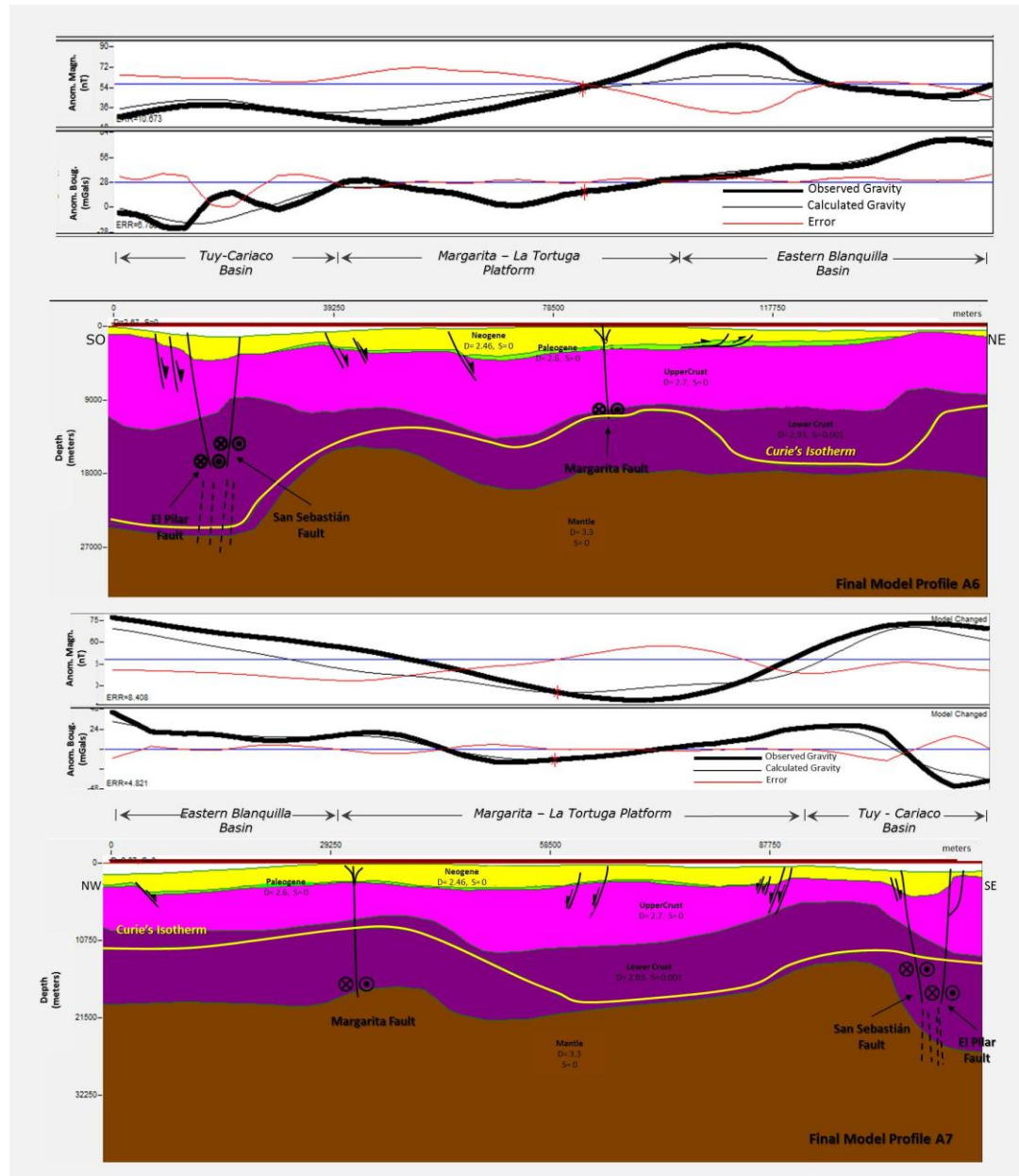


Figure 13. Proposed model for A6 and A7 profiles, referred to the behaviour of San Sebastian-El Pilar fault system. It shows the extension proposed by Magnani et al. (2009) to the upper mantle for this system, as evidenced by the thickness variations obtained on each side of the system, corroborated.