REVIEW ARTICLE

Magnetic anomalies in the Eastern Caribbean

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Abstract Despite the many different studies on the origin and evolution of the Caribbean Plate, no proposal has been widely accepted so far. A key element within this field of research is the characterization of the plate subsurface oceanic crust, as it would clarify the conditions in which it originated, the geological period when it formed and its possible geographical location at this first evolution stage. Based on partial results of this research work, we can say that the conclusions of previous studies are valid to a great extent, namely the NE–SW orientation of the striped magnetic anomalies in the Venezuelan Basin's western section and the existence of W–E preferentially oriented stripes parallel to the Leeward Antilles. The magnetic response of the triangular section in the southeast of the Venezuelan Basin represents cretaceous magnetic quiet zone (CMQZ) and therefore shows a considerable attenuation of the stripe pattern, indicating that the whole East Caribbean subsurface features oceanic crustal material. As for the period recorded by the Caribbean magnetic stripes, we propose the interval between chrons M23 and M0, and part of CMQZ. The wavelengths of the identified anomalies suggest that the ridge associated with the formation of

Caribbean ocean floor was slow-spreading when compared to average currently active ridges.

Origin of the Caribbean Plate

The origin and evolution of the Caribbean Plate is controversial (Meschede and Frisch 1998; James 2006, 2009; Pindell et al. 2006; Pindell and Kennan 2009), because its oceanic spreading center has not been identified so far. There are two opposite evolution models: The autochthonous model that suggests in situ formation of the plate and the allochthonous model that proposes origin in the Pacific region and drift into its current position. There is also an intermediate option of an Atlantic origin, close to its position near the boundary with the Pacific and moderate eastward drift.

The autochthonous model suggests that the Caribbean region formed in the period from 130 to 80 Ma, while South America moved southeast relative to North America (Frisch et al. 1992). According to this model, the Caribbean Plate would have an affinity with the Western Atlantic lithosphere.

Nowadays, most authors accept that the Caribbean Plate formed in the Pacific region, probably as oceanic lithosphere of the Farallón plate during the process of separation of the North and South American plates. From there it migrated E–NE until it reached its current position (Wilson 1966; Malfait and Dinkelman 1972; Burke 1988; Pindell and Barrett 1990; Mann 1999; Pindell et al. 2006).

The Caribbean Plate's Pacific origin has been defended with the following arguments (Pindell and Barrett 1990):

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(a) Cayman Trough limits and magnetic anomalies associated with the emergence of oceanic crust in this zone act as a spreading source between the North American and Caribbean plates (McDonald and Holcombe 1978; Ross et al. 1986), suggesting a relative displacement of more than 1,000 km since the Eocene.

(b) Magmatism of the Lesser Antilles subduction zone has been present since the Eocene, suggesting the eastward displacement of the Caribbean Plate between the North and South American plates for the same time period.

(c) Two rock groups of the same age (Jurassic–Upper Cretaceous/Paleogene) coexist in the Caribbean, but are genetically incompatible, namely platform terrigenous or carbonate sequences and island arc magmatic and ultramafic complexes. The way in which the latter are currently superimposed on the former suggests a diachronous juxtaposition of tectonic origin associated with the Caribbean Plate eastward drift.

Below, we present a simplified account of the evolution sequence for each scenario:

Pacific origin

During the Jurassic, Proto-Caribbean crust formed by spreading between North and South America, due to disparity in the initiation of the North Atlantic opening (Pindell and Dewey 1982; Burke et al. 1984; Pindell and Barrett 1990). To the west, an island arc (i.e. Great Caribbean Arc) developed as a result of the east—dipping subduction of the Farallón Plate beneath the Americas (Burke 1988). Sometime in the Middle Cretaceous, polarity reversal occurred, fostering NE migration of the Great Arc and penetration of the Farallón Plate overriding the Proto-Caribbean. There is no consensus among researchers on the moment and cause of this polarity inversion (White et al. 1999). It has been argued that it was caused by the collision of an anomalously thick Caribbean crust with the Great Arc, which stopped the subduction and forced the polarity reversal (Burke et al. 1984; Pindell and Barrett 1990). This proposal is difficult to accept because of the interval (88–90 Ma) during which Caribbean thickening occurred (Duncan and Hargraves 1984; Hoernle et al. 2004; Pindell et al. 2006). Another east-dipping subduction developed, giving rise to the Central America Arc and separating the Caribbean from the Pacific (Burke et al. 1978; Pindell and Dewey 1982).

During the Eocene, the Caribbean Plate started eastward migration with respect to a fixed point in South America, as a result of the collision of the northern part of the Great Arc

with the Bahamas platform (Burke et al. 1984; Mann 1999). Underthrusting of the Caribbean beneath South America developed during the Early Miocene accommodating convergence between the Americas, when relative motion changed from left–lateral transtensional to north–northeast compressional (Müller et al. 1999). Along Venezuela's northern coast, collision between the Caribbean and the South American Plate caused the formation of onshore fold and thrust belts. Offshore, the collision is responsible for the development of the South Caribbean Deformed Belt and the deformation of the Leeward Antilles together with basin development on adjacent terrains.

Atlantic origin

This model proposes the formation of the Caribbean crust west of its current position, but between the two Americas (Ball et al. 1969; Sykes et al. 1982; Donnelly 1985; Meschede et al. 1997; Meschede and Frisch 1998). The referential frame is based on the reconstruction of relative motions of North America, Africa, South America, and Farallón during the Cenozoic and the Mesozoic (Duncan and Hargraves 1984; Ross et al. 1986; Pindell and Barrett 1990).

As in the Pacific-origin model, the sequence starts in the Jurassic with opening of the North Atlantic. An ocean ridge extended between the Americas, opening the Proto-Caribbean. This spreading continued until the initiation of South Atlantic opening (126 Ma), generating the striped oceanic crust described for the Caribbean floor (Ghosh et al. 1984).

In the Early Cretaceous, the (Pacific) Farallón Plate suffered northeast-dipping subduction beneath the Americas and the Proto-Caribbean, forming the Costa Rica–Panama Arc and blocking communication between (Pacific) Farallón and Proto-Caribbean. To the northeast, Atlantic crust subducted beneath Proto-Caribbean with southwest polarity, forming the Greater Antilles Arc.

By the Santonian (85 Ma), a first episode of basalt flows had already occurred (90–88 Ma), thickening the Proto-Caribbean and defining the Caribbean Plate. Some authors have reported occurrence of first LIP cycle in the Early Cretaceous (Kerr et al. 2003). Northeast-dipping subduction continued in the west, while Atlantic crust subducted to the south beneath the Greater Antilles.

In the Campanian (72 Ma), Atlantic subduction beneath the Caribbean continued, and development of the Greater Antilles Arc was accompanied by beginning of Aves Ridge activity.

In the Paleocene, opening of the Grenada Basin was associated with cessation of the Aves Ridge activity and beginning of activity in the Lesser Antilles Arc. Since the

Eocene, the sequence in this model is like the one described for the Pacific-origin model.

Caribbean magnetic data and anomalies

Magnetic data are the least used in earth tectonic studies, due to the complexity implied in the management of vectorial data and to the existence of other techniques, such as gravimetry and seismicity, which provide information more easily visualized. Nowadays, there is a wide range of data sources to study the Caribbean tectonics, notably those that combine gravimetric and magnetic satellite data (Pavlis et al. 2008; Maus et al. 2009) and those including the results of aerial (USGS 2003) and marine surveys from the last four decades (Quesnel et al. 2009).

Ghosh et al. (1984)—an essential reference study for this work—compiled marine magnetic data. They concluded that the Eastern Caribbean marine subsurface has a stripe pattern and identified a spreading axis subparallel to the Beata Ridge, E–W anomalies in the south of the Venezuelan Basin, N–S anomalies parallel to the Aves Ridge, and a non-striped triangular zone in the southeastern edge of the above-mentioned basin (Fig. 1).

This study ratifies most of the results obtained by Ghosh et al. (1984). However, new elements emerge, deepening our knowledge about the Eastern Caribbean subsurface. From 1984 to the present marine and aerial geophysical

surveys contributed new information, while integrated models have added satellite data, enhancing knowledge needed to conduct a magnetic study of the region.

Nowadays, magnetic anomaly characterization of any region relies upon information integrating satellite, land, and marine data (Maus et al. 2009), allowing generation of continental maps useful at the early stages of regional geophysical studies.

In this study, we used the third version of the National Geophysical Data Center's degree-720 integrated magnetic model (Maus 2010) to analyze long- and intermediate-wavelength anomalies (from dozens to hundreds of kilometers) over the Eastern Caribbean. In this way, we generated the map shown in Fig. 2.

The vertical component anomalies of the Eastern Caribbean magnetic field (Fig. 2) range from −200 to 200 nT. The Greater Antilles Arc shows a continuous positive anomaly over Puerto Rico and the Dominican Republic, but loses lateral continuity over the Anegada Passage to the east. North of the arc, over the associated Puerto Rico trench, there is an extensive negative anomaly from the Anegada Passage to the east front of Montserrat Island in the Lesser Antilles.

The Lesser Antilles Arc features positive anomalies and a significant lateral rupture with a magnetic low that extends between Guadalupe and Martinique. The Leeward Antilles are associated with a magnetic high. At the western edge (Aruba-Curaçao), this high connects with
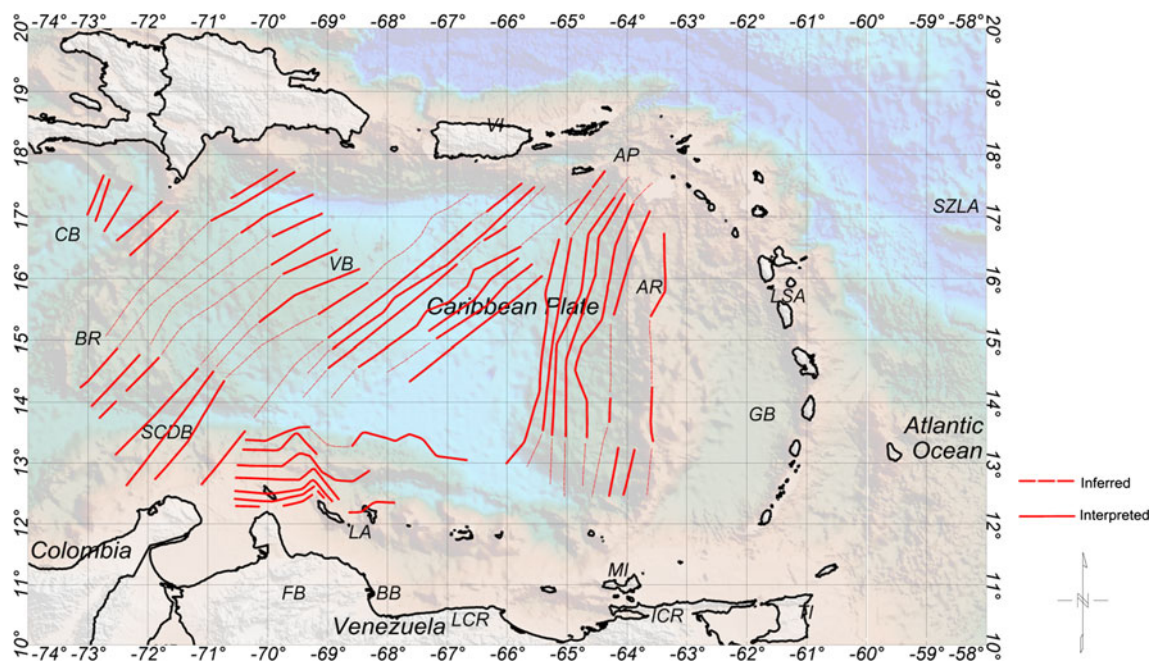

Fig. 1 Magnetic stripes in the Venezuelan Basin from Ghosh et al. (1984) *SCDB* Southern Caribbean Deformed Belt, *FB* Falcón Basin, *BB* Bonaire Basin, *BR* Beata Ridge, *LCR* Litoral Coastal Range, *LA* Leeward Antilles, *AR* Aves Ridge, *VB* Venezuelan Basin, *CB* Colombian Basin, *GB* Grenada Basin, *ICR* Interior Coastal Range, *LSA* Lesser Antilles, *AP* Anegada Passage, *SZLA* Subduction Zone of the Lesser Antilles
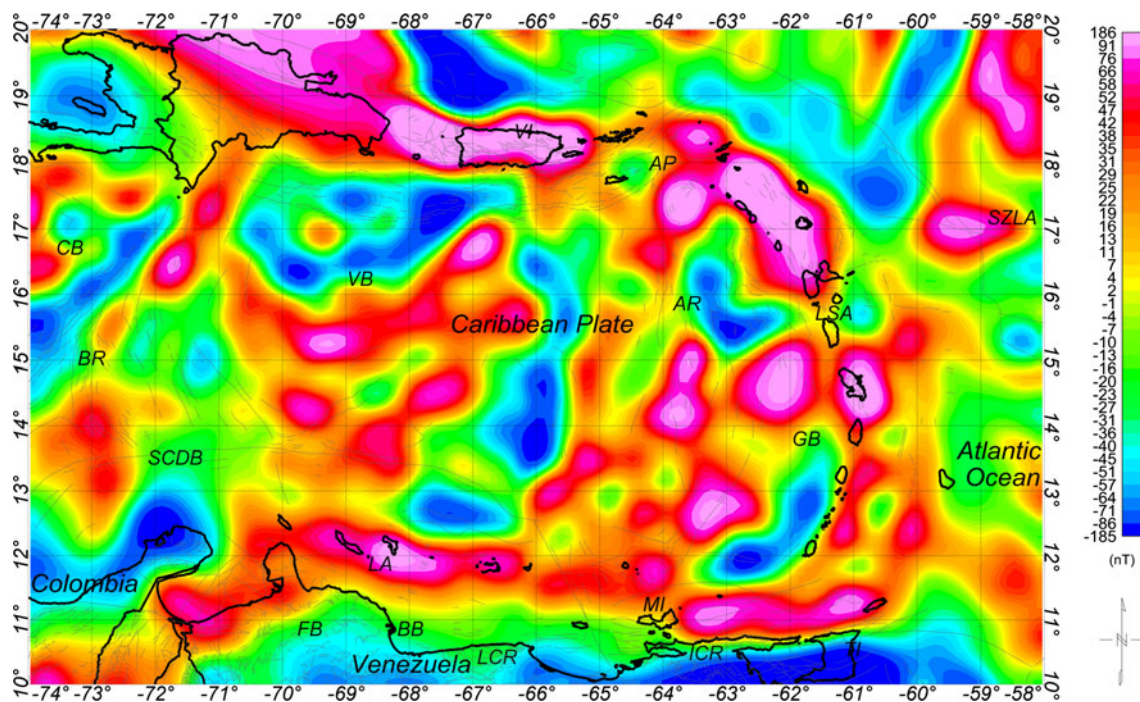
Fig. 2 Vertical component of the Eastern Caribbean magnetic field NGDC-720 (Maus 2010) *SCDB* Southern Caribbean Deformed Belt, *FB* Falcón Basin, *BB* Bonaire Basin, *BR* Beata Ridge, *LCR* Litoral Coastal Range; *LA* Leeward Antilles; *AR* Aves Ridge, *VB* Venezuelan Basin, *CB* Colombian Basin; *GB* Grenada Basin, *ICR* Interior Coastal Range, *LSA* Lesser Antilles, *AP* Anegada Passage, *SZLA* Subduction Zone of the Lesser Antilles

NE–SW-oriented positive anomalies from the inner Venezuelan Basin. North of these islands, the Los Roques Basin is associated with a negative anomaly that connects at the northeast with the anomaly of the Venezuelan Basin triangular zone (Ghosh et al. 1984).

The Beata Ridge shows a negative anomaly, while its flanks have positive anomalies. The Venezuelan Basin basically features NE–SW-oriented positive and negative anomalies, subparallel to the Beata Ridge. A revision of short-wavelength anomalies requires data from marine or aerial surveys with sampling grids capable of capturing signal associated with contrasts between smaller geographical elements.

In the database of the United States' National Geophysical Data Center (NGDC: www.ngdc.noaa.gov/mgg/dat/), there are many marine surveys with magnetic data revealing the existence of stripes in the whole Eastern Caribbean. However, the coverage of these surveys is not regular enough to further characterize the Eastern Caribbean magnetic anomalies. Hence, we considered the anomalies reported in aeromagnetic surveys of the region as well (NGDC 2002).

The anomaly distribution of the aeromagnetic map (Fig. 3; USGS 2003) completely fits with the descriptions presented above. In addition, short-wavelength anomalies associated with the West Indies and the inner plate are apparent in aerial survey data. Contrasts of magnetic susceptibility can be related to shallow subsurface sources or those of small dimension.

The Beata Ridge and the Venezuelan Basin reflect the same anomalies described on the basis of the map that incorporates satellite data, but with higher resolution. Anomalies in Fig. 2 basically reflect the sources associated with longer wavelengths (larger or deeper sources), while the map in Fig. 4 reflects anomalies associated with the shorter-wavelength anomalies (smaller or shallower sources).

The Lesser Antilles manifest a discrete chain of magnetic highs (Fig. 4). At the northeast of the Lesser Antilles southern segment, a discontinuous magnetic high extends from the south of Martinique to the south of the Aves Ridge. This NE–SW high is subparallel to anomalies over the Beata Ridge and the Venezuelan Basin. This positive anomaly is also reflected in the map that incorporates satellite data (Fig. 2).

The Aves Ridge is expressed as a north–south alignment of discrete magnetic highs. NE–SW-trending magnetic highs and lows occur between the ridge and the Lesser Antilles. The negative magnetic anomaly of the triangular zone (Fig. 1) at the southeast of the Venezuelan Basin is apparent in both maps, along with its prolongation under the Los Roques Basin.
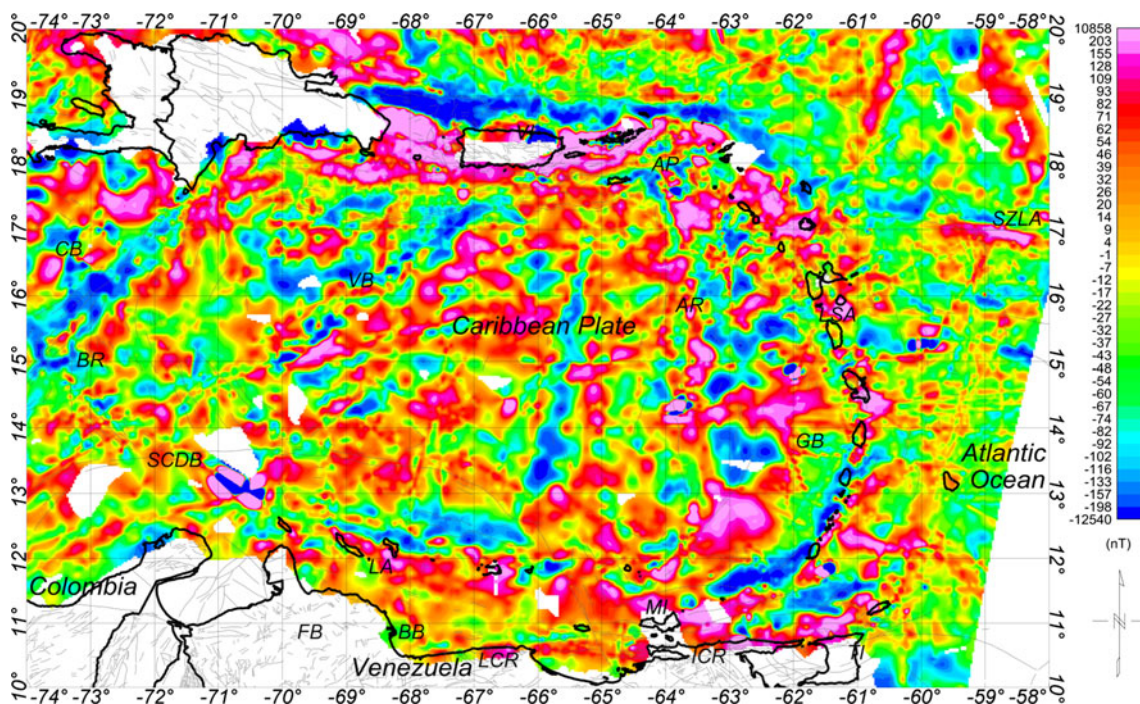
Fig. 3 Map of total magnetic field anomalies in the Eastern Caribbean based on the integration of aerial surveys (Data from USGS 2003) *SCDB* Southern Caribbean Deformed Belt, *FB* Falcón Basin, *BB* Bonaire Basin, *BR* Beata Ridge, *LCR* Litoral Coastal Range, *LA* Leeward Antilles, *AR* Aves Ridge, *VB* Venezuelan Basin, *CB* Colombian Basin, *GB* Grenada Basin, *ICR* Interior Coastal Range, *LSA* Lesser Antilles, *AP* Anegada Passage, *SZLA* Subduction Zone of the Lesser Antilles
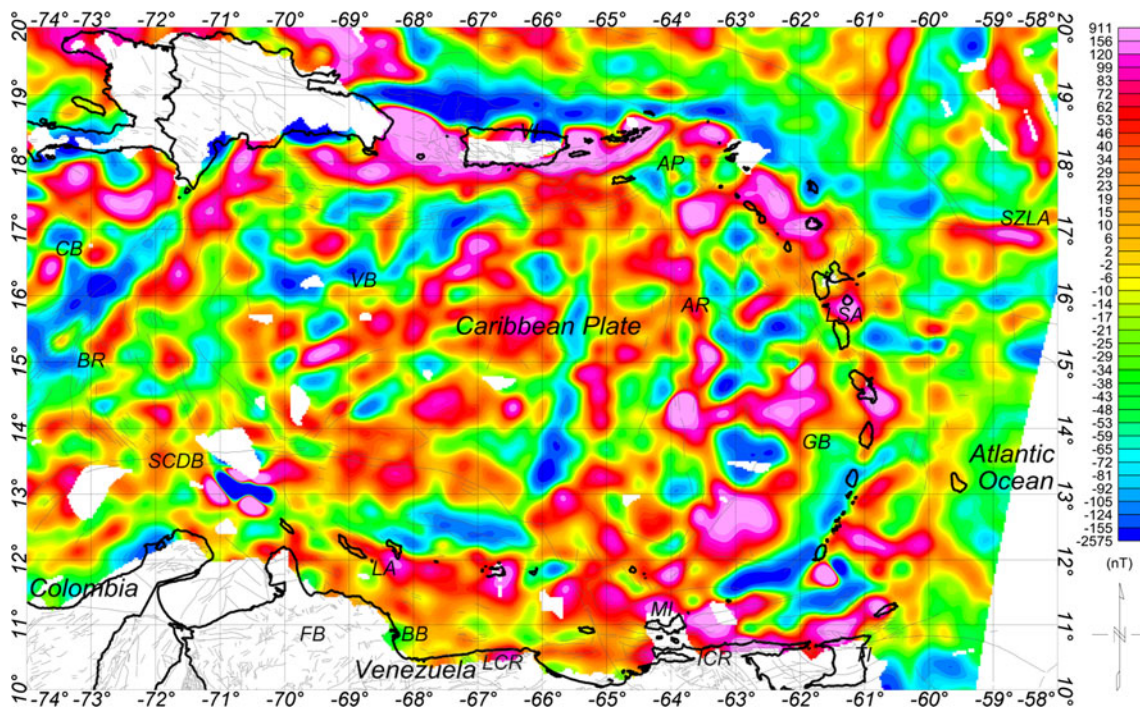

Fig. 4 Regional component of the Eastern Caribbean aeromagnetic map *SCDB* Southern Caribbean Deformed Belt; *FB* Falcón Basin, *BB* Bonaire Basin, *BR* Beata Ridge, *LCR* Litoral Coastal Range, *LA* Leeward Antilles, *AR* Aves Ridge, *VB* Venezuelan Basin, *CB* Colombian Basin, *GB* Grenada Basin, *ICR* Interior Coastal Range, *LSA* Lesser Antilles, *AP* Anegada Passage, *SZLA* Subduction Zone of the Lesser Antilles

Main results

The three data sets described above provide the information needed to characterize the magnetic anomalies of the Eastern Caribbean. The qualitative account in the previous paragraphs establishes the general expression of anomalies related to each source and quantification of contributions.

This task was performed using the profiles from marine and/or aerial surveys, revealing regional trends with the map of the combined magnetic model (Fig. 2). Another way to derive regional trends was through regional-residual separation of aeromagnetic data available (Fig. 4).

The maps that reflect longer-wavelength magnetic anomalies (Figs. 2, 4) provide the input needed to estimate the Curie isotherm depth, that is to say, the surface that describes the maximum depth at which the Caribbean subsurface rocks are capable of retaining magnetism from Earth's magnetic field induction. Following the methodology described for these types of studies (Wasilewski et al. 1979; Tanaka and Ishikawa 2005; Sharma et al. 2006; Trifonova et al. 2009) and revising previous works that have implemented it (Bansal et al. 2011; Chiozzi et al. 2005; Rajaram et al. 2009; Anand et al. 2010) made possible the estimation of the Curie isotherm depth in the Eastern Caribbean (Fig. 5) using the NGDC-720 combined model (Fig. 2).

Preliminary results (Fig. 5) suggest that this surface features important variations, with a minimum depth of about 17 km in the southeastern zone of the Venezuelan Basin, matching up with the negative anomalies zone proposed as a non-striped triangular area (Ghosh et al. 1984). The maximum depth established for the Curie isotherm in the marine section is 24 km below the western edge of the Venezuelan Basin and the Grenada Basin. The lowest gradient of this surface occurs on the western edge of the Venezuelan Basin, between the Beata Ridge and northwestern Venezuela.

This behavior of the Curie isotherm is associated with high heat flow in the eastern Venezuelan Basin (Clark et al. 1978). The measurement reported in the area that cuts the isotherm in the minimum depth zone reflects a heat flow of 2.70 μcal/cm^2 s, exceeding the average value expected for an oceanic basin (1.98 ± 0.22 μcal/cm^2 s) (Smith 1975).

This combination of factors reveals an area with high heat flow and a shallow Curie isotherm in the eastern Venezuelan Basin and supports the idea that there are traces of what can be considered an extinct mantle activity in the Caribbean subsurface. Two basic results are obtained from the collection and revision of the Caribbean magnetic anomalies: the existence of a Curie isotherm with significant lateral variations and the presence of magnetic striped patterns.
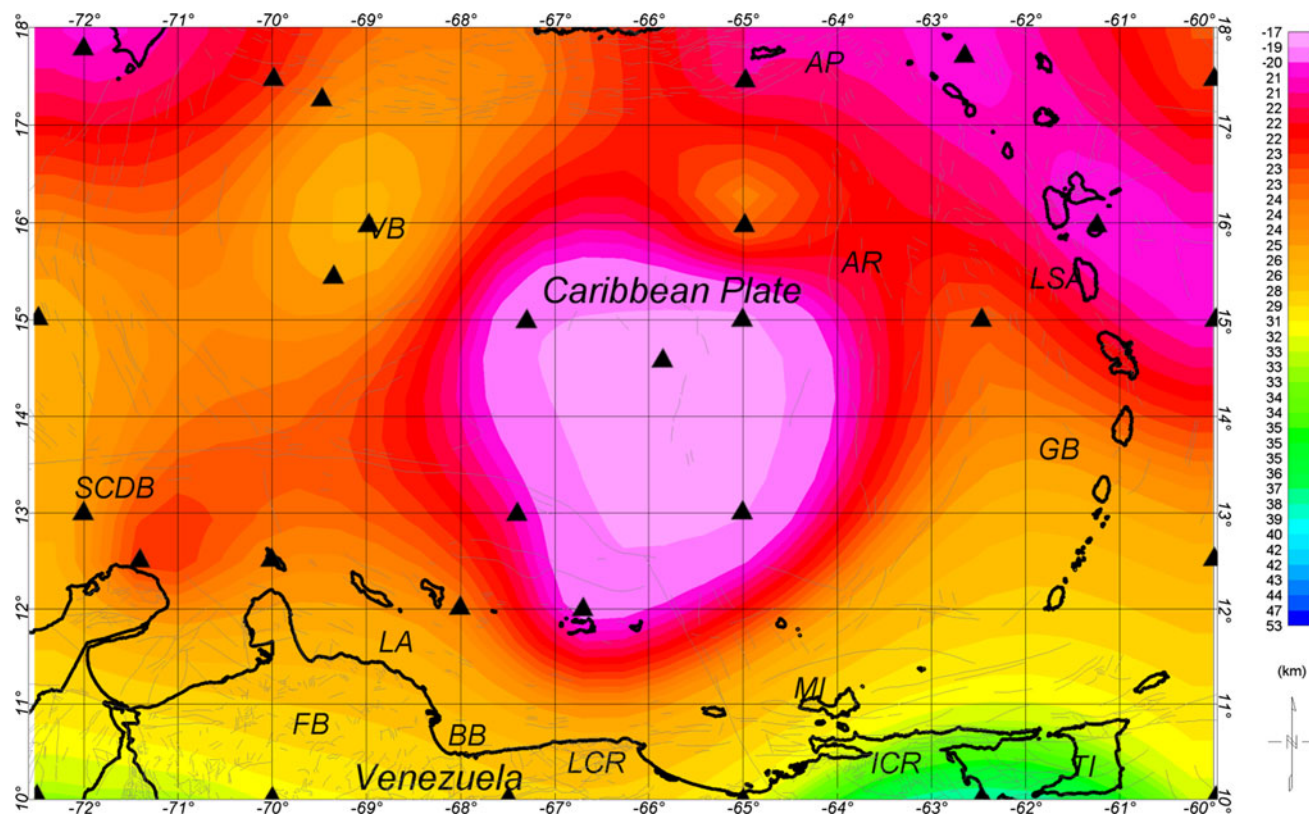

Fig. 5 Curie isotherm depth of the Eastern Caribbean

Curie isotherm and mantle activity of the Eastern Caribbean

Identifying the Caribbean Plate as a large igneous province (LIP) (Coffin et al. 2006) implies associating it with a mantle activity. Most models that seek to explain the origin of this tectonic plate state that it formed to the west of its present location (Pindell et al. 2006; Hastie and Kerr 2010), within the Pacific Ocean, thereby implying that both the anomaly stripes and the LIP coverage originated in that region and supporting the allochthonous nature of the Caribbean Plate.

The results presented here suggest an alternative explanation to the origin of the LIP, proposing the existence of a mantle activity relict in the Eastern Caribbean subsurface. It generated intrusive and extrusive mafic rocks of the Caribbean LIP (Sinton et al. 1998; Révillon et al. 2000).

The occurrence of mantle activity in the subsurface of the Earth has a number of consequences for physical values measured by geophysical studies of the mantle. Among the most relevant are seismic wave propagation velocity decrease, the mantle transition zone reduction and lateral velocity variations at the D" layer of the 200- to 300-km-thick mantle–core interface, associated with the zone of mantle activity enrichment and formation.

Variations in the wave propagation velocity

Seismic tomography studies of the upper mantle (Miller et al. 2009) report anomalies with decrease of wave propagation velocity along the eastern border of the area covered by the thinning of the Curie isotherm (Fig. 6). The referred study does not include the western area, but it does cover the central–eastern section of the zone proposed for the location of the mantle activity.

Mantle transition zone thinning

As part of the Broadband Ocean-Land Investigations of Venezuela and the Antilles Arc Region (BOLIVAR) project (Levander et al. 2006), results of a study were published with the characterization of the mantle transition zone within the Caribbean Plate southern border (Huang et al. 2010). Part of the southern section of the Curie isotherm thinning zone is covered by this study (Fig. 7), suggesting the existence of lateral variations of the mantle transition zone, with a tendency to thinning in the area proposed as the location of the Eastern Caribbean extinct mantle activity.

D" lateral variations

A study on the seismic tomography of the D" layer in the Caribbean (Hung et al. 2005) reports lateral variations in the shear wave velocities estimated by different methods.
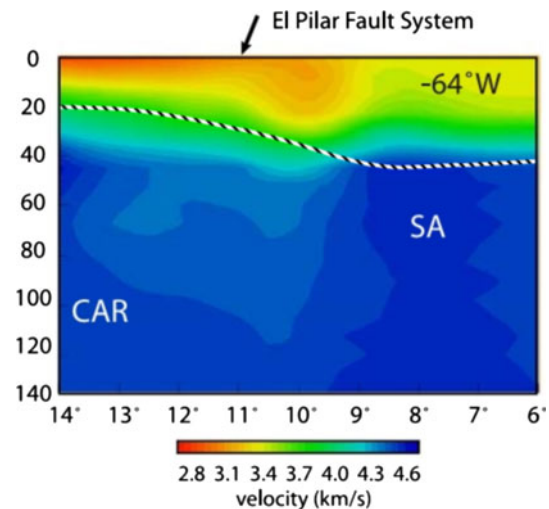

Fig. 6 Cross section of the seismic tomography model in the border zone between the Caribbean Plate (CAR) and the South American Plate (SA)—low velocity zone between latitudes 11 and 14 (Adapted from Miller et al. 2009)
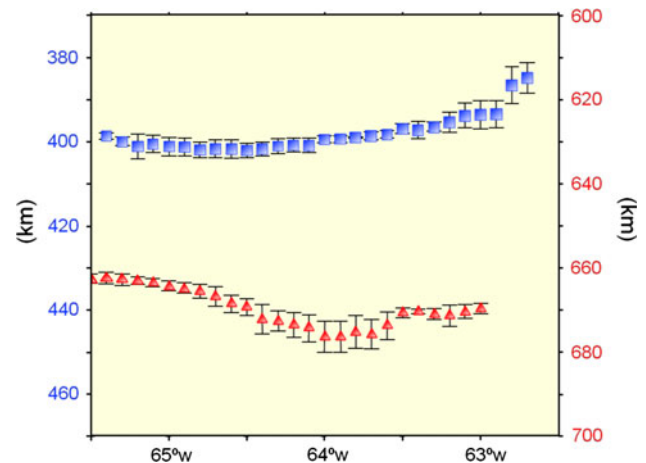

Fig. 7 Average lateral variation between latitudes 10.5° and 12° of the mantle transition zone, top: 410 km (blue rectangles, left axis) to bottom: 660 km (red triangle, right axis), from Huang et al. (2010)

The results indicate a complex Caribbean subsurface and important lateral variation of the core–mantle boundary in the region (Fig. 8). In particular, there is an outstanding section in the Eastern Caribbean with a N–S trend at D" level with a high velocity contrast within the levels found between those reported at the hot spots of Galápagos and Bermuda. This value supports the proposal of Hung et al. (2005) that there might be a mantle activity in the Caribbean subsurface.

The Curie isotherm in the Caribbean region explains the magnetic minimum in the eastern Venezuelan Basin (triangular area, Fig. 1) and contributes—along with LIP coverage—the surrounding positive anomalies distributed between the basin and the Aves Ridge. This contribution is

Fig. 8 Share wave velocity variation on D" layer estimated with a finite frequency model— *GA* Galápagos hot spot, *RA* Ratón, *BE* Bermuda, from Hung et al. (2005)
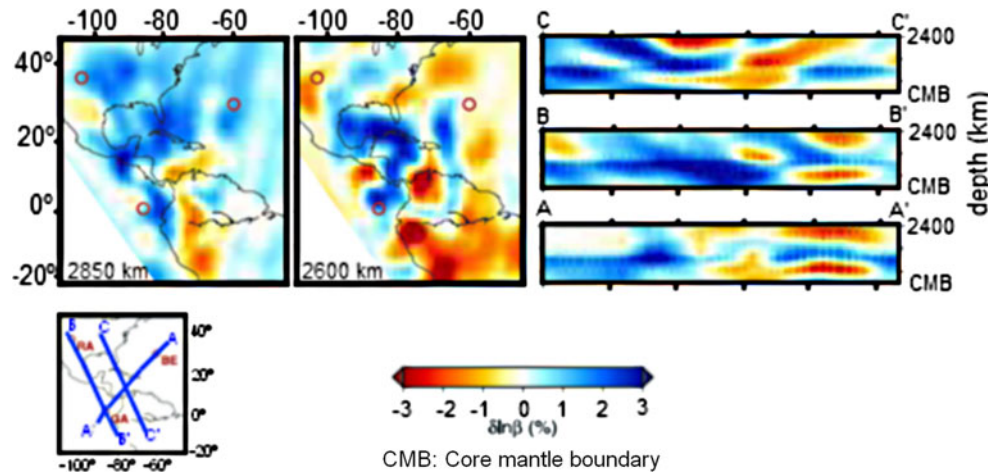
a key feature of the anomaly pattern, which previous works used to explain the absence of magnetic stripes in the triangular area (Ghosh et al. 1984).

Magnetic anomaly profiles

Characterization of different anomaly sources is based on six profiles reported in marine and aerial surveys. In one case, the locations of marine and aerial profiles match and allow consistency among different sources to be assessed (Fig. 9).

The presented profiles reflect magnetic anomaly (nT) versus position (degrees) measured from the starting point of the profile. In all cases, there are W–E and N–S trends. Aerial profile anomalies were all normalized to zero; marine surveys do not have a single standardization level. All graphs show 200–600 nT magnetic anomalies on the vertical axis, in order to facilitate comparison in all cases.

All the presented profiles incorporate the anomaly extracted from the NGDC-720 combined model, in order to assess the anomalies associated with longest wavelengths. In this study, anomaly expression is of great use in explaining the effect of the Curie isotherm and the LIP coverage in the area. The six profiles were selected on the basis of their geographical location (Fig. 9) to illustrate the behavior of the magnetic anomalies in:

(1) The NE–SW magnetic striped zone on the Venezuelan Basin western border, where influence of Curie isotherm is minimal (Fig. 9a); (2) the W–E striped zone parallel to the Leeward Antilles (Fig. 9b); and (3) the zone of maximum influence of the Curie isotherm in the eastern section of the Venezuelan Basin (Fig. 9c).

Discussion

The analysis is based on qualitative interpretation of maps (Figs. 2, 3, 4), characterization of 6 profiles (Fig. 9) and

quantitative estimations obtained from generic models (Fig. 10) representing a WE-trending profile located at latitude 14°N without remnant magnetization, magnetic susceptibility of 0.0025 cgs for basalts of both the LIP and the stripes, and of 0.005 cgs for the upper mantle above Curie isotherm.

Magnetic anomaly sources

There are three sources of magnetic anomalies superimposed in the study area:

1. Long-wavelength anomalies, associated with the Earth's magnetic field and expressed as a field with a SE–NW trend.
2. Short-wavelength anomalies, associated with shallow contrasts over the Antilles.
3. Intermediate-wavelength anomalies, which incorporate three sources: the magnetic effect of the Caribbean LIP, the magnetic effect of the stripes associated with the oceanic basin beneath the LIP, and the magnetic effect related to Curie isotherm variations.

The established ages for the LIP coverage (Sinton et al. 1998; Révillon et al. 2000)—88–91 Ma cycle I, 76 Ma cycle II, 55 Ma possibly cycle III—and the formation period suggest that it will not have associated stripes and that its intermediate wavelength is associated with its extension in the region. The magnetic anomaly stripes of the oceanic crust and those generated by lateral variations of the Curie isotherm are associated with a middle wavelength, due to the depth of the source, which, in this case, can reach depth levels above the average, as a result of the crustal flexure formed because of the LIP load.

Characteristics of middle wavelength anomalies

Based on the magnetic anomaly profiles of the Eastern Caribbean, we estimated the theoretical effects of each of

the abovementioned middle wavelength sources using the GM-SYS modeling of Oasis Montaj software module (Geosoft Inc. 2007).

The results of the conducted modeling let us describe the general characteristics for the magnetic sources in the region:

1. Magnetic anomaly stripes caused by oceanic crust spreading (Fig. 10a).

   a. Located in the Venezuelan Basin and flanks of the Aves Ridge, the Beata Ridge and the Leeward Antilles.
   b. Peak-to-peak amplitudes from 100 to 150 nT in areas without significant variations associated to other sources of middle wavelength anomalies.
   c. Alteration without losing striped character in areas with Curie isotherm lateral thinning.

2. Anomalies associated with LIP coverage (Fig. 10b)

   a. Slight amplifying effect (10 %) of magnetic anomaly stripes in areas with large LIP coverage provided that magnetization is equal or higher than that of the original oceanic crust, and there is no load-related flexure.
   b. 50–70 nT peak-to-peak amplitudes with wavelengths longer than those of the stripes.
   c. Flat attenuation effect of anomaly stripes in areas with extensive LIP coverage and flexure resulting from associated loads.
   d. Wavelength increase of anomaly stripes on those segments where LIP layers overlap with oceanic layers.

3. Anomalies associated with lateral variations of Curie isotherm (Fig. 10c)

   a. Although their effect is associated with slight changes in the magnetic properties of the upper mantle rocks, they are more significant than the LIP coverage influence.
   b. The maximum peak-to-peak amplitude is 150 nT, and it is associated with the area of the most significant Curie isotherm thinning within the triangular area.

Integration of effects produced by the three abovementioned sources suggests that the Eastern Caribbean reflects intermediate-wavelength magnetic anomalies dominated by the striped effect of original crust. This is confirmed by both marine and aerial profiles. In all cases (Fig. 9), the profiles reflect magnetic anomaly stripes with superimposed LIP expression and Curie isotherm variation, even though these two sources are not able to overshadow the striped effect. This is due to the vertical magnetic contrasts produced by the stripes versus the subhorizontal

contrasts of the LIP effect and the greater depth of the Curie effect (Fig. 10d).

Magnetic anomaly stripes

Anomaly characterization was based on the aeromagnetic map of Fig. 3, where magnetic alignment is apparent in the southern and western Venezuelan Basin. In the central section, a complex convergence of sources hinders monitoring of potential striped sequences. This difficulty is due to the complex sum of anomaly sources, as well as to the strong influence of cultural noise associated with the surveys.

To support the characterization of the anomaly stripes, it is necessary to resort to the magnetic profiles of Fig. 9. The first point to underline is the consistency of the three anomaly sources identified in the region. In all cases, the anomaly derived from the combined model reflects the envelope of marine and aerial anomalies, showing the deep (Curie) and large (LIP) sources of each profile. Comparison of the response for shorter wavelengths (striped crust) also reflects similar behavior in both source location and anomaly amplitude.

The profiles of Fig. 9a—located in an area of little LIP and Curie isotherm influence, as revealed by the low amplitude and smoothness of the curve derived from the combined model—reflect the striped pattern of the original crust and the consistency of stripe distribution in the two reported data sets (aerial: CV06, and marine: DSDP15GC).

The profiles of Fig. 9b—perpendicular to the Leeward Antilles (Fig. 11)—reveal the occurrence of two striped anomalies of different wavelength and lateral correlation, as reflected by the map in Fig. 3.

The profiles of Fig. 9c are perpendicular transects across the Venezuelan Basin in N–S and W–E directions. In both cases, LIP and Curie isotherm influence are evident. The latter especially has a more marked effect on the southern and eastern borders. The amplitude difference between these two profiles is due, on the one hand, to the orientation with respect to the existing stripes and, on the other hand, to the location of the N–S profile almost entirely on the thin Curie area. The West–East profile reveals an anomaly of shorter wavelength than the stripes and higher amplitude, located on the Curie thinning influence limit.

Anomaly stripes with low influence of Curie isotherm

The behavior reflected by the Curie isotherm map (Fig. 5) serves to understand that the vertical component (Fig. 2) reflects a section of long-wavelength anomalies of near-zero amplitude in the segment between the south of the Beata Ridge and northwestern Venezuela. This also explains that on that same segment, the map of Fig. 4 reveals anomaly stripe sequences with little deformation (Fig. 9a).
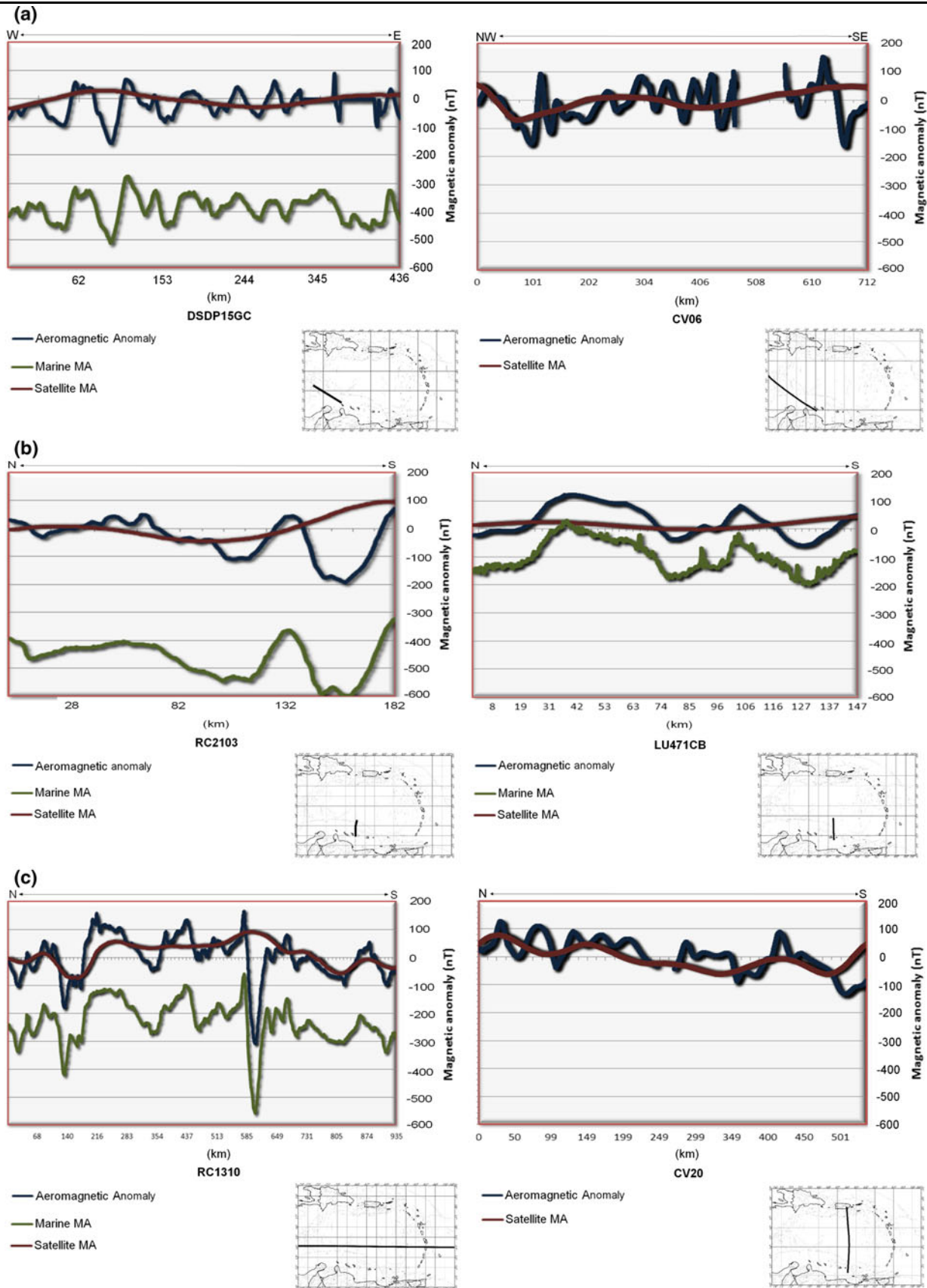
Fig. 9 a Magnetic profiles in the Venezuelan Basin's southwestern section, **b** magnetic profiles perpendicular to the Leeward Antilles, **c** magnetic profiles on the triangular area
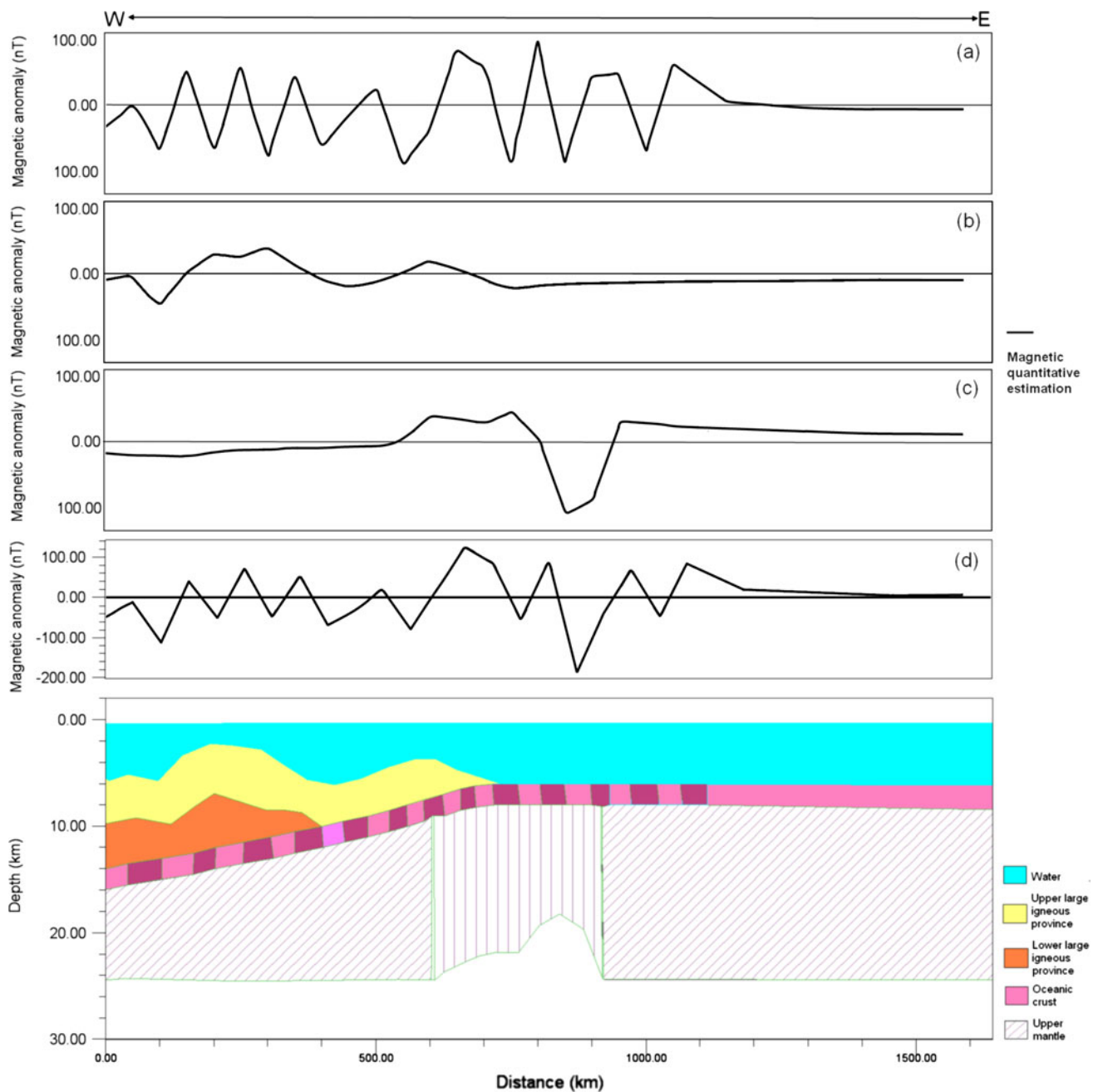
Fig. 10 Magnetic anomalies stripes [effect of striped crust (**a**), LIP coverage (**b**), Curie isotherm (**c**), integration of the three sources (**d**)]

Based on favorable conditions for the characterization of the Caribbean striped sequence from profiles located on that segment of the Venezuelan Basin, Fig. 11 presents DSDP15GC profile (Fig. 9a) on a scale that facilitates the comparison of the striped pattern with the one reported for the North Atlantic (Bird et al. 2007) in the M25–M0 chron sequence.

The striped sequence identified for the North Atlantic as signatures of chrons between M0 and M25 (Bird et al. 2007) suggests that the striped sequence of the Eastern Caribbean reflects the M4–M23 chron sequence of the

interval of 150.69–126.57 Ma (Late Jurassic to Early Cretaceous)—at least in the section analyzed in this study.

The signatures of anomalies associated with different chrons are unique in the whole world. The basic difference between the various spreading centers is related to the wavelength (distance among chrons), which depends on the spreading velocity on each ridge. The distance between chrons M21 and M20 of the Atlantic profile in Fig. 11 is about 17 km—the same separation to the one reflected by same chrons of the Caribbean profile. When comparing these chron lengths of the Nauru Basin in the Pacific Ocean
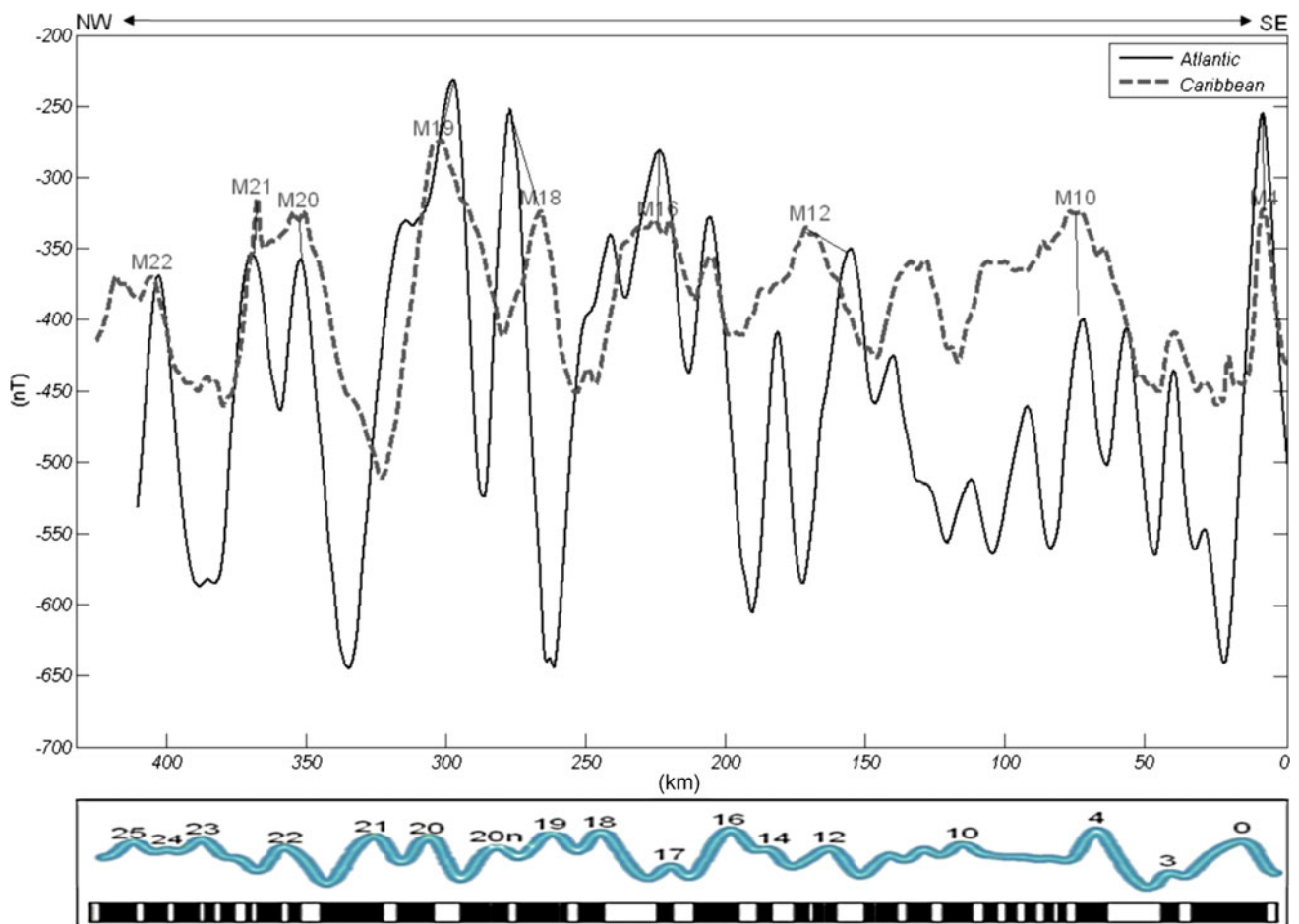
Fig. 11 Comparison of DSDP15GC profile's striped sequence (*above*) with a profile located in the North Atlantic (*below*) between latitudes 31° and 34°N (Adapted from Bird et al. 2007)

(Murphy 2004), it is found that the separation between M21 and M20 reaches 74 km. These lengths suggest that for equivalent time periods (146.56–144.70 Ma) the spreading velocity of the ridge that formed the Caribbean and the North Atlantic was 0.91 cm/a, while the average velocity of the Pacific stripes was 3.98 cm/a.

A similar comparison of chrons M19 and M18 allows establishment of 20 km separation in Atlantic chrons, 31 km in the Caribbean, and 61 km in the Pacific, revealing spreading rates of 1.08, 1.68, and 3.30 cm/a, respectively.

The Caribbean stripes reveal a sequence with wavelengths indicating that the spreading velocity of the associated ridge was low compared to the velocities of the currently active ridges. The spreading rates show more affinity with the Atlantic than with the Pacific.

Cretaceous magnetic quiet zone (CMQZ)

A chron sequence typical of the Mesozoic (M25–M0) in the Caribbean and its eastward age decrease (youngest segments in the west of the Venezuelan Basin) make us

wonder about the possible presence of a magnetic record of the cretaceous magnetic quiet zone (CMQZ). The signature of this zone begins with an anomaly that has an amplitude above the average of Mesozoic chrons, followed by an anomalous sequence with no established pattern and amplitudes of the order of tens of nano-Tesla until reaching chron C34, which starts the sequence of Cenozoic anomalies. The Venezuelan Basin eastern section reveals anomalies similar to those associated to the beginning of the CMQZ without reaching chron C34. Thus, the triangular section identified as non-magnetic (Ghosh et al. 1984) might reflect part of the CMQZ with the added influence of the Curie isotherm thinning.

Conclusions

Analysis of partial results of Eastern Caribbean magnetic data allows following conclusions:

1. Magnetic anomalies of the Venezuelan Basin have three clearly defined sources: lateral variations of the

surface described by the Curie isotherm, magnetic stripes associated with oceanic crust formed in a low-spreading ridge between Late Jurassic and Early Cretaceous, and the magnetic effect of LIP coverage.

2. The most distinguishable magnetic signature is the one associated with the oceanic crust stripe pattern underlying the LIP. This source is present in the whole Venezuelan Basin, Aves Ridge slopes, and Beata Ridge.

3. The magnetic effect associated with the upper mantle has two origins: the lateral variations of the Curie isotherm, and the presence of narrow vertical areas of high magnetization lateral contrasts. Characterization of these narrow sections reflected by the magnetic anomalies reveals that the latter could be associated with the upwelling of lava during the Caribbean LIP formation period. Supporting for this suggestion would require more specific modeling.

4. The magnetic striped pattern of the Eastern Caribbean is associated with a low-spreading center compared to the velocity of the currently active ridges. Velocity estimation suggests that the Caribbean stripes are similar to those of the North Atlantic.

5. The Curie isotherm thinning is associated with the presence of mantle activity based on the occurrence of velocity anomalies both in the upper mantle and in the mantle–core interface and the existence of a heat flow above the world average for oceanic basins.

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