Structure, age, and origin of the Caribbean Plate unraveled

Andreína García-Reyes, Jérôme Dyment

Structure, age, and origin of the Caribbean Plate unraveled

García-Reyes, Andreína and Dyment, Jérôme*

Université de Paris, Institut de physique du globe de Paris, CNRS, F-75005 Paris,

** Corresponding author: jdy@ipgp.fr*

ABSTRACT

Our compilation of marine magnetics of the Caribbean Plate allows us to identify magnetic anomalies from the Cretaceous Normal Superchron (CNS) in the Colombia and Venezuela basins, from which we propose a model for the age and origin of the Caribbean Plate and its Large Igneous Province (CLIP). The comparison of selected marine magnetic profiles across these basins with high resolution profiles from other areas across the CNS indicates that the Colombia Basin formed 73-92 million years ago (Ma) and the Venezuela Basin 92-108 Ma. The two basins and the older part of the CLIP formed at a ridge axis in the Pacific Ocean, near the Central American Seaway. These results strongly constrain regional plate tectonic models for America and the Pacific Ocean.

INTRODUCTION

The Caribbean plate is a small tectonic plate trapped between two major continental plates, the North and South American plates, and two major subduction zones. The oceanic lithosphere of the Atlantic and Pacific oceans subducts beneath the Caribbean plate at its eastern and western ends, respectively. At its northern and southern ends, the Caribbean plate is bounded by two large transform systems which accommodate its eastward motion with respect to the North and South American plates. Its core is made of the Caribbean Large Igneous Province (CLIP) resulting from extensive volcanism in the Cretaceous. Fragments of the CLIP are found all around the Caribbean islands. The CLIP includes the thickened oceanic crust of the Colombia Basin and most of the Venezuela Basin (e.g., Diebold et al., 1981).

Different models have been proposed for the origin of the Caribbean plate, either formed in situ (e.g., Meschede and Frisch, 1998) or transferred from the Pacific Ocean to its present location (e.g., Pindell, 1990). Therefore, many questions remain on the structure and age of the plate. The main reason for these uncertainties is that no clear magnetic anomaly is observed in most of the Caribbean plate. This is partly because the plate is located at low latitude, but also because it was probably formed during the Cretaceous Normal Superchron (CNS). The CNS is a 35 to 40 million years-long episode of stable normal geomagnetic polarity between 83 and ~120 Ma: the lack of geomagnetic reversals results in the absence of the typical lineated seafloor spreading anomalies used to date the seafloor. The sequence of anomalies 18 to 1 (46-0 Ma) has been identified on both flanks of the Cayman Ridge, the only active spreading center bounding the Caribbean plate (Leroy et al., 2000). The oceanic crust of the Colombia and Venezuela basins display set of anomalies interpreted as anomalies 27-33 (70-83 Ma) in the central and southern Colombia Basin (Christofferson, 1973). Several attempts to recognize lineated anomalies in the Venezuela Basin led to contradictory interpretations due to the low amplitude of the signal and the paucity of data (Donnelly, 1973; Ghosh et al., 1984; Orihuela et al., 2013).

Here we take advantage of our new marine magnetic anomaly map of the Caribbean Plate (Garcia-Reyes, 2018) together with recent results obtained from the detailed analysis of the CNS in other oceanic basins to reinvestigate the structure, age, and origin of the Caribbean plate.

METHODS

We gathered total marine magnetic field measurements from the National Centers for Environmental Information (NCEI) and French Research Institute for Exploitation of the Sea (IFREMER). After removing spurious data, excluding noisy tracks and performing quality control over navigation and acquisition time along marine tracks, we subtracted models of the internal geomagnetic field (CM4, Sabaka et al., 2004 for the period 1960-2002.5; IGRF-11, Thébault et al., 2015 for other periods) to obtain magnetic anomalies. Internal and external cross-over correction allowed to significantly reduce the misfit (see details in García-Reyes, 2018). We removed wavelengths shorter than 3 km. The resulting magnetic anomaly map of the Caribbean Plate is presented in Figure 1b.

Several factors result in low magnetic anomaly amplitudes, of the order of ±50 nT, in the Caribbean Plate area:

(1) Magnetic anomalies created and/or observed at low latitude are usually weak, depending on the direction of their causative source body. For instance, elongated bodies (such as prisms of given geomagnetic polarity created at a spreading center) trending toward the geomagnetic pole show no anomaly at the magnetic equator, because the ambient geomagnetic field vector is aligned to the source body.

(2) The lineated magnetic anomaly pattern of the oceanic crust may also be blurred in areas where extensive volcanics (and their strong and complex three-dimensional anomalies) overlay and possibly demagnetize such pre-existing oceanic crust. Coherent linear magnetic anomalies are only observed on a Large Igneous Province (LIP) when the LIP is formed at a ridge axis and displays a thicker but otherwise similar oceanic crust, as in Iceland (Jónsson et al., 1991), the Azores Plateau (Gente et al., 2003), and the Shatsky Rise (Sager et al., 2019).

(3) Last but not least, the lack of geomagnetic reversals during the CNS may also explain the absence of prominent seafloor spreading magnetic anomaly pattern on the Caribbean Plate, if the plate was actually formed during this period. However, Granot et al. (2012) have used selected magnetic anomaly profiles from different oceans to show that three main periods, with different geomagnetic fluctuation patterns, can be distinguished within the CNS, separated by two ubiquitous anomalies named Q1 and Q2, tentatively dated ~92 and ~108 Ma. The older period, between Anomaly M0 (~120 Ma) and Q2, displays moderate fluctuations; the intermediate period, between Q2 and Q1, shows strong and rapid variations; and the younger period, between Q1 and Anomaly 34 (84 Ma), is characterized by a very smooth field, almost devoid of short wavelength variations. These observations opened the way for magnetic anomaly identifications in areas formed during the CNS (e.g., Granot and Dyment, 2015).

We extracted a set of representative magnetic profiles in the Colombia and Venezuela basins from the map. These profiles were drawn, as much as possible, across areas displaying linear anomalies (for instance the strong linear anomalies in the Colombia Basin) and avoided three-dimensional anomalies characterizing off-axis volcanism. We also selected measured marine magnetic anomaly profiles with similar orientation, where available. We compared the profiles with the CNS magnetic patterns and recognized anomalies 33-34, the characteristic second and third periods of the CNS as well as marker Q1 (Granot et al., 2012). By this approach, we derive the structure and age of the Colombia and Venezuela basins. The identification of these anomalies confirms that this part of the CLIP was formed at a ridge axis, most likely in the Pacific Ocean. We finally propose a possible evolution model for the Caribbean Plate that takes into account these new observations.

RESULTS: SEAFLOOR SPREADING MAGNETIC ANOMALIES IN THE CARIBBEAN PLATE

The main magnetic anomalies displayed in Figure 1b are related to major structural features such as the Hess Escarpment separating the Lower Nicaragua Rise and the Colombia Basin, the western flank of Beata Ridge, the basement of the Greater Antilles from Hispaniola to Puerto Rico, and the Lesser Antilles volcanic arc, to cite only the most prominent. A complex, hummocky magnetic pattern is observed on the Lower Nicaragua Rise, Aves Ridge, and to a lesser extent Beata Ridge. This pattern likely marks late off axis volcanics overlying the thickened oceanic crust. Finally, only three areas qualify to investigate seafloor spreading anomalies: (1) the Cayman Trough, where anomalies 18 to 1 (46-0 Ma) have been identified (Leroy et al., 2000) – we do not further consider this area; (2) the Colombia Basin north of 13°N in a narrowing sector flanked by the Hess Escarpment and Beata Rise and abutting the southern tip of Hispaniola; and (3) the entire Venezuela Basin.

Magnetic anomalies in the Colombia Basin

Among the magnetic anomalies interpreted by Christofferson (1973) as Chrons 27 to 33 in the southern and central Colombia Basin, only two prominent East-West trending anomalies observed between 11.5 and 14°N appear to be linear enough to reflect seafloor spreading. The amplitude of these anomalies varies between ±200 nT, making them the strongest anomalies in the area. Further West and South, the complex hummocky magnetic pattern previously mentioned on the Lower Nicaragua Rise overlaps the Hess Escarpment and partially covers the Colombia Basin, interrupting and masking any preexisting linear magnetic anomalies. This pattern marks volcanics obviously erupted in a later stage, long after the formation of the thickened oceanic crust of the Colombia Basin (Sigurdsson et al., 1996; Durkefalden et al., 2019). Further Northeast, no major boundary separates the Colombia Basin *sensu stricto* and an elongated triangle pinched between the Hess Escarpment to the west and Beata Ridge to the east, as confirmed by the Vertical Gradient of Gravity (VGG; Sandwell et al., 2014; Figure 1a), suggesting that both belong to the same oceanic basin.

We extracted a 700 km-long profile running through the whole basin, first cutting across the prominent East-West anomalies of the central Colombia Basin then bisecting the elongated triangular basin northeastward, pinched between the Lower Nicaragua Rise on the west and the Beata Ridge on the east. The profile location and magnetic anomaly are displayed on Figures 1c and 2a, respectively.

The profile shows clear magnetic anomalies of high amplitude between 11.5 and 14°N and a magnetically smooth area with anomalies of short wavelength and low amplitude further northeast. We try to identify this sequence of magnetic anomalies – including the smooth part – by comparing it with profiles derived from the Geomagnetic Polarity Time Scale and consider that the smooth pattern marks the younger part of the CNS, i.e., the smooth third period of Granot et al. (2012). The strong anomalies in the central Colombia Basin would therefore be anomalies 33-34 (73 -83 Ma). The VGG map (Figure 1a) reveals a linear structure parallel to the magnetic anomalies which probably marks the location of an extinct spreading center, suggesting the presence of a local ridge jump and duplicated anomalies 33-34 in this basin (Figure 1c). Further South, the thick sediments of the North Panama deformed belt and of the Magdalena Fan make the anomalies difficult to identify due to larger distance to and possible thermal demagnetization of the magnetic basement (e.g., Granot and Dyment, 2019).

The Colombia Basin show a sequence of magnetic anomalies extending from the third period of the CNS to anomaly 33, representing ages of (less than) 92 Ma to 73 Ma.

Magnetic anomalies in the Venezuela Basin

The Venezuela Basin shows a prominent N-S structure on its eastern side on the VGG map (Figure 1a), associated with a marked low on the magnetic anomaly map (Figure 1b). We interpret these anomalies as reflecting a major fracture zone. Other weaker N-S trending magnetic anomalies in the center of the basin may correspond to secondary fracture zones. A band of dominantly positive magnetic anomalies extends along a general NE-SW direction, parallel to the anomalies tentatively recognized by Ghosh et al. (1984); the northwestern corner of the basin shows negative magnetic anomalies, and the southeastern corner presents smooth low amplitude anomalies. At a local scale however, the anomalies trend E-W and are left-laterally offset by the secondary N-S fracture zones, resulting in the general NE-SW direction. We extracted two N-S, ~450 km-long magnetic profiles across the Venezuela Basin (Figure 1c). The two profiles show similarities that confirm that the observed anomalies record geomagnetic signal. However, they do not present the character of classical marine magnetic anomalies associated to polarity reversals as recorded by seafloor spreading. We suggest that they record the strong geomagnetic intensity variations observed within the second period of the CNS. The magnetically smooth area bounding them to the south is similar to the one observed north of the Colombia Basin. We interpret it as reflecting the third period of the CNS, as in the northern Colombia Basin, its northern limit corresponding to marker Q1 (Figure 2a). Alternative explanations for the smooth area include (1) thermal demagnetization of the extrusive basalt under sediments that are twice thicker in this area than in the other parts of the Venezuela Basin

(Straume et al., 2019) as suggested by Granot and Dyment (2019), and (2) crustal thickness variation as this area displays a normal oceanic crust in contrast to the thick oceanic plateau seismically imaged in the other parts of the basin (Diebold et al., 1981).

The Venezuela Basin therefore shows a sequence of magnetic anomalies extending from the second to third periods of the CNS, including Q1 at 92 Ma and extending at most from Q2 (108 Ma) to C34 (83 Ma) (Figure 2b). Comparing the tiny wiggles of our profiles across the Venezuela Basin to the profiles presented by Granot et al. (2012) suggests a more likely age interval of about 100-90 Ma (Figure 2c), although the correlation among individual “tiny wiggles” is faint and questionable.

DISCUSSION: AGE AND ORIGIN OF THE CARIBBEAN PLATE

A plateau formed at a spreading center

The observation of identifiable magnetic anomalies 33-34 and Q1 as well as the second and third periods of the CNS in the Colombia and Venezuela basins has an important implication. It means that the part of the CLIP making these basins was formed at a spreading center. Although quite a difficult exercise considering the paucity of constraints, we attempted to estimate spreading rates from the identified anomalies. The clear anomaly 33r in the Colombia Basin leads to spreading rate values of 35 km/Myr in the West, where this anomaly is well developed, to 25 km/Myr in the East where it shows a significant narrowing. The third CNS period in the Colombia Basin suggests a spreading rate much faster than 63 km/Myr, the period being uncomplete as marker Q1 is not observed south of Hispaniola. Conversely, the uncomplete second and third CNS periods in the Venezuela Basin predict a minimum spreading rate value of 22 km/Myr if the whole second and third periods are considered. A spreading rate of ~55 km/Myr is obtained if our tentative ages of 100-90 Ma are adopted. If so, fast to intermediate spreading rates would be prevalent on the Caribbean Plate. The magmatic oceanic lithosphere formed at these rates is a much better recorder of tiny magnetic variations such as those of the CNS than lithosphere formed at slow spreading rates. Fast to intermediate spreading rates, similar to those observed on the Pacific plate, are therefore in better agreement with a Pacific origin than an *in situ* origin. The oceanic lithosphere of the northern Pacific plate recorded an important reorganization of the Pacific-Farallón spreading center at the time of anomaly 33r, resulting in a change of the transform fault direction and the development of multiple splays and intermediate ridge segments (Granot et al., 2009). The different widths of anomaly 33r in the Colombia Basin may result from such ridge jump.

Age of the Caribbean Plate

Summarizing the ages given by magnetic anomalies in the Colombia and Venezuela basins gives a maximum range interval of 108 to 73 Ma at most for the part of the CLIP formed at a spreading center. Several authors suggest that the Venezuela Basin may be of Early Cretaceous age (Diebold et al., 1999; Fox and Heezen, 1975; Officer et al., 1957), a bit older but not inconsistent with the second CNS period (108-92 Ma). Based on an extensive collection of samples from many locations of the Caribbean Plate, Whattam and Stern (2015) proposed that the CLIP formed in three magmatic pulses at 124-112 Ma, 92-88 Ma and 76-72 Ma, respectively. Our results support the two later pulses but the formation of most of the Caribbean plate at a spreading center suggests a more progressive building of the CLIP. The hummocky magnetic pattern observed on the Lower Nicaragua Rise and the western part of the Colombia Basin may represent an evidence for the latest proposed pulse, contemporaneous with the youngest magnetic anomaly 33 and the inferred fossil spreading center.

Reconciling constraints from geology, marine magnetics, and plate kinematics

Three principal sets of constraints should be reconciled in any model describing the Caribbean Plate and the CLIP evolution: (1) the CLIP was mainly formed at a spreading center, although additional off-axis volcanism was also produced, and (2) it was formed between 120 and 73 Ma, as emphasized above; and (3) the CLIP reached its present position between North and South America between 73 and 45 Ma, as proven by numerous geological studies in the Caribbean Islands, the Central American Isthmus, and the north of South America (e.g., Burke et al., 1978; Duncan and Hargraves, 1984; Pindell and Barrett, 1990; among many others). These constraints should be accommodated within the known motion of the main plates including the opening of the Atlantic Ocean, the spreading reorganizations of the Pacific Ocean, and the consumption of the latter in the subduction zone bounding the Americas to the West. A major difficulty is that most plate tectonic reconstruction models do not predict a spreading center where the CLIP is supposed to have been at 73 Ma, just before entering between North and South America. The available models predict that the Pacific-Farallón spreading center was located more than 4000 km further west, too far from the required location if reasonable spreading rates and asymmetry are considered. We therefore examined alternative options while honoring the incomplete knowledge of the Pacific Plate evolution in the Cretaceous. A first observation is that magnetic anomalies 33r and 34 are not observed between Clarion and Marquesas fracture zones, over a distance of more than 2700 km along the inferred Pacific-Farallón spreading center, although anomalies more recent than anomaly 33 young (73 Ma) are depicted at the same latitudes (e.g., Seton et al., 2012). This suggests that the Pacific-Farallón spreading center may have been relocated to the position predicted by the plate reconstructions by a westward ridge jump at 73 Ma. Our first option is therefore assuming that the Pacific-Farallón spreading center was located further East with respect to its predicted location during the formation of the CLIP up to 73 Ma. A second observation is, before 85 Ma the inferred Farallón-Chazca spreading center was cutting across the Pacific Ocean from the Pacific Plate to the subduction zone bounding the Americas to the West on plate reconstruction models (e.g., Matthews et al., 2016). The lack of magnetic anomalies 33r and 34 between Clarion and Marquesas fracture zones does not allow to identify any kink (also called "magnetic bight") marking the possible trace of a triple junction and the continuation of the Farallón-Chazca spreading center beyond 85 Ma. Our second option is therefore assuming that the Farallón-Chazca spreading center was active until 73 Ma and the CLIP was emplaced on this spreading center. A third alternative option would be to consider an independent Caribbean plate as early as 134 Ma, as proposed by Matthews et al. (2016). However, we see no clear reason which would have led to such an individualization. Furthermore, recent paleomagnetic evidences suggest that the Caribbean Plate was not independent from the Farallón plate before 100 Ma (Boschman et al., 2019). We therefore do not consider this option anymore.

A plate tectonic evolution model for the CLIP and Caribbean Plate

In Figure 3 we are gathering the constraints obtained from our marine magnetic anomaly analysis, previous geological studies, and available plate kinematics in a series of eight sketches that summarize the possible evolution of the Caribbean Plate since the initiation of the CLIP at 120 Ma. We assumed South America as fixed and built the evolution of the surrounding plates and continents from finite rotations taken from the compilation of Matthews et al. (2016). For 120 Ma, we included the angular correction suggested by Torsvik et al. (2019) for the Pacific Plate and other plates underlying the Pacific Ocean. It should be noted, however, that the concepts illustrated by these sketches are generally compatible with most plate reconstruction models of the area. During the period considered, the Gulf of Mexico was fully open, and the Yucatan Block was in its present position with respect to North America. In the initial phases (Figure 3, at 120, 83 and 73 Ma) we attached the Chortis Block to North America along the southwestern shore of today's Mexico (Rogers et al., 2005) and let it drift eastward together with the Caribbean Plate after 45 Ma, as proposed by previous authors (Gose, 1985; Pindell et al., 1988).

At 120 Ma (Figure 3), active spreading centers in the Central Atlantic and (inferred) Proto-Caribbean oceans were separating Laurasia (here North America and the Chortis and Yucatan blocks) from Gondwana (here Africa and South America). The Pacific Plate was exclusively surrounded by spreading centers and therefore expanding. Among them, the Pacific-Farallón and Pacific-Chazca spreading centers formed the most recent Hawaiian and Phoenix M-series magnetic anomalies and converged at a triple junction which third arm, the (inferred) Farallón-Chazca spreading center, tentatively drawn up to the major subduction zone bounding North and South America to the west. We infer that the Caribbean Plateau initiated at this triple junction (called the Tongareva Triple Junction by Hochmuth et al., 2015), as observed for other oceanic plateaus such as the Mozambique and Agulhas Plateaus (e.g., Gohl et al., 2012) or the Shatsky Rise (e.g., Sager et al., 2019). It was probably coincident with the Galapagos hotspot, as suggested by geochemical studies (Hauff et al., 1997; Kerr et al., 2003; Geldmacher et al., 2003; Thompson et al., 2004) and geodynamic modelling (Nerlich et al., 2014). At that time, this triple junction was about 1500 km away from the major plateau formed at ~120 Ma and constituted by the present-day Ontong Java, Manihiki, and Hikurangi plateaus (Taylor, 2006; this plateau lies just beyond the southwestern corner of Figure 3, 120 Ma).

As previously explained, two options for plate reconstructions are considered at 83 and 73 Ma. We first discuss what is common to both options, then examine them successively for both times. At 83 Ma, spreading was taking place all along the Mid-Atlantic Ridge (MAR) in the Central, Equatorial and South Atlantic oceans (since 105 Ma; Granot and Dyment, 2015), between Africa and both North and South America, whereas motion decreased considerably in the Proto-Caribbean domain, between North and South America. The spreading center separating North and South America was connected at a triple junction to the Central and Equatorial MAR. Plates of the Pacific Ocean were subducting beneath North America, the Proto-Caribbean domain, and South America. Our Option A considers a large Farallón Plate, subducting beneath the Americas to the East and bounded by the Pacific-Farallón spreading center to the West, as in most plate reconstruction models. The only difference with these models is that our Option A places the spreading center between Clarion and Marquesas fracture zones further East. We speculate that this part of the ridge drifted eastward through asymmetric spreading to remain in close vicinity of the Galapagos hotspot, allowing the progressive construction of the CLIP on the spreading center, as observed in other areas affected by ridge-hotspot interactions (e.g., Dyment, 1998; Müller et al., 1998). Conversely, our Option B considers two plates, Farallón to the North and Chazca to the South, subducting beneath the Americas to the East and bounded by spreading centers to the West. The Farallón-Chazca spreading center extended from a RRR triple junction with the Pacific Plate to the subduction zone eastward. Again, we speculate that this ridge remained in the close vicinity of the Galapagos hotspot, allowing the progressive construction of the CLIP on the spreading center.

At 73 Ma (Figure 3), the Atlantic Ocean continued opening between Africa and both North and South America and is still doing so at present – we will not mention it again in further sections. The proto-Caribbean domain was encountering slow convergence between North and South America, that we symbolized with a subduction feature South of the Florida Block and Bahamas Platform. The detailed history of this complex episode is beyond the scope of this paper. The linearity of the Belize-Yucatan margin suggests a transform margin that is necessarily older than the Cayman Trough system and may therefore have been active at this period. Motion along this transform fault would have split the so-called Caribeana terrane and transported its western part to the North, to be later accreted to the Greater Antilles (Garcia-Gasco et al., 2008). The CLIP reached the subduction zone bounding the Americas to the West and collided with the Chortis Block, later to detach from North America and join the Caribbean Plate in its eastward journey (Rogers et al., 2007; Sanchez et al., 2016). Further East, the buoyancy of the thick and light CLIP prevented it to enter into subduction, which resulted in inverting the subduction polarity (Hoernle and Hauff, 2007). After this event, the Proto-Caribbean lithosphere was going to subduct westward beneath the CLIP (e.g., Pindell et al., 2001). In the Pacific Ocean, seafloor spreading ceased on the section of the Pacific-Farallón spreading center between Clarion and Marquesas fracture zones (Option A) or the Farallón-Chazca spreading center (Option B), leaving behind a fossil spreading center on the CLIP (now located in the Colombia Basin). At that time, the CLIP had reached its maximal extension. A westward ridge jump (Option A) or the attachment of the Chazca Plate to the Farallón Plate (Option B) resulted in the plate configuration predicted by the reconstruction models (e.g., Matthews et al., 2016) in the Pacific Ocean, as in the next evolution stages which we will not describe further.

At 45 Ma (Figure 3), the Caribbean Plate, including the CLIP and the Chortis Block, exists as an independent plate in a configuration similar to the present one. The older subduction separating it from South America retreated eastward and consumed the whole Proto-Caribbean lithosphere. To the West, a new subduction zone initiated to accommodate the faster eastward motion of the Farallón Plate with respect to that of the Caribbean Plate, with the former subducting under the latter. Since that time, the Caribbean Plate has been bracketed by these two subductions. Two major transform fault systems separate the Caribbean Plate from North and South America, respectively. The Cayman Trough, a short spreading center part of the northern transform system, started to open shortly before 45 Ma (Leroy et al., 2000). Significant parts of the CLIP probably accreted to the Equatorial Andes during this period (Jaillard et al., 2009).

Since 45 Ma (Figure 3, 45, 25 and 0 Ma), the CLIP was subject to strong deformation due to the convergence between the North and South American continents. As a result, it split into at least two main blocks, roughly representing the Colombia and Venezuela Basin, separated by a convergent boundary, the reactivated Beata Ridge. Both blocks probably rotated, the sense and magnitude of the rotation depending on which model does apply. For Option A (Pacific-Farallón spreading center), a full counterclockwise rotation of 45° is required, whereas for Option B (Farallón-Chazca spreading center), a full clockwise rotation of 20° is sufficient to explain an East-West fossil spreading center in the Colombia Basin (e.g., Burmester et al., 1996). Paleomagnetic investigations on undeformed parts of the Colombia and Venezuela basins would help to test these hypotheses. The Caribbean Plate has shortened, with incipient subductions at Muertos Trough south of Puerto Rico and the South American Deformed Belt off Colombia.

Both Options A and B succeed in taking into account the major constraints derived from both our new magnetic anomaly interpretation, i.e., the CLIP being formed at a spreading center between 120 and 73 Ma, and from many previous geological studies, i.e., the CLIP being emplaced between North and South America between 73 and 45 Ma. Although some elements constituting the complex geological history proposed above have been already suggested by previous works, the peculiarity of this work is to investigate the possibilities of a spreading center lying in the close vicinity of the Central American Seaway, either through a large but local jump of the Pacific-Farallón spreading center at 73 Ma (Option A) or through the Farallon-Chazca activity being extended by 12 Ma, until 73 Ma (Option B).

CONCLUSION

In the Colombia Basin, we identify a sequence of strong magnetic anomalies in the South and a smooth magnetic zone extending to the North that we interpret as Chrons 33-34 and the youngest part of the Cretaceous Normal Superchron (CNS), respectively. In the Venezuela Basin, we identify a major N-S fracture zone on both the gravity and magnetic data; a consistent pattern of magnetic anomalies in the central part of the basin is interpreted as the intermediate part of the CNS, whereas a smooth area in the southern part of the basin may correspond to its younger part. The observation of recognizable magnetic anomalies in the Caribbean Large Igneous Province (CLIP) means that the CLIP was mostly formed at the axis of a spreading center, although secondary volcanics also overlie preexisting structures such as the Lower Nicaragua Rise and the Beata Ridge where they generate disordered magnetic anomaly patterns. Our magnetic anomaly identifications suggest that the CLIP was formed between 108 and 73 Ma, in good agreement with published ages measured on samples from all over the Caribbean Plate (Sinton et al., 1998;

Kerr et al., 2003). We propose a model in which the CLIP was formed at a spreading center in the Pacific Ocean located in the vicinity of the present Central America.

Data availability: A low-resolution version of the magnetic anomalies supporting the findings of this study will be incorporated in the WDMAM version 2.1. The full resolution version is available from the corresponding author upon request.

We downloaded marine total magnetic field measurements from the National Center for Environmental Information (formerly National Geophysical Data Center; www.ngdc.noaa.gov/mgg/geodas/trackline.html). Magnetic anomalies on land are from the World Digital Magnetic Anomaly Map (wdmam.org). Vertical gradients of gravity are available from the Scripps Institution of Oceanography, University of California in San Diego (topex.ucsd.edu).

ACKNOWLEDGMENTS

AGR thanks Fundayacucho (Venezuela), Campus France, IPGP, Caribbean Basin Tectonics and Hydrocarbon Project of the Stavanger and Houston Universities, Commission of the Geological Map of the World of UNESCO, and the Pause Program of the French Government for their support at various stages of this work. We thank Udo Barckhausen for providing recently acquired N-S trending magnetic profiles in the Colombia Basin in 2016 that helped to validate the quality of our magnetic anomaly map but were not included. This is IPGP contribution XXXX.

REFERENCES CITED

Burke, K., Fox, P., and Şengör, A., 1978, Buoyant ocean floor and the evolution of the Caribbean: Journal of Geophysical Research: Solid Earth, v. 83, p. 3949–3954, doi:10.1029/JB083iB08p03949.

Burmester, R.F., Beck Jr, M.E., Speed, R.C., and Snoke, A.W., 1996, A preliminary paleomagnetic pole for mid-cretaceous rocks from Tobago: Further evidence for large clockwise rotations in the Caribbean-South American plate boundary zone: Earth and Planetary Science Letters, v. 139, p. 79–90, doi:10.1016/0012-821X(96)00012-X.

Christofferson, E., 1973, Linear magnetic anomalies in the Colombia Basin, central Caribbean Sea: Geological Society of America Bulletin, v. 84, p. 3217–3230, doi:10.1130/0016-7606(1973)84<3217:LMAITC>2.0.CO;2.

Diebold, J., Driscoll, N., and others, 1999, New insights on the formation of the Caribbean basalt province revealed by multichannel seismic images of volcanic structures in the Venezuelan basin: Sedimentary Basins of the World, v. 4, p. 561–589, doi:10.1016/S1874-5997(99)80053-7.

Diebold, J., Stoffa, P., Buhl, P., and Truchan, M., 1981, Venezuela basin crustal structure: Journal of Geophysical Research: Solid Earth, v. 86, p. 7901–7923, doi:10.1029/JB086iB09p07901.

Donnelly, T.W., 1973, Magnetic anomaly observations in the Eastern Caribbean sea: Initial reports, Deep Sea Drilling Project, v. 15, doi:10.2973/dsdp.proc.15.133.1973.

Duncan, R., and Hargraves, R., 1984, Plate-tectonic evolution of the Caribbean region in the mantle reference frame: *in* Bonini, W.E., Hargraves, R.B., and Shagam, R., The Caribbean-South American plate boundary and regional tectonics, Geological Society of America Memoir 162, https://doi.org/10.1130/MEM162-p81.

Dyment, J., 1998, Evolution of the Carlsberg Ridge between 60 and 45 Ma: ridge propagation, spreading asymmetry, and the Deccan-Reunion hotspot. Journal of Geophysical Research – Solid Earth, v. 103, p. 24067-24084, doi:10.1029/98JB01759.

Fox, P.J., and Heezen, B.C., 1975, Geology of the Caribbean crust, *in* The Gulf of Mexico and the Caribbean, Springer, p. 421–466, doi:10.1007/978-1-4684-8535-6_10.

Garcia-Casco, A., Iturralde-Vinent, M.A., and Pindell, J., 2008, Latest Cretaceous collision/accretion between the Caribbean plate and Caribeana: Origin of metamorphic terranes in the Greater Antilles: International Geology Review, v. 50, p. 781–809, doi:10.2747/0020-6814.50.9.781.

Garcia-Reyes, A., 2018, Magnetic anomalies and plate tectonic history of the Caribbean plate and the Gulf of Mexico [PhD thesis]: Université Sorbonne Paris Cité, 221 p., doi:10.5281/zenodo.4118079

Geldmacher, J., Hanan, B.B., Blichert-Toft, J., Harpp, K., Hoernle, K., Hauff, F., Werner, R., and Kerr, A.C., 2003, Hafnium isotopic variations in volcanic rocks from the Caribbean Large Igneous Province and Galápagos hot spot tracks: Geochemistry, Geophysics, Geosystems, v. 4, doi:10.1029/2002GC000477.

Gente, P., Dyment, J., Maia, M., and Goslin, J., 2003, The Azores plateau: An example of ridge-hot spot interaction, *in* 8th International Congress of the Brazilian Geophysical Society, European Association of Geoscientists & Engineers, p. cp–168, doi:10.3997/2214-4609-pdb.168.arq_801.

Ghosh, N., Hall, S., and Casey, J., 1984, Seafloor spreading magnetic anomalies in the Venezuelan Basin: Geological Society of America Memoirs, v. 162, p. 65–80.

Gohl, K., Uenzelmann-Neben, G., and Grobys, N., 2012, Growth and dispersal of a Southeast African Large Igneous Province: South African Journal of Geology, v. 111.3-4, p. 379-386, doi:10.2113/gssajg.114.3-4.379

Gose, W.A., 1985, Paleomagnetic results from Honduras and their bearing on Caribbean tectonics: Tectonics, v. 4, p. 565–585, doi:10.1029/TC004i006p00565.

Granot, R., Cande, S.C., and Gee J.S., 2009, The implications of long-lived asymmetry of remanent magnetization across the North Pacific fracture zones: Earth and Planetary Science Letters, v. 288, p. 551-563. doi: 10.1016/j.epsl.2009.10.017.

Granot, R., and Dyment, J., 2015, The cretaceous opening of the south Atlantic Ocean: Earth and Planetary Science Letters, v. 414, p. 156–163.

Granot, R., and Dyment, J., 2019, The influence of post-accretion sedimentation on marine magnetic anomalies: Geophysical Research Letters, v. 46, p. 4645–4652, doi:10.1029/2019GL082265.

Granot, R., Dyment, J., and Gallet, Y., 2012, Geomagnetic field variability during the Cretaceous Normal Superchron: Nature Geoscience, v. 5, p. 220–223, doi:10.1038/ngeo1404.

Hauff, F., Hoernle, K., Schmincke, H.-U., and Werner, R., 1997, A mid cretaceous origin for the Galapagos hotspot: Volcanological, petrological and geochemical evidence from Costa Rican oceanic crustal segments: Geologische Rundschau, v. 86, p. 141–155, doi:10.1007/PL00009938.

Hochmuth, K., Gohl, K. and Uenzelmann-Neben, G., 2015, Playing jigsaw with Large Igneous Provinces – A plate tectonic reconstruction of Ontong Java Nui, West Pacific, Geochemistry, Geophysics, Geosystems, v. 16, p. 3789-3807, doi:10.1002/2015GC006036.

Hoernle, K., and Hauff, F., 2007, Oceanic Igneous Complexes, *in* Bundschuh, J., Alvarado, and G.E., eds., Central America: Geology, Resources and Hazards, Volume 1: London, Taylor & Francis/Balkema, p. 523-547, ISBN-13: 978-0-415-41648-1.

Jaillard, E., Lapierre, H., Ordonez, M., Alava, J.T., Amortegui, A., and Vanmelle, J., 2009, Accreted oceanic terranes in Ecuador: Southern edge of the Caribbean plate? Geological Society, London, Special Publications, v. 328, p. 469–485, doi:10.1144/SP328.19.

Jónsson, G., Kristjánsson, L., and Sverrisson, M., 1991, Magnetic surveys of Iceland: Tectonophysics, v. 189, p. 229–247, doi:10.1016/0040-1951(91)90499-I.

Kerr, A.C., White, R.V., Thompson, P.M., Tarney, J., and Saunders, A.D., 2003, No oceanic plateau—no Caribbean plate? The seminal role of an oceanic plateau in Caribbean plate evolution, *in* Bartolini, C., Buffler, R.T., and Blickwede, T. eds., The circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics, AAPG Memoir, v. 79, p. 126–168.

Leroy, S., Mauffret, A., Patriat, P., and Lépinay, B.M. de, 2000, An alternative interpretation of the Cayman trough evolution from a reidentification of magnetic anomalies: Geophysical Journal International, v. 141, p. 539–557, doi:/10.1046/j.1365-246x.2000.00059.x.

Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., and Mueller, R.D., 2016, Global plate boundary evolution and kinematics since the Late Paleozoic: Global and Planetary Change, v. 146, p. 226–250.

Meschede, M., and Frisch, W., 1998, A plate-tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean plate: Tectonophysics, v. 296, p. 269–291, doi:10.1016/S0040-1951(98)00157-7.

Müller, R.D., Roest, W.R., and Royer, J.-Y., 1998, Asymmetric sea-floor spreading caused by ridge–plume interactions: Nature, v. 396(6710), p. 455-459, doi:10.1038/24850

Nerlich, R., Clark, S.R., and Bunge, H.-P., 2014, Reconstructing the link between the Galapagos hotspot and the Caribbean plateau: GeoResJ, v. 1, p. 1–7, doi:10.1016/j.grj.2014.02.001.

Officer, C., Ewing, J., Edwards, R., and Johnson, H., 1957, Geophysical investigations in the Eastern Caribbean: Venezuelan basin, Antilles island arc, and Puerto Rico trench: Geological Society of America Bulletin, v. 68, p. 359–378, doi:10.1130/0016-7606(1957)68[359:GIITEC]2.0.CO;2.

Orihuela Guevara, N., García, A., and Arnaiz, M. 2013, Magnetic anomalies in the Eastern Caribbean. *Int J Earth Sci (Geol Rundsch)* **102,** 591–604. doi:10.1007/s00531-012-0828-6

Pindell, J., 1990, Geological arguments suggesting a Pacific origin for the Caribbean Plate, *in* Larue, D./K, and Draper, G., Eds, Transactions 12th Caribbean Geological Conference, St Croix, US Virgin Islands, Miami Geological Society, p. 1-4.

Pindell, J.L., and Barrett, S.F., 1990, Geological evolution of the Caribbean region: A plate tectonic perspective: The Caribbean region: Boulder, Colorado, Geological Society of America, Geology of North America, v. H, p. 405–432.

Pindell, J.L., Cande, S., Pitman III, W.C., Rowley, D.B., Dewey, J.F., LaBrecque, J., and Haxby, W., 1988, A plate-kinematic framework for models of Caribbean evolution: Tectonophysics, v. 155, p. 121–138, doi:10.1016/0040-1951(88)90262-4.

Pindell, J., Draper, G., Kennan, L., Stanek, K.P., and Maresch, W.V., 2001, Evolution of the northern portion of the Caribbean plate: Pacific origin to Bahamian collision, *in* SA abstracts from the IGCP project.

Sabaka, T.J., Olsen, N., and Purucker, M.E., 2004, Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data: Geophysical Journal International, v. 159, p. 521–547, doi:10.1111/j.1365-246X.2004.02421.x.

Sager, W.W., Huang, Y., Tominaga, M., Green, J.A., Nakanishi, M., & Zhang, J., 2019, Oceanic plateau formation by seafloor spreading implied by Tamu Massif magnetic anomalies, Nature Geoscience, 12, 661-666.

Sanchez, J., Mann, P., and Emmet, P.A., 2016, Late Cretaceous–Cenozoic tectonic transition from collision to transtension, Honduran borderlands and Nicaraguan rise, NW Caribbean plate boundary: Geological Society, London, Special Publications, v. 431, p. 273–297, doi:10.1144/SP431.3.

Sandwell, D.T., Müller, R.D., Smith, W.H., Garcia, E., and Francis, R., 2014, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure: Science, v. 346, p. 65–67.

Seton, M. et al., 2012, Global continental and ocean basin reconstructions since 200 ma: Earth-Science Reviews, v. 113, p. 212–270, doi:10.1016/j.earscirev.2012.03.002.

Sigurdsson, H., Leckie, M., Acton, G.D., Fox, P.J., Baldauf, J., and Francis, T.J., 1996, Ocean Drilling Program leg 165 Preliminary report Caribbean ocean history and the Cretaceous/Tertiary boundary event, *in* Proc. ODP, init. Repts, Citeseer, v. 165, p. 377–400.

Sinton, C.W., Duncan, R.A., Storey, M., Lewis, J.F., and Estrada, J., 1998, An oceanic flood basalt province within the Caribbean plate, Earth Planet. Sci. Lett., 155, 221–235.

Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., Abdul Fattah, R., Doornenbal, J.C., and Hopper, J.R., 2019, GlobSed: Updated total sediment thickness in the world's oceans: Geochemistry, Geophysics, Geosystems, v. 20, p. 1756–1772, doi:10.1029/2018GC008115.

Taylor, B., 2006, The single largest oceanic plateau: Ontong Java–Manihiki–Hikurangi : Earth and Planetary Science Letters, v. 241, p. 372–380, doi:10.1016/j.epsl.2005.11.049.

Thébault, E. et al., 2015, International geomagnetic reference field: The 12th generation: Earth, Planets and Space, v. 67, p. 79, doi:10.1186/s40623-015-0228-9.

Thompson, P., Kempton, P., White, R., Saunders, A., Kerr, A.C., Tarney, J., and Pringle, M., 2004, Elemental, hf–nd isotopic and geochronological constraints on an island arc sequence associated with the Cretaceous Caribbean Plateau: Bonaire, Dutch Antilles: Lithos, v. 74, p. 91–116, doi:10.1016/j.lithos.2004.01.004.

Torsvik, T.H., Steinberger, B., Shephard, G.E., Doubrovine, P.V., Gaina, C., Domeier, M., Conrad, C.P., and Sager, W.W., 2019, Pacific-Panthalassic reconstructions: Overview, errata and the way forward: Geochemistry, Geophysics, Geosystems, v. 20, p. 3659–3689, doi:10.1029/2019GC008402.

Whattam, S.A., and Stern, R.J., 2015, Late Cretaceous plume-induced subduction initiation along the southern margin of the Caribbean and NW South America: The first documented example with implications for the onset of plate tectonics: Gondwana Research, v. 27, p. 38–63, doi:10.1016/j.gr.2014.07.011.

FIGURE CAPTIONS

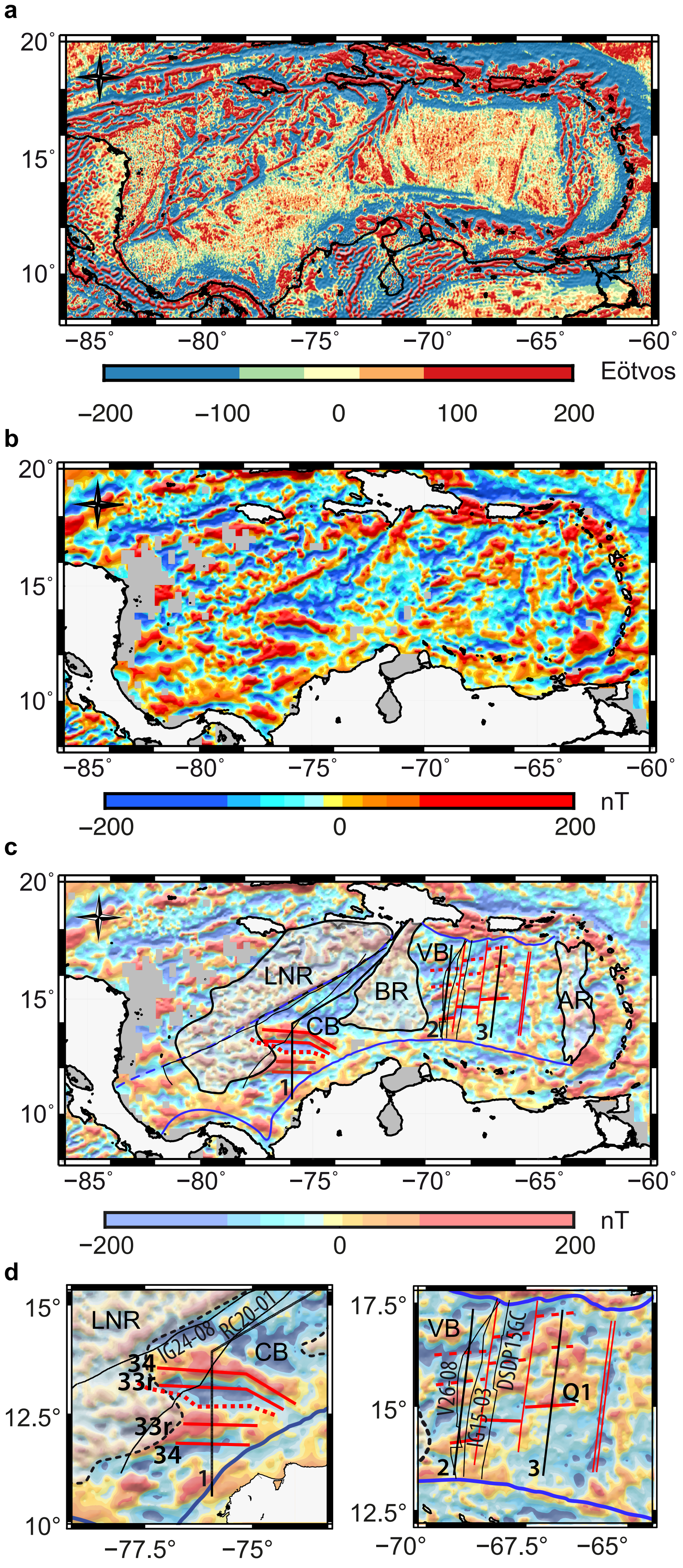
Figure 1. Potential field anomalies and interpretation in the Caribbean plate. (**a**) Vertical gradient of gravity (Sandwell et al., 2014), (**b**) marine magnetic anomaly (Garcia-Reyes, 2018), and interpretation (**c**) at the scale of the plate and (**d**) the Colombia Basin (CB) and Venezuela Basin (VB). Transparent polygons mark the Lower Nicaragua Rise (LNR), Beata Ridge (BR) and Aves Ridge (AR), formed by volcanic episodes post-dating the main emplacement of the Caribbean Large Igneous Province. Solid blue lines mark the front of accretionary prisms at, from North to South, Los Muertos Trough, South Caribbean Deformed Belt, and Panama Deformed Belt; dashed blue line delineates the Hess Escarpment; thick solid red lines represent conjugate magnetic anomalies 34 and 33 in the CB, and magnetic feature Q1 of the Cretaceous Normal Superchron (CNS) in the VB; dashed red lines underline other magnetic features of the

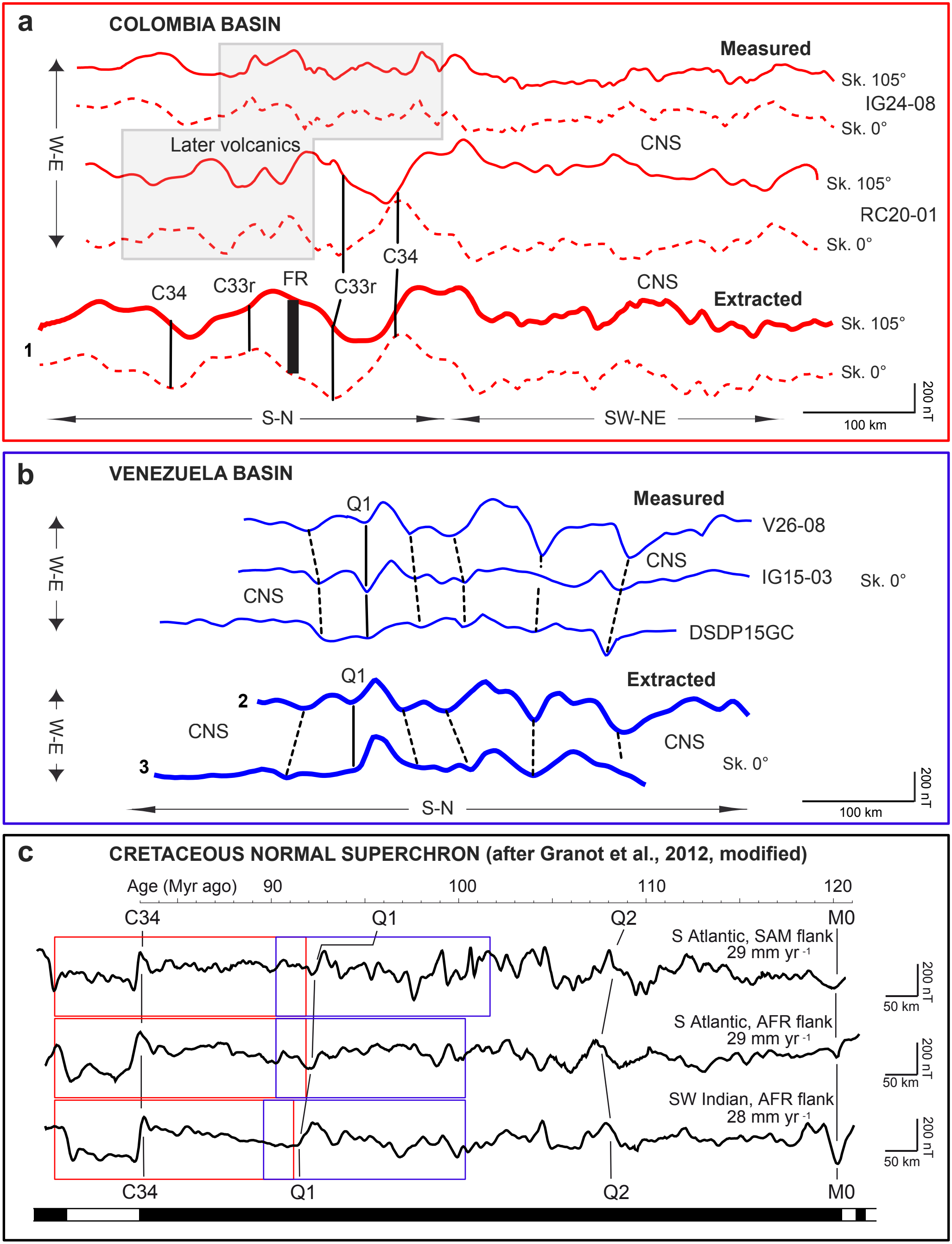
dynamic mid-CNS in the VB; dotted thick red line underline the fossil spreading center in the CB; thin red lines mark fracture zones in the VB; thick black lines identify the magnetic profiles 1-3 extracted from the magnetic map and thin black lines measured magnetic profiles displayed in Figure 2.

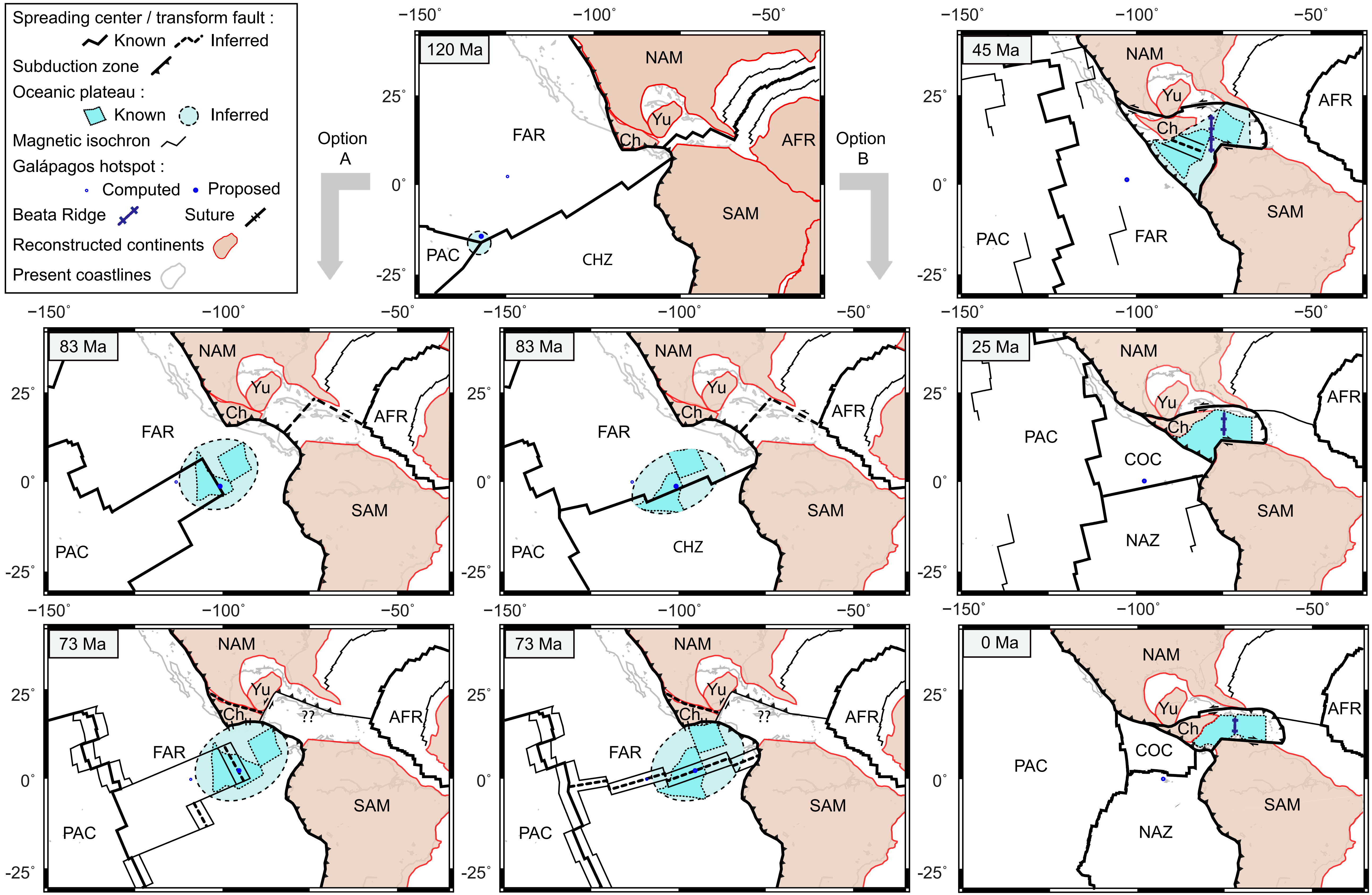
Figure 2. Interpretation of magnetic anomalies in the Colombia and Venezuela basins. Magnetic anomalies were extracted from the computed grid in the Colombia Basin (CB) and Venezuela Basin (VB) along Profiles 1, 2 and 3 (see location on Figure 1c). Other measured magnetic anomalies are also displayed where available along proper direction. These profiles are compared to selected magnetic anomaly profiles across the Cretaceous Normal Superchron (CNS). **(a)** In the CB, Profile 1 displays conjugate magnetic anomalies 33 and 34 on both sides of a fossil spreading center (FR) clearly depicted on the gravity data (Figure 1a); the smooth magnetic anomaly further Northeast correspond to the quiet more recent part of the CNS underlined by red boxes on (a) and (c). **(b)** In the VB, Profiles 2 and 3 show smooth magnetic anomalies in their southern side and more dynamic anomalies in their northern side, separated by a clear anomaly; they encompass the youngest and medium parts of the CNS, respectively, underlined by blue boxes on (b) and (c), the clear anomaly being identified with marker Q1 (Granot et al., 2012). **(c)** Sea surface anomaly profiles from different ocean basins showing consistent magnetic intensity variations within the CNS (after Granot et al., 2012). Magnetic anomaly profiles have been visually deskewed in the CB and on the reference CNS profiles from Granot et al. (2012) to restore the typical boxcar shape of anomaly 33r. This cannot be achieved in the VB, where the original anomalies are displayed. See text for additional information.

Figure 3. Plate tectonic evolution model for the Caribbean Large Igneous Province (CLIP) and Caribbean Plate at 120, 83, 73, 45, 25 and 0 Ma. At **120 Ma**, the Caribbean Plateau initiated at the Tongareva triple junction, whereas the Proto-Caribbean Ocean was opening between North and South America. Two options are proposed at **83** and **73 Ma** for the formation of the CLIP at a mid-ocean ridge in the vicinity of the future Central America: in **Option A**, the CLIP formed at the Pacific-Farallon spreading center, later affected by a major westward ridge jump; in **Option**

B, the CLIP formed at the Farallón-Chazca spreading center. At **73 Ma**, the CLIP collided with the Chortis Block and the nearby subduction zone, which reversed its polarity and started to consume the Proto-Caribbean lithosphere. At **45 Ma**, the Central American subduction zone formed west of the CLIP and Chortis Block, which therefore constitute the new Caribbean Plate. The slow convergence between North and South America and the eastward motion of the Caribbean plate result, at **25** and **0 Ma**, in compression on Beata Ridge and rotation of the CB and VB. See text for additional information. The "computed" Galapagos hotspot location is computed from Matthews et al. (2016), whereas the "proposed" one is modified to better agree with a plateau formed by the hotspot at a spreading center from 120 to 73 Ma as proposed in our model.


a
20°
15°
10°
−85°
−80°
−75°
−70°
−65°
−60°
Eötvos
−200
−100
0
100
200
b
nT
c
LNR
BR
CB
VB
AR
1
2
3
d
IG24-08
RC20-01
34
33r
V26-08
IG15-03
DSDP15GC
Q1
17.5°
12.5°
−77.5°
−67.5°


a
COLOMBIA BASIN
Measured
Sk. 105°
IG24-08
Sk. 0°
Later volcanics
CNS
Sk. 105°
RC20-01
Sk. 0°
W-E
C34
C34
C33r
FR
C33r
CNS
Extracted
Sk. 105°
1
Sk. 0°
S-N
SW-NE
200 nT
100 km
b
VENEZUELA BASIN
Measured
Q1
V26-08
CNS
IG15-03
Sk. 0°
CNS
DSDP15GC
W-E
Q1
Extracted
2
CNS
3
CNS
Sk. 0°
W-E
S-N
200 nT
100 km
c
CRETACEOUS NORMAL SUPERCHRON (after Granot et al., 2012, modified)
Age (Myr ago)
90
100
110
120
C34
Q1
Q2
M0
S Atlantic, SAM flank
29 mm yr -1
200 nT
50 km
S Atlantic, AFR flank
29 mm yr -1
200 nT
50 km
SW Indian, AFR flank
28 mm yr -1
200 nT
50 km
C34
Q1
Q2
M0



Spreading center / transform fault :
Known
Inferred
Subduction zone
Oceanic plateau :
Known
Inferred
Magnetic isochron
Galápagos hotspot :
Computed
Proposed
Beata Ridge
Suture
Reconstructed continents
Present coastlines
Option A
Option B
120 Ma
45 Ma
83 Ma
83 Ma
25 Ma
73 Ma
73 Ma
0 Ma
NAM
SAM
AFR
FAR
PAC
CHZ
COC
NAZ
Yu
Ch
??
−150°
−100°
−50°
25°
0°
-25°