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SEISMIC EVIDENCES OF RECURRENT VOLCANISM ACROSS THE NORTH BRAZILIAN AND THE FERNANDO DE NORONHA RIDGES – BRAZILIAN EQUATORIAL ATLANTIC OCEAN

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ABSTRACT. This study, based on the interpretation of LEPLAC (the Brazilian Continental Shelf Survey Project) deep seismic lines (~16.0 s twtt), reveals for the first time across the Brazilian Equatorial Atlantic Ocean seismic evidences that buried portions of individual volcanic edifices of the North Brazilian and the Fernando de Noronha volcanic ridges are laterally coupled with a series of volcanic wedges. Our analyses evidence that these magmatic occurrences are presented as layered volcanic bodies as wide as 80 km and as thick as 1.2 s (twtt) close to the volcanic edifices. Volcanic wedges occur as layered prograding bodies stemming directly from the major volcanic edifices of both ridges. Seismic analyses also reveal that numerous layered volcanic accumulations associated to a same individual volcanic edifice may occur along variable stratigraphic levels. These occurrences indicate that the evolution of the North Brazilian and the Fernando de Noronha volcanic ridges is followed by a long history of recurrent volcanic activities that may have possibly been synchronous in distinct volcanic edifices distant apart.

Keywords: seamounts, guyots, volcanic seismic facies, volcanostratigraphy, intraplate volcanic ridges.

INTRODUCTION

The Eastern Brazilian Equatorial Atlantic, segment to the east of the Amazon Fan, is characterized by a series of fracture zones (e.g., Hayes and Ewing, 1970; Le Pichon and Hayes, 1971; Bryan et al., 1973; Gorini, 1977; Houtz et al., 1977; Rabinowitz and Labrecque, 1979; Azevedo, 1991; Matos, 2000; Ernesto, 2006; Moulin et al., 2010; Matos et al., 2019; Aslanian et al., 2021) and morphologic features including a series of prominent seamounts with a relative relief that commonly exceeds 3,000 m (e.g., Le Pichon and Hayes, 1971; Gorini, 1977; Azevedo, 1991). These seamounts are physiographically isolated or connected, forming submarine ridges aligned in E-W or NW-SE directions, named the North Brazilian Ridge (herein NBR) and the Fernando de Noronha Ridge (herein FNR; Figure 1).

Previous works approaching the regional structural evolution of the Brazilian Equatorial Margin ascribed the origin of the NBR and the FNR to volcanic processes related to the tectonic and geodynamic evolution of the Equatorial Atlantic Ocean (e.g., Hayes and Ewing, 1970; Le Pichon and Hayes, 1971; Bryan et al., 1973; Gorini, 1977; Houtz et al., 1977; Figure 2). However, there is relatively scarce published material about the petrographic nature of these volcanic edifices (e.g., Mizusaki et al., 2002; Guimarães et al., 2020). Information on how volcanism related to the NBR and the FNR occurred through time and across the volcanic ridges is also scarce.

The objective of the present work is to report for the first time, based on deep seismic reflection data, that the volcanic edifices of the NBR and the FNR, lying across the Eastern extent of the Brazilian Equatorial Atlantic Ocean, evolved followed by recurrent volcanic activities, variable both in volume and importance across each volcanic ridge, and from one individual seamount or guyot to another, as well as through time. As we do not dispose of any dating nor petrographic data, our work does not intend to approach questions related neither to the origin nor to ages nor to the petrological nature of the volcanism in the region.

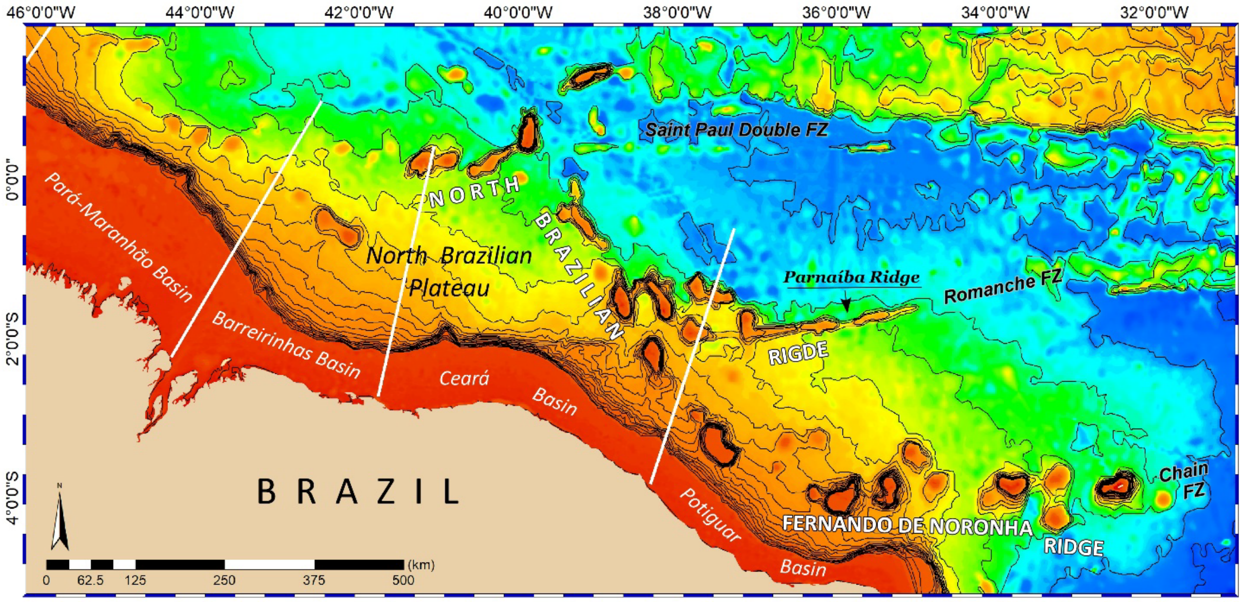

Figure 1: Bathymetric map of the eastern segment of the Brazilian Equatorial Atlantic Ocean, showing the main fracture zones that interact with this margin segment: Saint Paul, Romanche and Chain Facture Zones, the North Brazilian Ridge and the Fernando de Noronha Ridge. White lines represent the official limits of the Maranhão, Barreirinhas, Ceará and Potiguar marginal basins (according to the Serviço Geológico do Brasil - CPRM). Bathymetric data are from ETOPO1 (NOAA National Geophysical Data Center, 2009: ETOPO1 1 Arc-Minute Global Relief Model). Bathymetric contours are at 250 m intervals.

REGIONAL GEOLOGY

The Brazilian Equatorial Atlantic Margin evolved in three distinct extensive tectonic phases (Azevedo, 1991; Bizzi et al., 2003; Soares Júnior et al., 2008) following the propagation of the Central Atlantic extension since the Neo-Triassic (~200 Ma) and subsequent transtensional events from Barremian to Albian, that finally established the Central and Equatorial Atlantic connection (Matos, 2000; Soares Júnior et al., 2008). As the continental drift evolved, NE-SW transcurrent faults began to act across the entire set of Equatorial rifts, resulting in a complex transform and oblique margin multi-stage segmentation, that led to the development of a series of Mesozoic-Cenozoic basins, such as Pará-Maranhão, Barreirinhas, Ceará and Potiguar (Matos, 2000; Ernesto, 2006; Moulin et al., 2010; Matos et al., 2019; Aslanian et al., 2021-Figure 1).

Directions of the Saint Paul Double Fracture Zone (also referred to as São Paulo Fracture Zone in the literature) and Romanche Fracture Zone are geographically related to both E-W segments of the NBR (Hayes and Ewing, 1970; Le Pichon and Hayes, 1971; Bryan et al. 1972; Francheteau and Le Pichon, 1972; Matos, 2000; Moulin et al., 2010; Aslanian et al., 2021), whereas the Central NBR segment, oriented N30°W, would correspond according to different authors to ancient spreading centers, resulted from ridge jumps (e.g., Le Pichon and Hayes, 1971; Gorini, 1977; Azevedo, 1991).

The NBR and the FNR have distinct configurations: (i) the NBR has its northern E-W segment aligned with the Saint Paul Double Fracture Zone; while its southern E-W segment is aligned with the Romanche Fracture Zone (e.g., Hayes and Ewing, 1970; Le Pichon and Hayes, 1971; Ulbrich et al., 2004; Moulin et al., 2010; Aslanian et al., 2021). Its intermediate N30°W segment connects the northern and southern segments (Figure 1). Indirect evidences, based on sedimentation rates from shallow cores, suggest that the ridge volcanic emplacement ages are from 80 to 100 Ma (Hayes and Ewing, 1970); (ii) the FNR presents in its turn only one E-W segment. According to several authors (e.g., Le Pichon and Hayes, 1971; Gorini, 1977; Almeida, 2006), the E-W-oriented FNR is aligned with the extension of the Charcot Fracture Zone. However, other works (e.g., Azevedo, 1991; Matos, 2000; Matos et al., 2019) including more recent geodynamic reconstructions of the Equatorial Atlantic Ocean (e.g., Moulin et al., 2010; Aslanian et al., 2021) outline that the FNR volcanic ridge is actually aligned with the Chain Fracture Zone (Figure 2B)

The origin of the volcanism related to the NBR and the FNR is still a matter of debate and several hypotheses were put forward to explain it:

1. Hayes and Ewing (1970) were the first authors to propose that the NBR was probably formed by an excess of oceanic volcanism associated with the seafloor spreading mechanism, that should have occurred as soon as the initial rifting rupture. In addition to that, Le Pichon and Hayes (1971) suggested that the ridge volcanism would possibly have resulted from significant shifts in the pole of rotation between African and South American plates. Gorini (1977) later proposed a conjunction of processes to be at the origin of the NBR volcanism: isostatic overload caused by anomalous

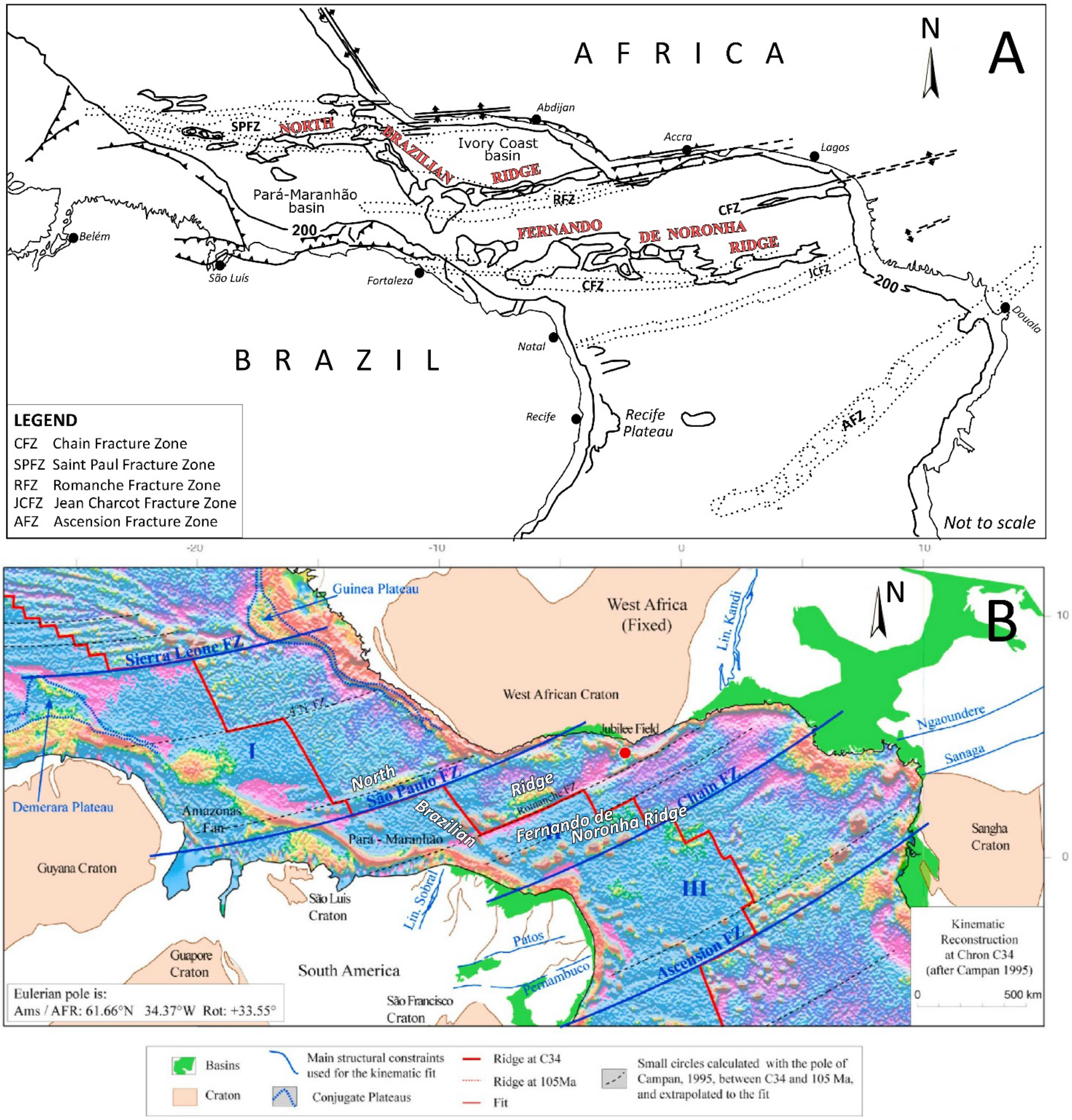

Figure 2: Models of paleogeographic reconstruction of the Equatorial Atlantic Ocean, placed into a 40-year perspective. **A**. The North Brazilian and the Fernando de Noronha Ridges set down in a simplified paleogeographic reconstruction of the geodynamic evolution of the Equatorial Atlantic Ocean (not to scale), redrawn and slightly modified from Le Pichon and Hayes (1971). **B**. Paleogeographic reconstruction of the Equatorial Atlantic at Chron C34 (84 Ma) (slightly modified from Moulin et al., 2010). The figure shows, on each plate, the gravity data from Sandwell and Smith (1997) between the coast and the anomaly C34.

sediment accumulation across the North Brazilian Plateau could have led to lithospheric flexure, isostatic pressure unbalance and finally to magmatism. According to this author, magmatism would have occurred in pulses, due to the relation between sedimentation and flexure versus pressure relief and magmatism. On the other hand, O'Connor and Duncan (1990) associated the origin and evolution of the NBR to the presence of a mantle plume, the same one that was responsible for the onset of the Ceará and Sierra Leone rises, formed at around 80 Ma, which would subsequently have also given rise to the development of the Fernando de Noronha Ridge;

2. most studies regarding the origin of the FNR associate its volcanism as a result of the westward movement of the South American plate over the Fernando de Noronha plume (e.g., Fodor et al., 1998; Fodor et al., 2002; Almeida, 2012).

Ages associated with the volcanism along the NBR and the FNR are not at all well constrained. Samplings are scarce and usually rely on chain dredge rock samples. Volcanism has been commonly associated with the continuity of onshore Mecejana Volcanism, that occurs as plugs and domes of alkaliphonolitic, tephritic and phonophritic rocks on the continent, as well as in the form of pyroclasts and numerous alkaline dikes. Ages for these continental occurrences were attributed to the Upper Eocene to Lower Oligocene, between 36 ± 2 and 29.9 ± 0.9 Ma (Cordani, 1970, Teixeira et al., 1978, Braga et al., 1981, Guimarães et al., 1982). Dating of superficial samples collected across the far East portion of the Fernando de Noronha Archipelago reveals 40Ar/39Ar ages between 12.5 and 1.3 Ma (Guimarães et al., 2020).

MATERIAL AND METHODS

The bathymetric and seismic data used in this study were provided by the Brazilian Continental Shelf Project (LEPLAC), coordinated by the Brazilian Navy. The seismic dataset includes 119 seismic lines acquired during the geophysical missions LEPLAC- Phase I and LEPLAC- Phase II, encompassing single channel and deep multichannel seismic lines with different signal penetration depth and seismic resolution (Figure 3). (1) LEPLAC Phase I seismic lines were acquired with a multichannel system of 120 channels (nearly 3,000 m of cable) using an air-gun seismic source holding a maximum operational volume of 4,000 inch^3 and were recorded up to 16 s two-way travel time; (2) LEPLAC Phase II comprises both single channel and multichannel seismic lines. A set of single channel seismic lines was acquired using an air-gun source of 270 inch^3 in volume and 300 m of cable to record 10s two-way time interval. Multichannel lines were acquired with a 1,950 inch^3 air-gun source, using a 480 trace streamer of 6,000 m in length and were recorded up to 10 s two-way travel time.

The bathymetric Digital Terrain Model (DTM) used in the work was developed by the LEPLAC team (Alberoni et al., 2020), available at https://www.marinha.mil.br/dhn/?q=node/249. The DTM was built based on a large dataset extracted from variable sources (Figure 4): (i) bathymetric, 3.5 kHz and seismic data acquired by the LEPLAC project, integrated with bathymetric data collected by the Brazilian Navy; (ii) bathymetric and seismic data acquired and provided by PETROBRAS and other oil companies, made available by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP); (iii) bathymetric data made available by SHOM (*Service Hydrographique et Océanographique de la Marine* – France) and Ifremer (*Institut Français de Recherche Pour l'Exploitation de la Mer* – France); (iv) single-beam and multi-beam public data available in GEODAS (*Geophysical Data System* – NGDC/NOAA); (v) satellite data (SRTM30_plus) were also integrated into the grid to cover deeper distal ocean regions (Figure 4).

The available database allowed the building of a Digital Terrain Model (DTM), based on a mathematical model using the minimum curvature method and a cell size of 2,500 m (for further details concerning the processing methodology, please refer to Alberoni et al., 2020). 2D and 3D depth-to-basement maps in their turn were built considering depth values measured in two-way travel time (twtt), since the available seismic reflection grids (Figures 3 and 4) are not time migrated.

RESULTS

Seamounts morphology of the North Brazilian and the Fernando de Noronha ridges

The 3D DTM model reproduced in this study (Alberoni et al., 2020) clearly outlines how remarkable is the morphological imprint of the NBR and the FNR on the Eastern Equatorial Atlantic Ocean adjacent to the Eastern Brazilian Equatorial Margin (Figure 5). These ridges extend for thousands of kilometers long as alignments of impressive volcanic edifices sometimes rising as high as 4,250 m above their surroundings seafloor, constituting seamounts and guyots located some 30-100 km apart, presenting basal diameters that can be as large as 80 km in the present bathymetry (Figure 5).

The North Brazilian Ridge (NBR)

The NBR runs for a total length of ~ 1,060 km, describing a zed-like feature in plan view. The ridge is segmented into three main branches: the Northern, the Central and the Southern segments (Figure 6).

The ***Northern NBR segment*** (Northern E-W segment of Alberoni et al., 2020) runs in an E-W direction for ~370 km and is located around 250 km south of the Ceará Ridge. This segment is composed of seven seamounts (not individually nominated), that exhibit general elongated morphological features. This alignment of volcanic edifices lies in continuity with the Saint Paul Double Fracture Zone, bathymetrically expressed to the East. This Northern segment is morphologically isolated from the Central NW-SE segment by a gap of 70 km approximately (Figure 6). The morphology of the Northern segment seamounts varies from conical to elongated volcanic edifices with clear morphological peaks and basal horizontal section as large as 70 km in diameter. Seamounts may rise above seafloor as high as 500-3,250 m (mean relative relief of 1,850 m). Peaks of individual seamounts have depths ranging from 600 to 3,150 m (with a mean depth of about 2,300 m) (Figure 7A-A').

The ***Central NBR segment*** (NW-SE segment of Alberoni et al., 2020) is N30°W oriented and extends for ~ 235 km long. It is constituted by five seamounts, most of them representing guyots with elongated shapes in plan view; they can be as large as 125 km wide (across their longest axes-Figure 6). Individual seamounts are volcanic edifices that may stand as high as 650 to 3,200 m above the adjacent seafloor (mean relief of ~ 1,750m);

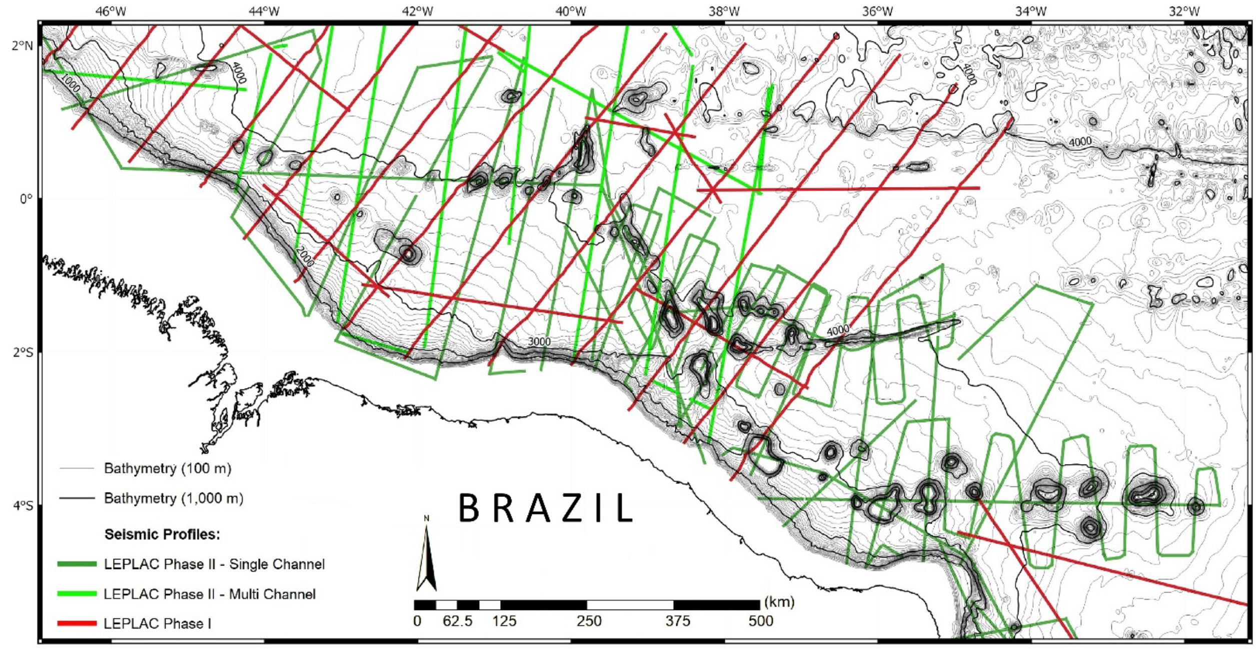

Figure 3: Location of the seismic dataset used in this work. Bathymetric contours are at every 100 m intervals.

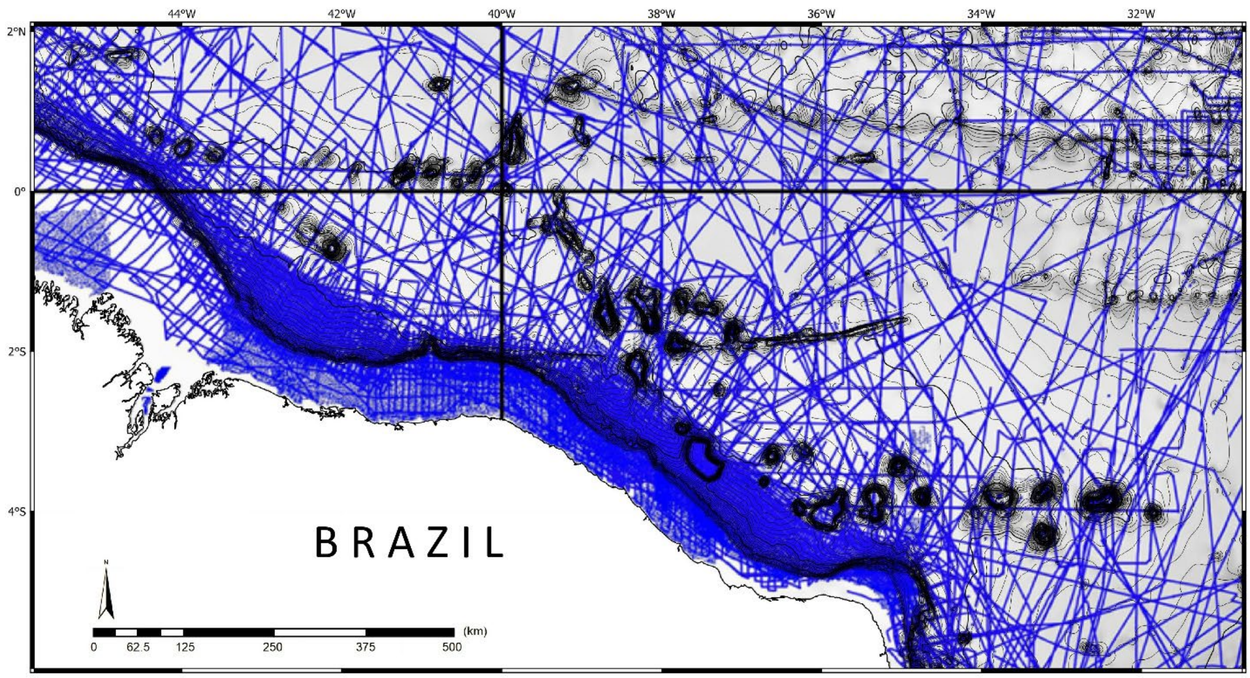

Figure 4: Acoustic dataset used to build the Digital Terrain Model (DTM) developed by the LEPLAC project (slightly modified from Alberoni et al., 2020).

and peak depths are between -50 and -3,300 m (mean depth ~1,910 m-Figure 7B-B').

The ***Southern NBR segment*** (Southern E-W segment of Alberoni et al., 2019) is again rather variable regarding seamounts distribution and their morphologies. It equally lies in a general E-W direction and continuously for ~ 470 km long, roughly aligned with the orientation of the Romanche Fracture Zone. However, seamounts configuration and related shapes in horizontal sections are quite variable (Figure 6). To the west, the *Southern NBR segment* is expressed by a cluster of four seamounts which are grouped as Ceará Seamounts. In plan view, they are either conical (~50 km wide) or elongated (~100 km wide) with well-defined peaky morphologies. Individual volcanic edifices may stand as high as 1,500 to 3,250 m above the adjacent seafloor (with a mean relative relief of ~2,575 m). Peaks of individual seamounts have depths that vary from 50 to 2,700 m (with a mean depth of about 975 m-Figures 7C1-C' and 7C2-C'). Around the Ceará Seamounts, the

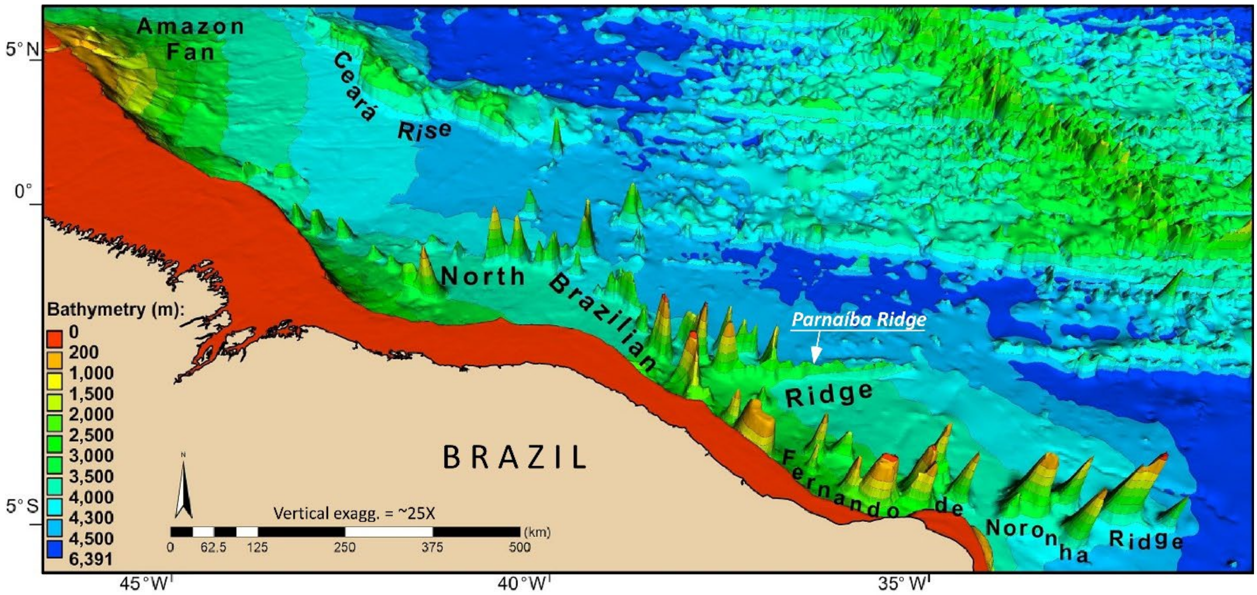

Figure 5: 3D morphological map of the Brazilian Eastern Equatorial Atlantic Ocean, highlighting the imposing bathymetric features of the North Brazilian Ridge (NBR) and the Fernando de Noronha Ridge (FNR). Bathymetric data were extracted from the LEPLAC Digital Terrain Model (DTM) developed by the LEPLAC project (Alberoni et al., 2020).

sediment dispersal seems controlled by the volcanic edifices themselves, leading to the onset of a local plateau morphological feature – the Paracuru Plateau (Figure 6). The eastern extent of the *Southern NBR segment* describes in its turn a real volcanic ridge in the bathymetry, that runs for ~ 250 km long and presents ~30 km width in cross section - known as Parnaíba Ridge (Figures 5 and 6). This ridge segment has a mean relative relief (above seafloor) of ~1,200 m, while its summit lies at a mean depth of 3,000-3,200 m (Figures 6 and 7C1-C').

The Fernando de Noronha Ridge (FNR)

The FNR differs considerably from the NBR since a few of its seamounts lie close to or above sea level as atolls or islands. It comprises 15 isolated (or semi-isolated) volcanic edifices spaced from ~10 to 60 km apart, that constitute an alignment of seamounts, guyots and islands that runs in an E-W direction for about 520 km long, in continuity with the Chain Facture Zone (Figure 6). Volcanic edifices may rise above seafloor as high as 1,200 - 4,550 m (mean relative relief of ~ 2,500 m), emerging in the Fernando de Noronha Archipelago and Rocas Atoll. The top plan of guyots and peaks of individual seamounts has depths ranging from -300 m (in the archipelago) to -2,000 m (with a mean depth of about 550 m-Figures 6 and 7D-D').

Depth-to-seismic basement map

The present understanding of the NBR and the FNR is mostly based on seafloor conventional and satellite bathymetric mapping as shown in Figures 5 and 6. However, depth-to-basement maps in 2D and 3D perspectives (Figure 8), built in the present work from seismic interpretation of the top basement surface (in two-way travel time – twtt-Figure 9), reveal outstanding features that bring light to the real configuration of the NBR and the FNR in seafloor below. Two aspects worthy of note in such maps are: (i) the basement lies at a regional depth of approximately 7.0 s twtt (Figure 8A); (ii) individual seamounts of both NBR and FNR are actually interconnected as continuous volcanic ridges, composing a rampart-like feature of thousands of kilometers long, that can rise as high as 7.5 s (twtt) above the regional basement depth (Figure 8B). Due to their continuous and imposing morphologies, these basal rampart-like features from which seamounts/guyots stem up are clearly capable of segmenting the crust in compartment sectors, involving either deep oceanic basins or margin domains of continental crust. Concerning the depth-to-basement features along the NBR and the FNR, Figure 8 shows that:

1. The ***Northern segment of the NBR*** is continuous for ~ 310 km long and presents volcanic edifices as high as ~3,250 m above seafloor. A continuous E-W elongated low basement is observed located just to the NW of the Northern NBR segment. This basement feature attains depths of 7.8 s (twtt; that means about 0,8 s below the mean basement regional depth) and represents a buried trough, surrounded by the pair of oceanic transverse ridges of the Saint Paul Double Fracture Zone. The ***Southern NBR segment*** is continuous for ~440 km; whereas the Central NBR segment extends for about 400 km up to joining the E-W oriented FNR (Figure 6);
2. The FNR presents itself as a continuous rampart across the basement regional depth; its easternmost portion is connected to the Ceará Terrace and the Canopus Bank, which in their turn are connected to the Southern and Central segments of the NBR. The total NR length reaches ~830 km (Figure 6).

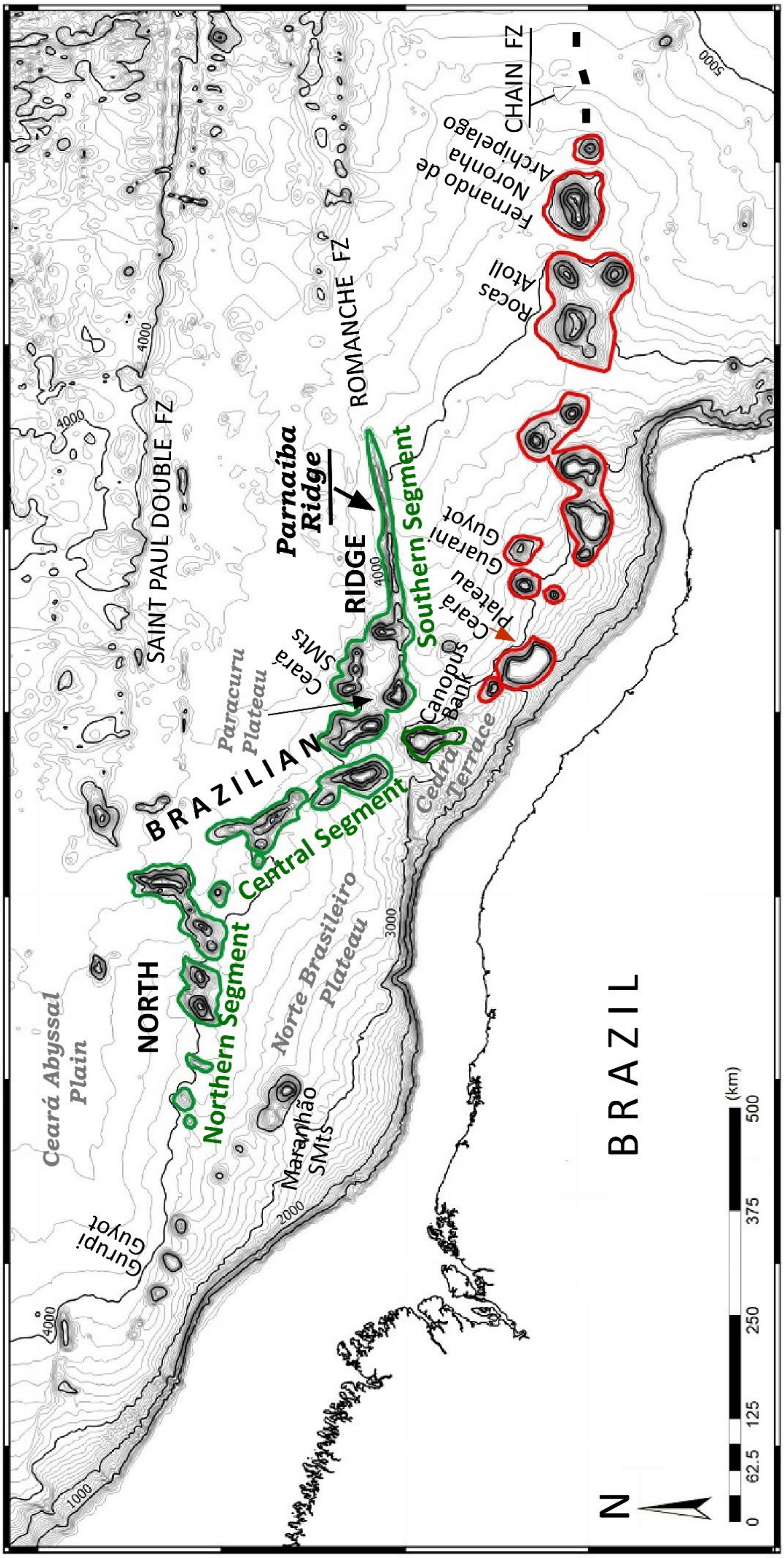

Figure 6: Location of the North Brazilian Ridge (in green), and its respective Southern, Central and Northern segments, and the Fernando de Noronha Ridge (in red). Bathymetric contours are at 100 m intervals. Bathymetric data were extracted from the LEPLAC Digital Terrain Model (DTM) developed by the LEPLAC project (Alberoni et al., 2020). SMts= seamounts.

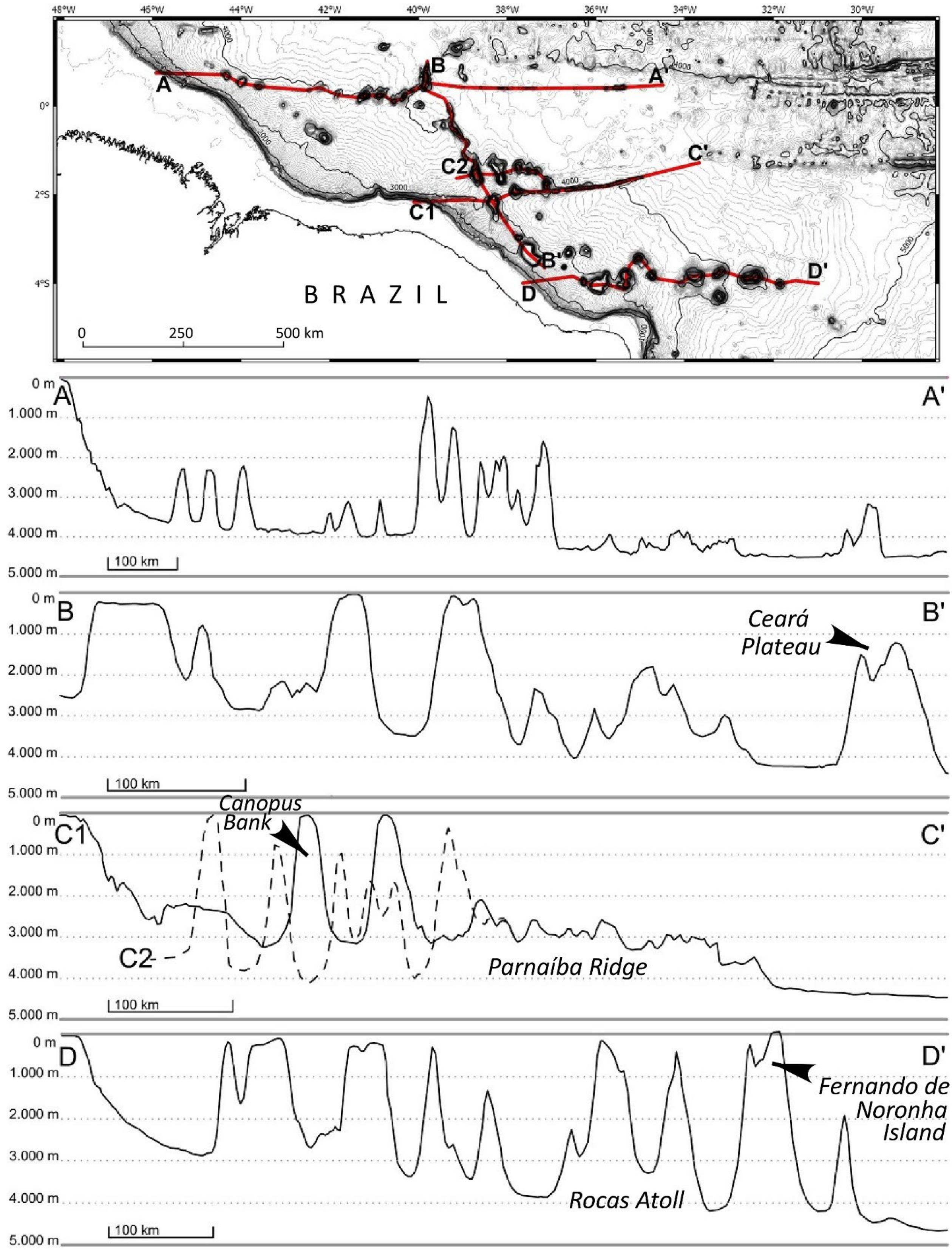

Figure 7: Bathymetric sections along segments of the North Brazilian and the Fernando de Noronha volcanic ridges. Bathymetric data were extracted from the LEPLAC Digital Terrain Model (DTM) developed by the LEPLAC project (Alberoni et al., 2020).

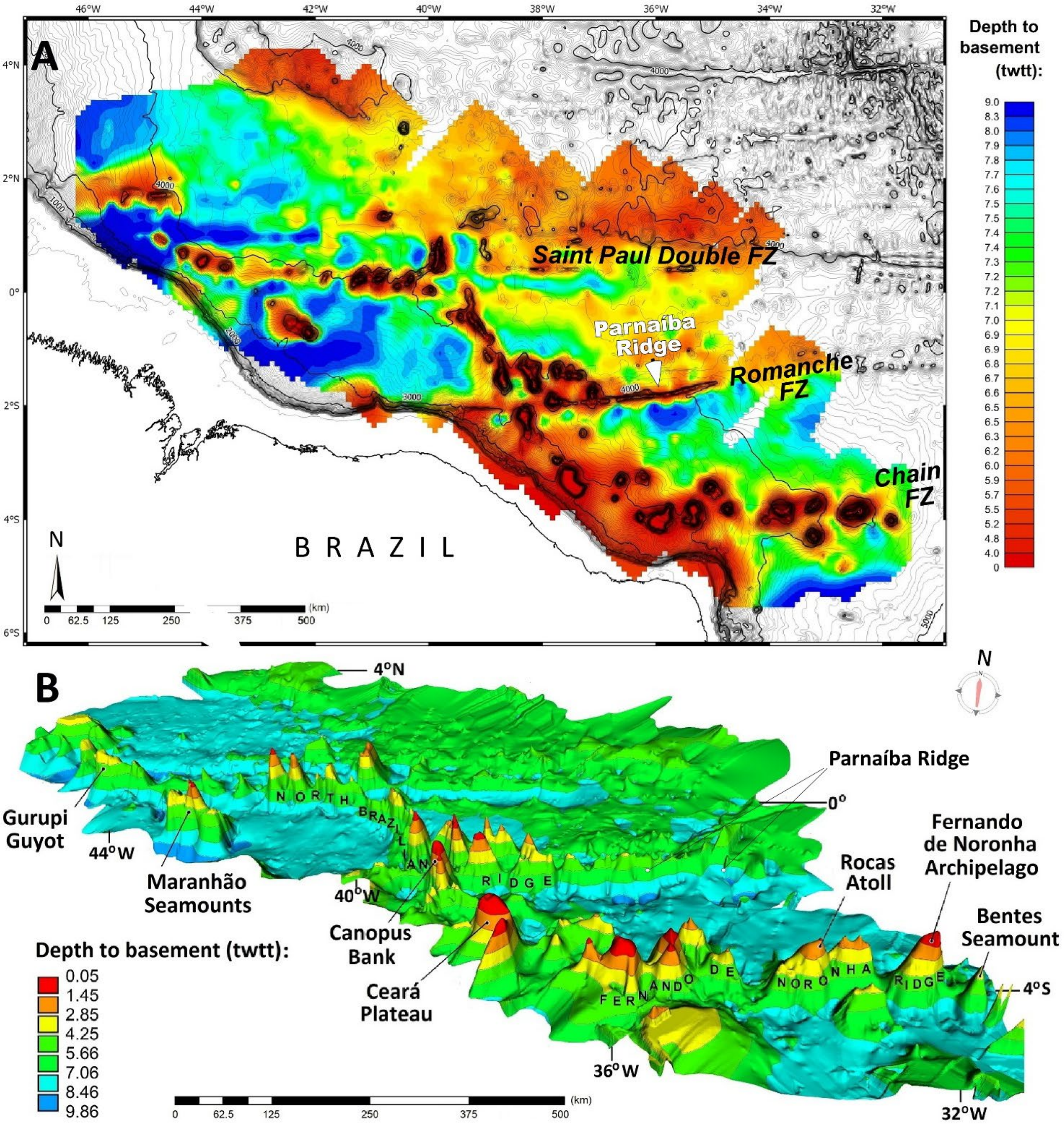

Figure 8: A - Depth-to-basement map built from seismic interpretation of the top basement surface (in two-way travel time - twtt). Bathymetric contours are at 50 m intervals. B - 3D depth-to-basement map evidencing the rampart-like features that interconnect seamounts/guyots as continuous volcanic ridges.

Seismic reconnaissance of magmatic features spatially related to the NBR and the FNR

The seismic interpretation depicted in Figures 8 and 9 highlights the seismic pick up of the regional top surface of the basement rock, both oceanic and continental crusts, as well as the conical and/or elongated shapes of the volcanic edifices that compose the NBR and FNR. However, a detailed seismic interpretation focused on seismic facies around the volcanic edifices brings to light outstanding morphological and seismic features spatially related and directly connect to the conical or guyots-like volcanic edifices. This detailed seismic facies interpretation revealed that many of those edifices are laterally coupled with wedge-like seismic features (or seismic bodies), which, along variable stratigraphic levels, stem directly from the edifices themselves, now interbedded with marine sedimentary units (Figures 10 and 11). Such wedge-like seismic features present rather distinct seismic signature in comparison to the surrounding seismic facies that reflect marine sedimentation:

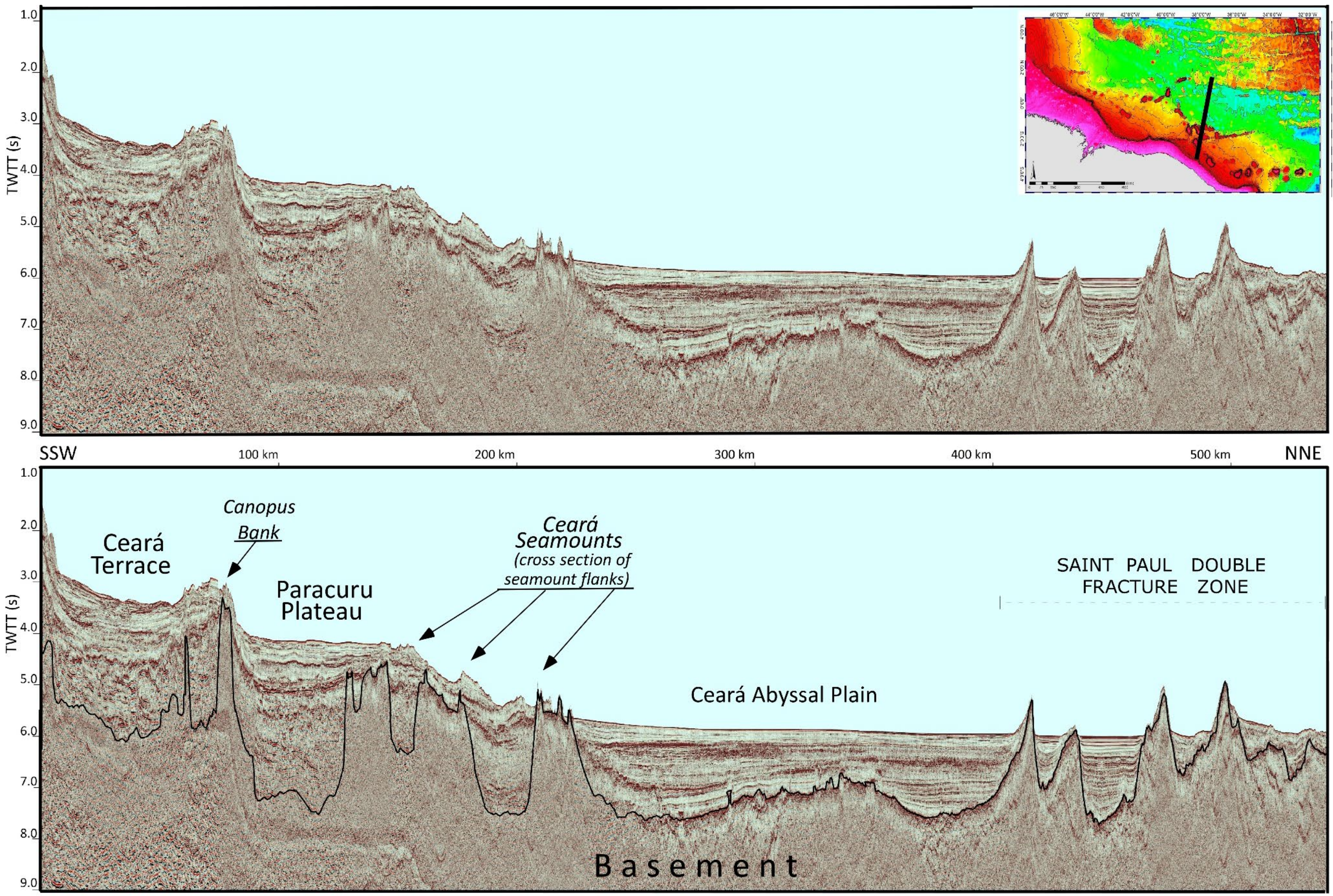

Figure 9: Uninterpreted (top) and interpreted (below) seismic section of the LEPLAC deep seismic survey, showing volcanic edifices that characterize the basement across the Eastern Brazilian Equatorial Atlantic Ocean.

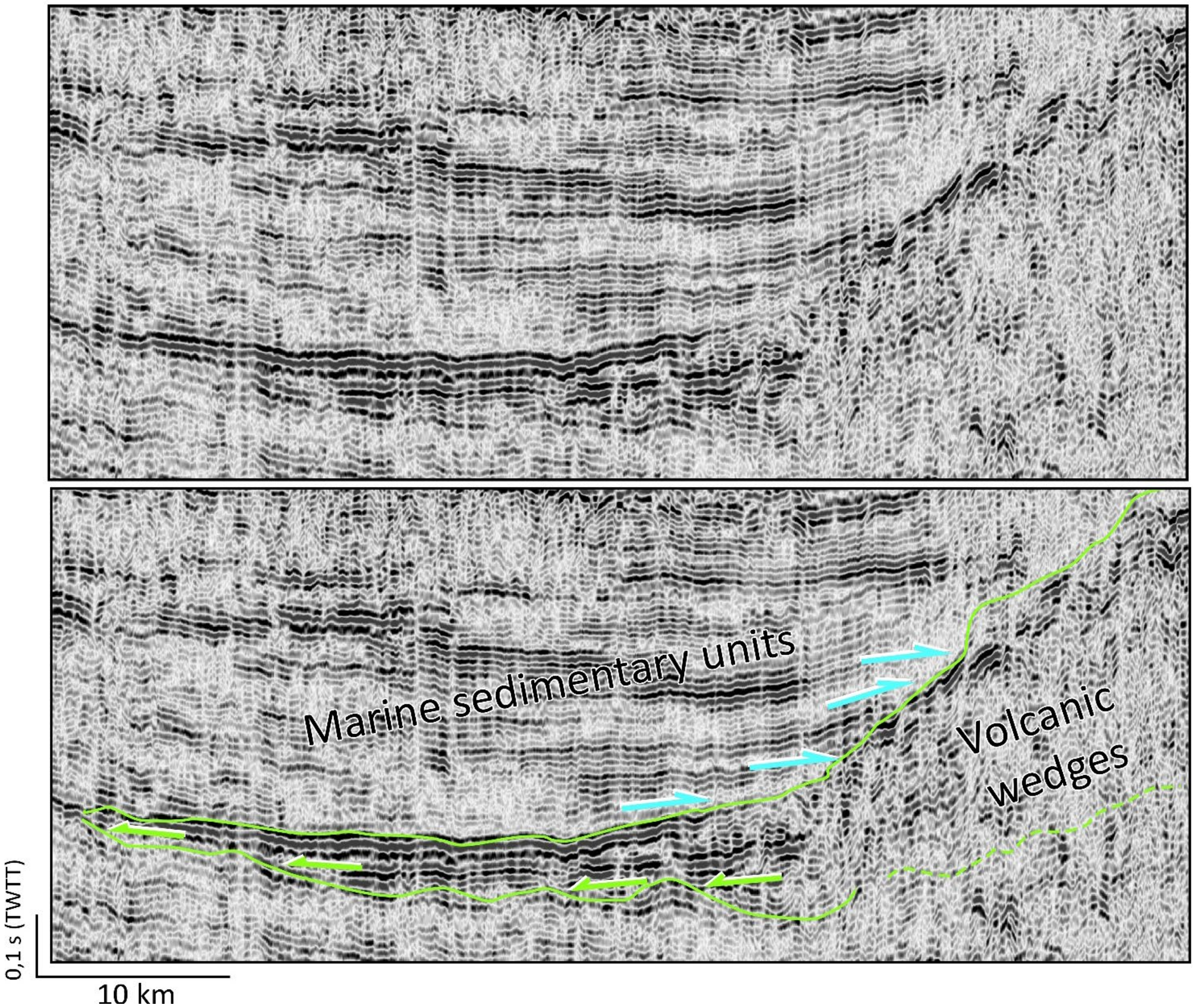

Figure 10: Zoom-out of a LEPLAC seismic line showing seismic facies characteristic of the volcanic wedges that are laterally attached to volcanic edifices that compose the North Brazilian and the Fernando de Noronha volcanic ridges, Brazilian Equatorial Atlantic Ocean.

1. wedge-like seismic features spread laterally from and in clear continuity with the volcanic edifices. Close to volcanic edifices they usually present their thickest portions, which can reach up to 1.2 s in thickness (twtt). These features all thin out with increasing distances form main volcanic edifices; with lateral extensions that can reach 30 km to 80 km long (Figure 10);
2. these seismic features are all characterized by top and basal continuous high-amplitude seismic reflectors, indicating very high impedance contrasts with the surrounding sedimentary seismic units. Close to volcanic edifices, the top reflectors tend to be slightly irregular and accompanied by a few hyperbolae, whereas distally they become quite planar (Figure 10);
3. internal reflections of the wedge-like seismic features are also quite distinct from the reflections of the marine sedimentary successions lying beneath and above these seismic bodies. Close to the volcanic edifices, we see seismic facies marked by very high-amplitude and discontinuous internal reflections. Away from the volcanic edifices, internal reflections continue to present high amplitudes but they are usually arranged as continuous bedded reflections (layered units) (Figure 10);
4. a few seismic configurations are worthy of note when referring to seismic relations between plan-parallel sedimentary reflections (representing marine sedimentation) and those reflections characteristic of wedge-like bodies. Away from volcanic edifices, the wedge distal internal reflections present prograding features above planar sedimentary reflectors, pointing to a “source” coming from the volcanic edifices. In their turn, overlying sedimentary successions onlap all seismic wedges towards the volcanic edifices (Figure 10).

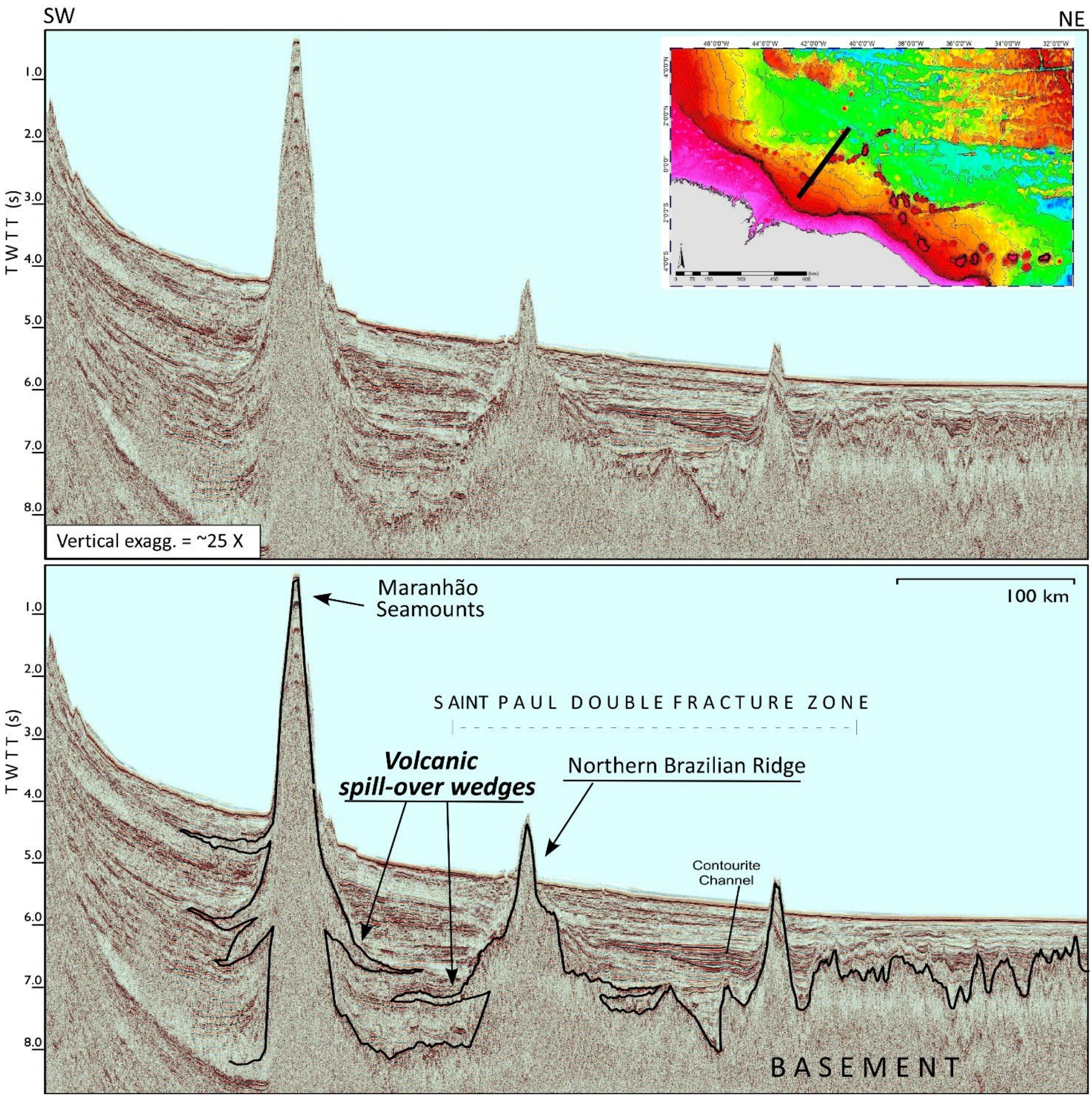

Figure 11: Uninterpreted (top) and interpreted (below) LEPLAC seismic line showing the complex configuration of buried portions of seamounts and guyots in the peculiar form of "Christmas pine trees", all along the North Brazilian and the Fernando de Noronha volcanic ridges, Brazilian Equatorial Atlantic Ocean.

DISCUSSION

The results presented in section 4 highlight for the first time in the Brazilian Equatorial Atlantic that the buried portions of seamounts and guyots along the NBR and the FNR volcanic ridges are laterally coupled with a series of wedge-like seismic features that all together compose seamounts and guyots with a peculiar shape of "Christmas pine tree", as depicted in Figure 11. The seismic interpretation work also reveals a much higher degree of complexity of the basement morphology, where the NBR and the FNR are represented by alignments of mostly individual conical and/or elongated volcanic edifices.

Seismic features interpreted as intrusive and/or volcanic units interbedded with sedimentary units have been described by different works in well-known volcanic provinces or margins worldwide (*e.g.,* Planke et al, 2000; Berndt et al, 2001; Planke et al, 2005; Rey et al., 2008; Infante-Paez and Marfurt, 2017). Some of these works report the occurrence of wedge-like layered seismic features quite similar to those identified in our study (Figures 10 and 11): Berndt et al. (2001), for instance, conducted a detailed volcanostratigraphic study of the Norwegian margin in which, among other types of magmatic bodies, they recognized and mapped the occurrence of layered magmatic features of high impedance contrast in relation to the surrounding sedimentary units in the Lofoten-Vesteralen Margin, in the southern Vøring Margin and in an area near the Jan Mayen Fracture Zone. Based on their shapes, reflection patterns and boundary reflections, those seismic features, quite similar to those attached to the NBR and the FNR volcanic ridges, were interpreted as volcanic seismic units related to small-volume submarine volcanism; another robust study was conducted by Infante-Paez and Marfurt (2017), in which it were recognized, mapped and sampled high-amplitude layered seismic features, within a Miocene sedimentary succession of the Taranaki Basin, New Zealand. Petrographic analyses from drilled samples from a series of wells revealed that the layered features in question, also seismically quite similar to the ones recognized in the present work, correspond to lava flow facies, at places intermingled with pyroclastic facies.

Accordingly, and considering the geodynamic setting of the present study, we interpreted the wedge-like seismic bodies attached to volcanic edifices of both the NBR and the FNR as equally representing magmatic accumulations sourced directly from individual volcanic edifices.

Besides that, across the Brazilian Equatorial Atlantic Ocean, the "Christmas pine tree" branches intermingled with the sedimentary succession evidence that magmatic processes occurred along with the deep-basin sedimentary infilling. Outcropping portions of volcanic ridges (above seafloor) are composed of rather "smooth" steep-sided seamounts and/or guyots, at least within the seismic resolution of available dataset (Figure 5), whereas the shape of their corresponding buried portions varies considerably. Occurrences of magmatic bodies laterally attached to individual edifices naturally raise questions about the nature of associated magmatic processes: if corresponding to intrusive magmatic bodies, or to submarine (or subaerial) volcanism.

A possible answer to that question may rely on our interpretation work that shows remarkable seismic stratigraphic relations between thick magmatic wedges and the surrounding marine sedimentary units (above and beneath them). A few specific observed seismostratigraphic features favor the interpretation of the layered magmatic bodies attached to the NBR and the FNR volcanic ridges as actually being volcanic in nature. Such statement relies on the fact that (Figure 10):

(i) away from the main volcanic edifices, internal reflections of magmatic wedges present prograding features above planar sedimentary reflectors below, forming layered magmatic bodies which progressively spread out to form accumulations as wide as 80 km and as thick as 1.2 s (twtt);

(ii) overlying sedimentary successions progressively onlap the magmatic wedges towards the main volcanic edifices, revealing they represent infilling sedimentary units recovering previously deposited volcanic units.

Seismic stratigraphic relations pointed out in (i) and (ii) above led us to conclude that all layered magmatic bodies laterally attached to the NBR and the FNR volcanic ridges and interbedded with sedimentary layers are clear indications that these magmatic bodies are not intrusive ones; they result from a process of volcanic spill-out sourced directly from the volcanic edifices and deposited directly over paleo seafloor surfaces as spill-over volcanic bodies or accumulations (Figure 11).

Well-constrained stratigraphic correlations between sedimentary deposition and volcanism are still to be done in the area so that timing and/or duration of long-term volcanic activities or episodic volcanic events could be defined and dated. Unfortunately, to our knowledge, there is not any well drilled around seamounts that could have sampled those volcanic layers; thus, precise dating seems now impossible. Nonetheless, our seismic interpretation shows that, across the same individual edifice, volcanic spill-over units may be interbedded with marine sedimentary units, and along variable stratigraphic levels (Figure 12). Hence, the NBR and the FNR volcanic ridges are the result of recurrent volcanism that occurred and persisted through time (Figure 12). In this study, we did not observed any layered volcanic deposits spreading directly over the present seafloor.

Understanding and defining if recurrent volcanism that formed segments of the NBR and the FNR occurred as episodic or long-term volcanic processes is far beyond the analytical possibilities of the database available for this study. However, the thick volcanic wedges overlain by thick onlapping sediment units, observed through seismic interpretation, point to processes of volcanic spill-over concerning one sole volcanic wedge that may have lasted, or may have been recurrent, for thousands or even millions of years (Figure 10).

Although the origin and ages of volcanism related to the NBR and the FNR are still a matter of debate (*e.g.*, Cordani, 1970; Hayes and Ewing, 1970; Le Pichon and Hayes, 1971; Bryan et al., 1973; Gorini, 1977; Houtz et al., 1977; Teixeira et al., 1978; Braga et al., 1981, Guimarães et al., 1982; O'Connor and Duncan, 1990; Fodor et al., 1998; Fodor et al., 2002; Almeida, 2012), the fact that recurrent volcanism (i) occurs attached to distinct volcanic edifices along apparently correlatable stratigraphic levels and that (ii) they may correspond to 'coeveal" volcanic spill-over units at different positions along the NBR and the FNR segments (Figure 12) would favor the hypothesis that the ridge volcanism could have resulted from leaking transform faults or leaking fracture zones, due to recurrent shifts in the pole of rotation between the African and South American plates, as originally put forward by Le Pichon and Hayes (1971). However, different authors consider that mantle decompression alone would not be able to explain huge volumes of magmatic material (*e.g.,* White, 1992; Turner et al., 1996; Hensen et al., 2019; Niu, 2021), as those able to build large volcanic edifices that may rise as high as 1,200 - 4,550 m above seafloor, as seen along

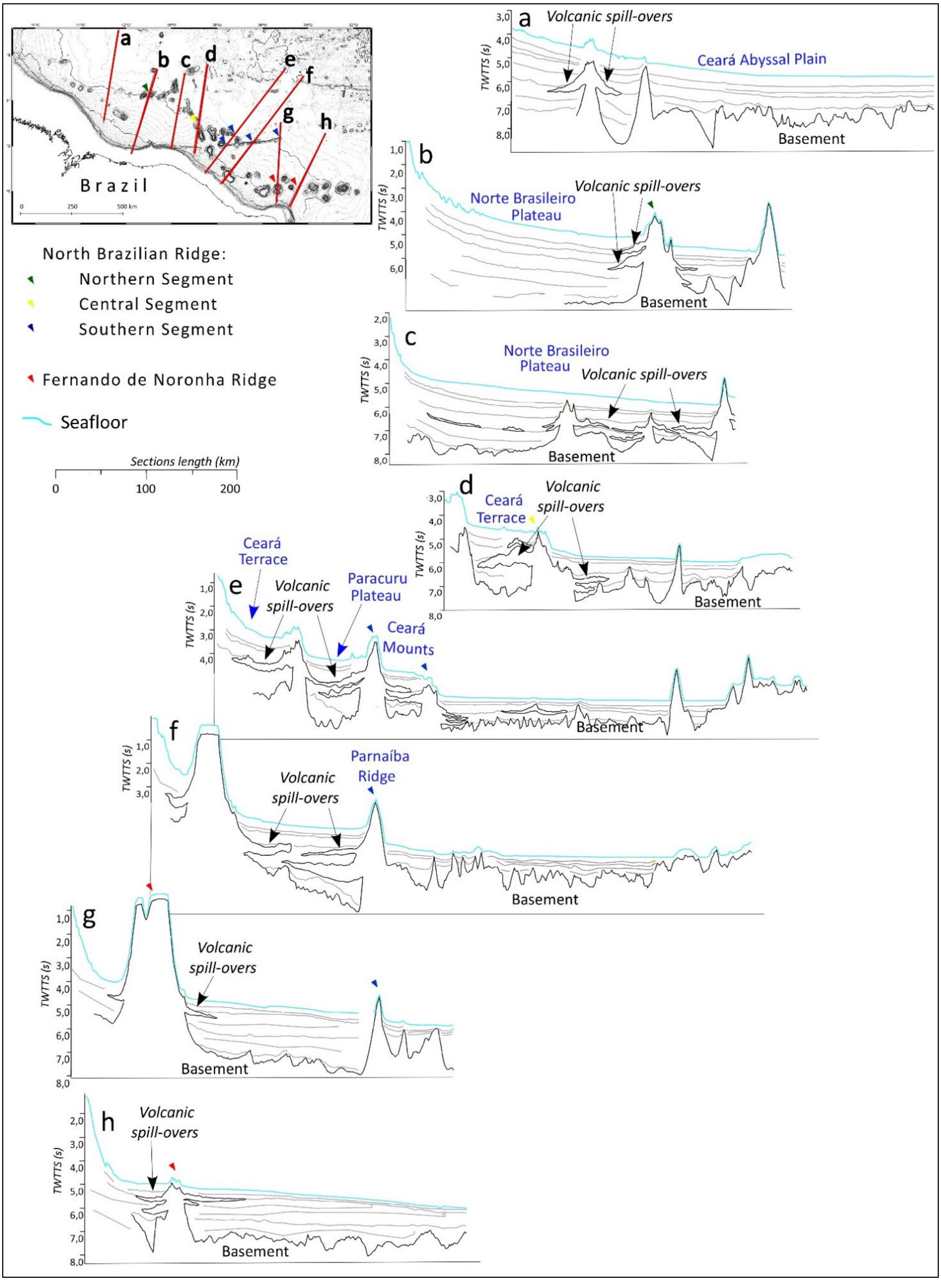

Figure 12: Line drawings of interpreted LEPLAC seismic lines, showing the complex configuration of buried portions of seamounts and guyots in the form of peculiar "Christmas pine trees", indicating a recurrent volcanism all along the North Brazilian and the Fernando de Noronha volcanic ridges, Brazilian Equatorial Atlantic Ocean.

the NBR and the FNR (Figure 5). In such a context, the hotspot hypothesis (*e.g.,* O'Connor and Duncan, 1990) is not at all to be excluded in order to explain the evolution of the NBR and the FNR. Nonetheless, our depth-to-basement maps in 2D and 3D perspectives (Figure 8) revealed that individual seamounts of both the NBR and the FNR are actually interconnected along a basal and continuous rampart-like volcanic ridge (Figures 5 and 6). This continuous basal volcanic ridge is clearly capable of segmenting the crust in several compartment sectors (Figure 8A). We thus interpret this basal volcanic rampart aligned with major transform fault systems as being a probable indication of the onset of a continuous proto ridge, developed in response to leaking transform faults or leaking fracture zones, due to shifts in the pole of rotation between the African and South American plates. In the context, the Parnaíba Ridge (Figures 6, 7C and 8A) could be interpreted as an example close to the volcanic feature configuration of a proto ridge development, which still stands today on the bathymetry as a clue to understand an initial phase of the NBR and the FNR volcanic evolution.

CONCLUSIONS AND CONSIDERATIONS

The seismic stratigraphic work carried out in this study reveals for the first time outstanding features associated to the North Brazilian Ridge (NBR) and the Fernando de Noronha Ridge (FNR): volcanic wedges attached laterally to buried portions of volcanic edifices that compose the NBR and the FNR were interpreted as volcanic spill-over bodies sourced directly from individual volcanic edifices that, interbedded with marine sediment layers or sequences, result in volcanic edifices characterized by a complex morphology in the form of "Christmas pine trees". Such morphological configuration attests to volcanic ridges as the result of recurrent volcanism that occurred and persisted through time. However, many questions related to recurrent volcanism along the NBR and the FNR ridges still remain opened:

(i) depth-to-basement maps revealed that individual seamounts of both the NBR and the FNR are actually interconnected as continuous volcanic ridges in depth, composing rampart-like features of thousands of kilometers long, that can rise as high as ~5.0 s (twtt) above the regional depth-to-basement map (Figure 8B). Continuous high relief ridges extending for thousands of kilometers long clearly seem capable of segmenting the deep oceanic basins, or margin domains of continental-oceanic crust, thus capable of controlling sediment dispersal as well as depocenters locations;

(ii) volcanic wedges attached to distinct volcanic edifices occur along apparently correlatable stratigraphic levels, pointing to the possibility of recurrent volcanism being active during the same time interval at different distant points of the NBR and the FNR. Direct dating of buried volcanic wedges is now impossible, but chronostratigraphic correlations of the basin sedimentary infilling from well data (now under way by our research group) may bring some time constraint to volcanic recurrences.

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