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Morphotectonic development of the Ceará Terrace: a marginal ridge on the western side of the Romanche Fracture Zone in the Brazilian Equatorial Margin

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Abstract

The evolution of a rifted and sheared continental margin may control the formation of marginal ridges, which are prominent morphostructural features located at the extremities of fracture zones. We investigate the Ceará Terrace, a marginal ridge located at the western limit of the Romanche Fracture Zone in the Brazilian Equatorial Margin. Our data consist of 2000 km of 2D seismic lines parallel and orthogonal to the continental equatorial margin, as well as four exploratory wells. The Ceará Terrace has an evolution similar to that of the Ivory Coast-Ghana Ridge, the corresponding conjugate end of the Romanche Fracture Zone in the western African continental margin. The Ceará Terrace surface morphology displays an asymmetric ridge; the north slope is aligned to the Romanche Fracture Zone, related to a bathymetric step at ~ 850 m. The paleo relief represents a ridge consisting of a rift sequence (Lower Cretaceous) that is similar to the Ivory Coast-Ghana Ridge. This ridge is bounded by two half-grabens to the southeast associated with the reactivation of preexisting tectonic weakness zones related to the Precambrian Transbrasiliano Lineament. This structure was buried by a drift sequence, which comprises three sedimentary units: Unit 1, shale; unit 2, limestone that interfingers with shale and sandstone; and unit 3, limestone and shale. The fossil ridge is located near a seamount associated with important Oligocene volcanic units. Both conjugate marginal ridges were formed by a Late Albian to Cenomanian transpressional event (marked by folds and tectonic uplift) and flexural uplift due to erosion and thermal exchanges with oceanic spreading centers. Differences in the amplitude of uplift are related to the thermal influences of the distinct oceanic spreading centers. Furthermore, the results indicate that the studied area is still tectonically active.

Introduction

The breakup of West Gondwana and the consequent separation of the South American and African continents formed two main diachronic segments with distinct characteristics (Szatmari et al. 1987; Matos 2000; Nemčok et al. 2013): the southern segment, which evolved as a typical rifted margin, and the equatorial segment, which evolved as a passive transform margin dominated by shear movements (Manscle and Blarez 1987; Matos 2000).

In the equatorial margin, the evolution of the transform margin involved four phases (Manscle and Blarez 1987; Boillot and Coulon 1998). During phase 1 (Fig. 1(C)), shear movement formed pull-apart basins and caused the rotation of crustal blocks. In phase 2 (Fig. 1(D)), divergent margins developed due to crustal thinning and rifting. Small divergent basins were created on both sides of the principal fracture zones, where the rates of sedimentation and subsidence were high (Manscle and Blarez 1987). Faults, folds, and uplifts in the new sedimentary cover occurred along the main fracture. At the extreme ends of these fracture zones, marginal ridges developed in both divergent basins. Phase 3 (Fig. 1(E)) marked the end of the active contact between the continental crusts; sedimentary deformation ceased, and a tectonic unconformity was generated (Manscle and Blarez 1987). The contact of the thicker continental crust with the thinner new oceanic crust resulted in a topographic step that generated a flexural uplift (Basile and Allemand 2002). The upwelling of the

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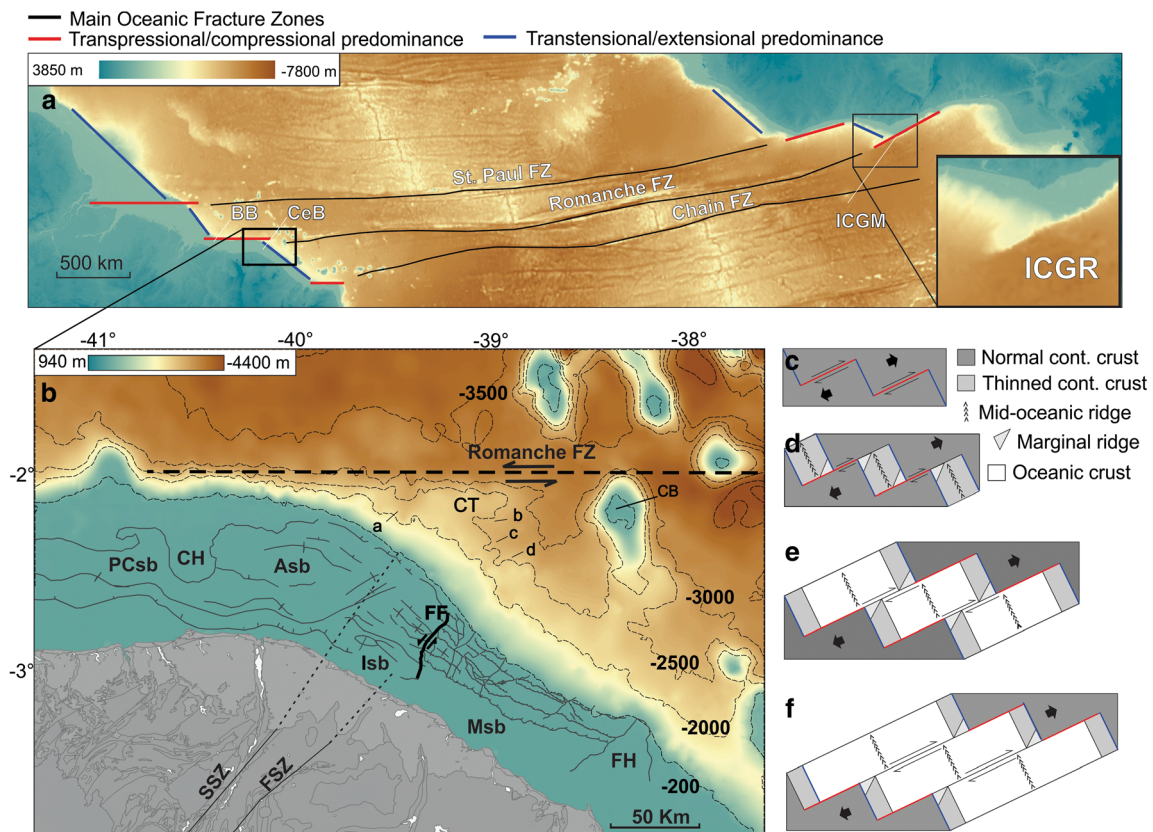
Fig. 1 (A) General Bathymetric Chart of the Oceans (2014). BB, Barreirinhas Basin; CeB, Ceará Basin; ICGM, Ivory-Coast Ghana Margin. ICGR, Ivory-Coast Ghana Ridge. (B) Ceará Basin. Sub-basins: Piauí-Camocim (PCSb), Acaraú (ASb), Icaraí (ISb), and Mundaú (MSb). Submarine canyons: a to d. Structural framework compilation from Antunes et al. (2008) and Costa et al.(1990). Bathymetry curve lines from the CPRM data bank and grid from the General Bathymetric Chart of the Oceans, 2014. SSZ, Sobral-Pedro II shear zone, FSZ, Forquilha shear zone, CT, Ceará Terrace, CB, Canopus Bank, CH, Ceará High, FH, Fortaleza High. (D to G) Phases 1 to 4 of the evolution of transform margins. Adapted from Manscle and Blarez 1987

oceanic lithosphere with the occurrence of a contact between the new and old continental crusts, where temperature exchange occurred, resulted in the uplift of the transform margin. In phase 4 (Fig. 1(F)), the transform movements were restricted to the oceanic crusts, and the margin evolved in a pattern similar to those of the divergent margins. The passage of the spreading center through the transform margin led to thermal exchange, which increased the uplift in the marginal ridge (Sage et al. 2000; Antobreh et al. 2009). In these models, marginal ridges are predicted to occur between fracture zones (Manscle and Blarez 1987; Basile and Allemand 2002; Attoh et al. 2004; Kearey et al. 2013); however, the evolutions of these ridges remain under debate.

The Ivory Coast-Ghana Ridge, which is located at the east end of the Romanche Fracture Zone, is the most-studied marginal ridge of the Equatorial Atlantic Margin (Fig. 1(A)) (e.g., Antobreh et al. 2009; Kearey et al. 2013). Several studies have discussed the evolution of the Ivory Coast-Ghana Ridge (Manscle and Blarez 1987; Basile et al. 1993; Pletsch et al. 2001; Attoh et al. 2005; Antobreh et al. 2009; Nemčok et al. 2013). The evolution of this ridge included a transpressional tectonic influence in the Late Albian-Cenomanian (Attoh et al.

2005), flexural uplift (Basile and Allemand 2002), and thermal influences due to the passage of the oceanic spreading center (Pletsch et al. 2001; Antobreh et al. 2009). Additionally, a survey of the Ocean Drilling Program (ODP Leg 159; Pletsch et al. 2001) included wells that reached Lower Cretaceous sediments and provided new insights into the uplift age and evolution of the Ivory Coast-Ghana Ridge (Pletsch et al. 2001; Attoh et al. 2004; Antobreh et al. 2009). However, little is known about the marginal ridges in the conjugate Brazilian margin.

The present study investigates the characteristics and evolution of a Brazilian marginal ridge, defined as the Ceará Terrace (CT in Fig. 1(B)), which is equivalent to its African counterpart. We use a set of 2D multichannel reflection seismic lines and wells to characterize the seismic stratigraphy and morphotectonic setting of the marginal ridge to understand the morphosedimentary response to the margin evolution. The aim of this work is to understand the driving mechanism of the formation of the Ceará Terrace through plate reconstruction, thus confirming the emersion of a marginal ridge in the evolutionary model of passive transform margins proposed by Manscle and Blarez (1987).

Geologic settings

The Ceará Terrace is located in the deep-water region of the Ceará Basin in the Brazilian Equatorial Margin, at the west end of the Romanche Fracture Zone (Fig. 1(A), (B)). The Romanche Fracture Zone limits to the north the E-W segments of the Ceará and Barreirinhas Basins in the Brazilian Equatorial Margin (Fig. 1(A)). In the African margin, the Romanche Fracture Zone limits to the south the Ivory Coast Ghana Margin (Fig. 1(A)). The Romanche Fracture Zone, including both margins, is approximately 5000 km long and has the largest mid-ocean ridge offset in the Atlantic (Fig. 1(A)).

Based on its distinct tectonic characteristics and structural features, the Ceará Basin has been segmented into four sub-basins, namely, Piauí-Camocim (PCSb), Acaraú (ASb), Icaraí (ISb), and Mundaú (MSb) (Fig. 1(B)) (Bizzi et al. 2003). The three first sub-basins (PCSb, ASb, and ISb) are located at the prolongation of the Romanche Fracture Zone and were consequently strongly deformed by a transpressional regime, which was characterized by the widespread development of shear zones and inversion tectonic structures (Costa et al. 1990; Zalan et al. 1985). The inversion of a transtensional to a transpressional regime in these basins probably occurred in the Late Albian-Cenomanian (Zalan et al. 1985; Davison et al. 2016) and generated folds, thrust faults, and depocenter inversion (Zalan et al. 1985; Castro 1992; Bizzi et al. 2003). Transtensional tectonics predominated in the Mundaú Basin (Matos 2000; Zalan 2012), which is dominated by NE-SW-striking oblique normal faults (Antunes et al. 2008) located to the south of the Romanche Fracture Zone.

The segmentation of the Ceará Basin was also influenced by the Transbrasiliano Lineament, a megashear zone that was generated in the Brazilian-Pan-African orogeny (740-560 Ma; Brito Neves et al. 2014). This lineament crosses the South American plate from northeastern Brazil down to Paraguay and Argentina (Cordani et al. 2013; De Castro et al. 2014) and extends to Africa from Togo to Algeria (Caby 1989; Cordani et al. 2013). The Sobral-Pedro II shear zone (SSZ) is considered to represent the onshore northeast extension of the Transbrasiliano Lineament in the Ceará Basin (Fig. 1(B)). The offshore prolongation of the SSZ delimits the Acaraú and Icaraí sub-basins as an anticlinal form in the continental shelf (Fig. 1(B)) (Zalan et al. 1985; Costa et al. 1990; Bizzi et al. 2003). The Icaraí and Mundaú sub-basins are separated by the Forquilha Fault (FF in Fig. 1(B)), an offshore reactivation of the Forquilha shear zone (FSZ) that is also associated with the Transbrasiliano Lineament and the Sobral-Pedro II shear zone, which have the same ages and orientations (Cunha 2007).

Three major tectono-stratigraphic sequences characterize the Ceará Basin. The syn-rift sequence (Mundaú Formation) consists of continental sediments deposited during the Aptian (Costa et al. 1990; Condé et al. 2007), which comprise conglomerates, sandstones, siltstones, and shales interspersed with gravitational flow deposits. The Paracuru Formation is a transitional sequence deposited between the rift stage and the wrench stage (Zalan 2012), representing the first marine transgression in the basin, which comprises variable-granulation sandstones interfingered with shale layers. This unit was initially accepted as being a post-rift sequence deposited in sag basin geometry; however, new studies demonstrated that the Paracuru sequence developed along growth faults (Morais Neto et al. 2003). The Ubarana Formation comprises all of the marine sedimentation in the basin and is considered a drift sequence (Condé et al. 2007).

Volcanic activity occurred in the Ceará Basin during the drift stage, which generated large seamounts. The principal volcanic activity had an alkaline nature and occurred in the Eocene and Oligocene. This volcanism is represented by the intrusive and extrusive basaltic and dolerite bodies observed in some exploratory wells (Condé et al. 2007). The Canopus Bank (CB in Fig. 1(B)), Ceará High, and Ceará Plateau are seamounts related to these volcanic events, which were associated with a hotspot (Mizusaki et al. 2002).

Seismic and well data

The dataset used in this study comprises multichannel reflection seismic and exploratory well data obtained from the deep-water region of the Ceará Basin (Fig. 2). These data were acquired by PETROBRAS in 2009 and were supplied by the Brazilian agency of oil, gas and biofuels (ANP). The seismic data consist of approximately 2000 km of conventional 2D post-stack seismic lines, with a sample interval of 4.0 ms and a maximum time record range of 8.0 s (TWT). These data were spatially distributed in 6 lines parallel to the continental margin (P1 to P6), spaced roughly 5.0 to 8.0 km apart, and in 15 lines transversal to the continental margin (T1 to T15), spaced roughly 7.0 to 15 km apart (Fig. 2). The 2D post-stack seismic data were provided with a standard processing flow (e.g., migrated post-stack).

We used OpenDetect 7.0 software for the seismic-borehole correlation and seismostratigraphic analysis. The interpretation of the seismic data was conducted in time scale due to the lack seismic velocity data information. Hence, the well data were converted to time scale using the sonic log acquired in each borehole. The interpretations were based on seismic patterns such as seismic terminations, seismic facies, and seismic units (Mitchum et al. 1977; Catuneanu 2006). We mapped the most significant reflectors, in terms of continuity and amplitude, which present chronological meaning. Structural features were mapped based on recognition of lateral reflector disruptions.

Four wells were used for the stratigraphic correlation with the seismic sections (Fig. 2). At a depth of 3723 m below the seafloor, the borehole BRAS1080 ((b) in Fig. 2) is the deepest
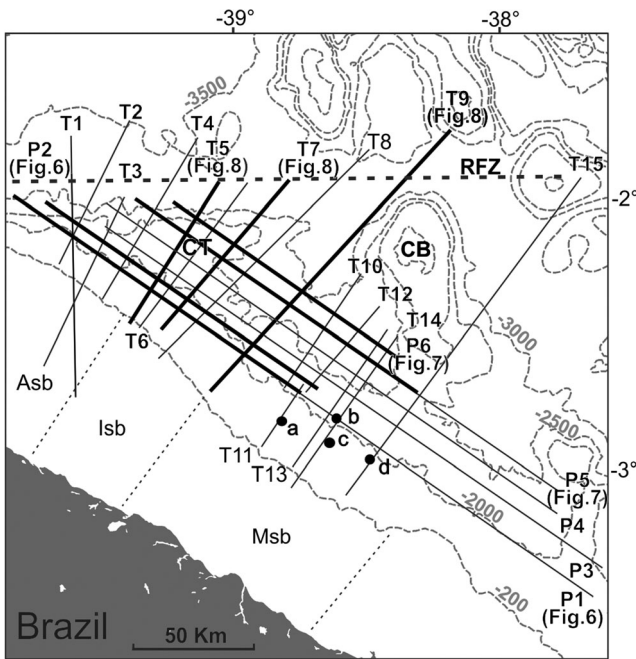
Fig. 2 Seismic lines (black lines). Wells (red dots): a, BRAS1150; b, BRAS1080; c, CES0112; c, CES111B. Highlighted segments are displayed in Figs. 4 and 5

drilled well; it reaches a depth of ~ 1250 m within the Mundaú Formation (Fig. 3). This borehole intercepts the seismic line P1 at a water depth of 2000 m (Figs. 2 and 3). The other three

boreholes are located in the lower continental slope at a water depth of 1500 m and have offsets in the seismic lines of less than 1000 m (BRAS1150 and CES0111B, (a) and (d) in Fig. 2) and 2500 m (CES0112, (c) in Fig. 2). Boreholes BRAS1150 and CES0111B have an average depth of 2500 m, but they do not reach the Mundaú Formation. These wells were tied to the seismic lines T11 and T15, respectively (Fig. 2). The CES0112 borehole also reaches the Mundaú Formation, with a depth of 2760 m, and it was tied to the seismic line T4 (Fig. 2). The boundary between the Paracuru and Ubarana formations was recognized in all wells, which was correlated with a high-amplitude reflector in all seismic lines. None of the boreholes reached the acoustic basement.

Additionally, we created 3D morphological models of the interpreted horizons, especially the top of the Paracuru Formation, which is a prominent reflector in our seismic data and is the most significant horizon identified in the Ceará Terrace. The coordinates and depths (in two-way travel time) of this horizon were extracted from each seismic line and interpolated to a 3×3-km grid using the kriging method in Oasis Montaj software. Moreover, the top of the boundary of the Mundaú and Paracuru formations is not visible in our data, probably due to the limits of the seismic resolution and penetration. Thus, the Mundaú Formation (continental sequence) and Paracuru Formation (transitional sequence) were entered
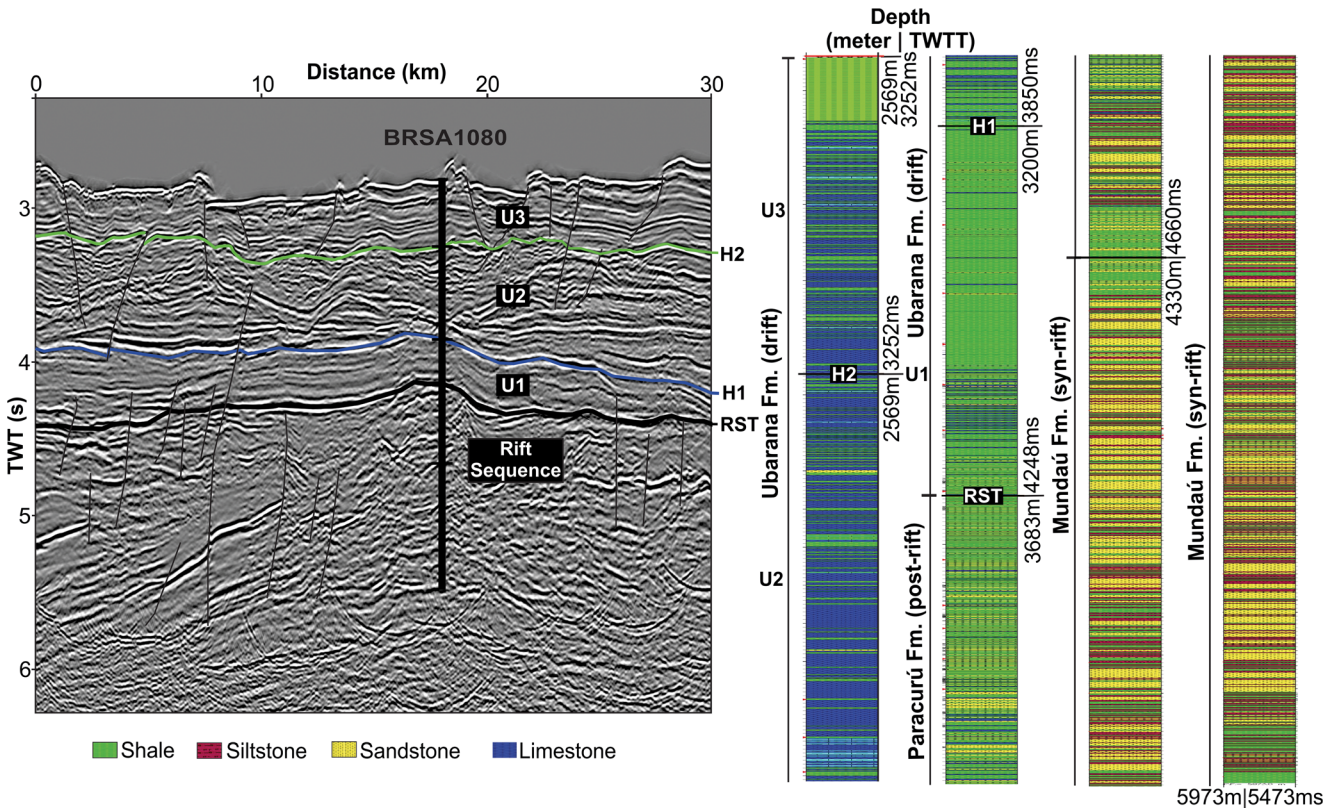

Fig. 3 Stratigraphic correlations based on the BRSA1080 well log. See Fig. 2 for location

as a unique rift sequence due to the lack of a reference reflector and the Paracuru Formation tectonic characteristics.

Results

Seismic stratigraphy

The sedimentary units of the deep-water Ceará Basin comprise two major sedimentary sequences separated by a regional unconformity. This unconformity is represented by a high-amplitude and very continuous reflector observed in all seismic lines (Figs. 3, 4, 5, 6, 7, and 8). Well data show that this unconformity is the boundary between the Paracuru and Ubarana formations, which can clearly be observed in the BRAS1080 well and is located at the seismic line P1 (RST in Fig. 3). This horizon represents the top of the rift sequence (RST in Fig. 3) and marks the uplifted morphology of a fossil ridge (3D surface in Fig. 5). However, the boundary surface between the Mundaú and Paracuru formations is not as evident or uninterrupted in the seismic sections (Fig. 3). Therefore, for the purposes of our study, these mega-

sequences may be divided into the rift sequence, which comprises the Mundaú and the Paracuru formations, and the drift sequence, which comprises the Ubarana Formation (shales and carbonates).

The rift sequence displays subparallel to wavy and discontinuous reflectors with moderate amplitudes (Fig. 4). Hence, the units on the rift sequence are not clearly distinguished, especially close to the Romanche Fracture Zone, where the seismic patterns of the sedimentary layers change to semi-chaotic seismic patterns. In this region, the strike-slip movements along the Romanche shear zone generated a dense strike-slip fault complex (Figs. 4, 6(a), (d), and 7(a), (c)).

The sedimentary deposits of the drift sequence are composed of three units: U1, U2, and U3 (Figs. 3 and 4). Unit U1 mainly consists of shale (Fig. 3) and displays a parallel seismic pattern with high-continuity reflectors exhibiting the lowest amplitudes (Fig. 4). This unit was mainly deposited in the deep areas in the southeastern part of the studied region, confined between the continental slope and the fossil ridge (Figs. 6, 7, and 8). Although unit U1 is part of the Ubarana Formation (drift sequence), it fills the three half-grabens of the rift sequence in a syn-tectonic process (Figs. 5 and 6); these

Units	Location			Canyons Influence	
	Fossil Ridge		Divergent Segment		
U3		Parallel pattern with varying amplitude	Not change		Inclined and descontinuos reflectors
U2		Prograding facies with high amplitude		Semi-parallel reflectors with high amplitude	Inclined and descontinuos reflectors
U1		Inclined parallel reflectors with low amplitude		Plane parallel reflectors with low amplitude	None

	Romanche shear zone		Fossil Ridge and Divergent Segment	
Rift Sequence		Semi-chaotic pattern due dense strike-slip faults set		Subparallel to undulate and disrupted reflectors with medium amplitude

Magmatism					
Shallow boundary (U3 unit)		Deep boundary		Gas percolation	
	Reflector separate chaotic to parallel patterns		Gradually change between parallel to chaotic patterns		Vertical structure banding top reflectors

Fig. 4 Seismic patterns correlated with the depositional units and magmatic features

Fig. 5 Map of the top of the rift sequence in two-way travel time (3 × 3 km grid) displaying a fossil ridge and Canopus Bank (CB) boundaries based on the mapping of seismic reflectors
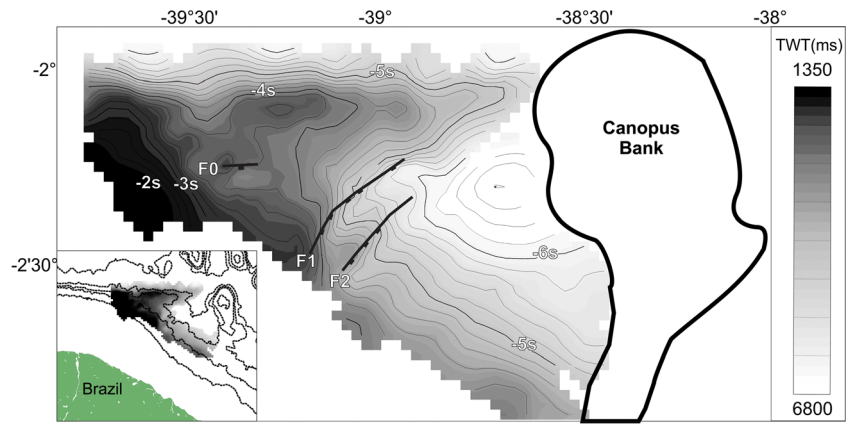
half-grabens are associated with a reactivation event and may be related to a second rift phase. In the proximal lines (P1 and P2 in Fig. 2), the average thickness is ~ 0.5 s and gradually increases seawards, reaching a thickness up to 1.0 s (Fig. 6(a),
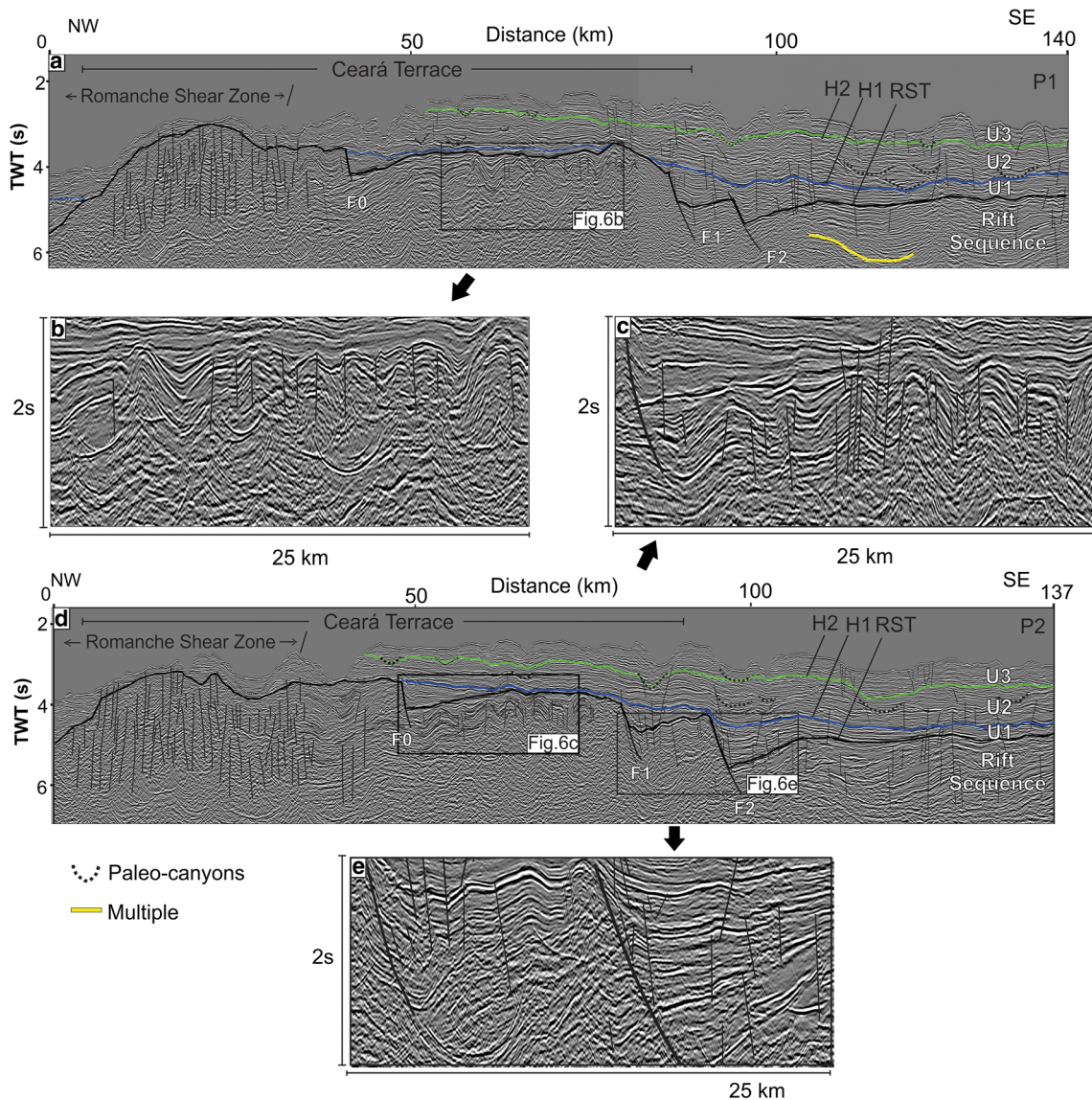

Fig. 6 Seismic lines P1 and P2 parallel to the coastline. Romanche Fracture Zone (RFZ): region affected by RFZ shear movements and thermal exchange. Location in Fig. 2
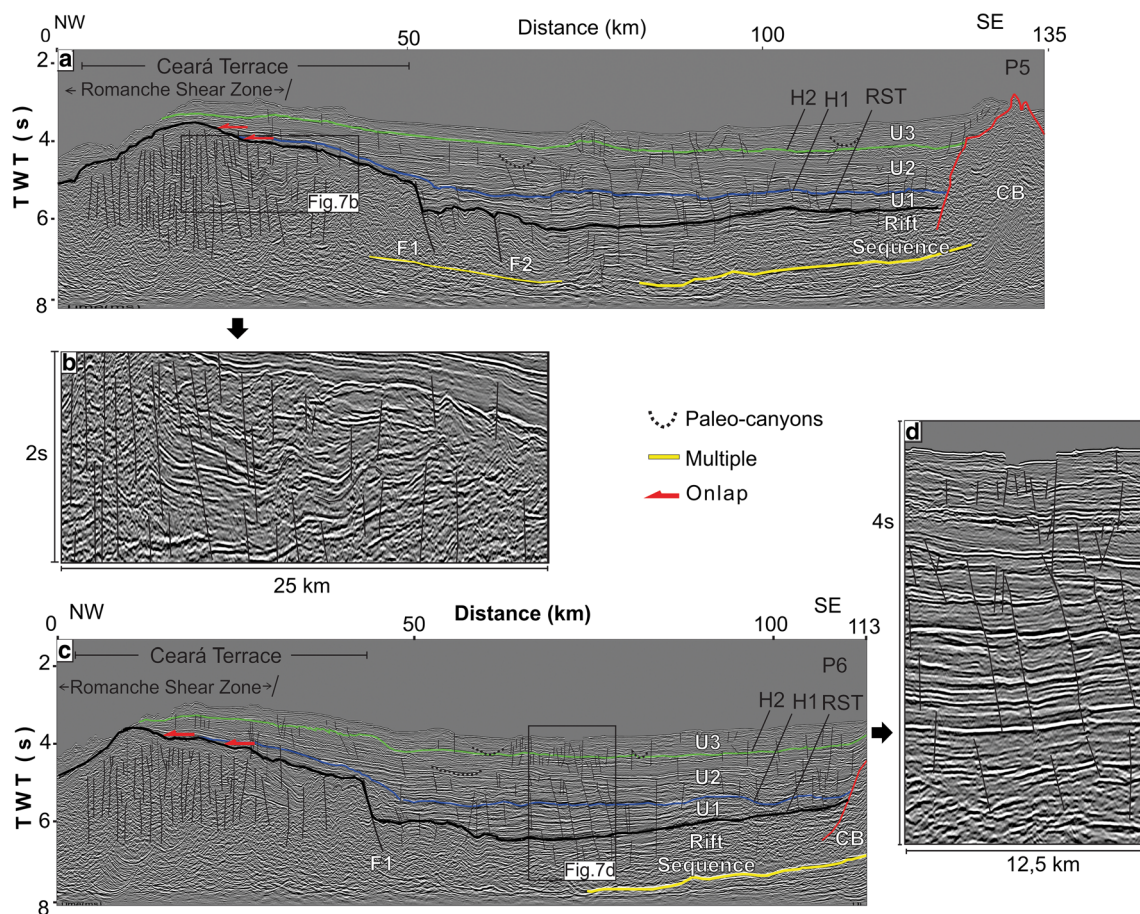
Fig. 7 Seismic lines P5 and P6 parallel to the coastline. Romanche Fracture Zone (RFZ): region affected by RFZ shear movements and thermal exchange. CB, Canopus Bank. Location in Fig. 2

(d), (g), and (h)). A thin, 0.2-s-thick layer of unit U1 covers a portion of the fossil ridge and is concordant to the top of the rift sequence (RST horizon in Figs. 6 and 7), onlapping onto the ridge flanks. The top horizon of this unit onlaps over the fossil ridge to the northwest and terminates to the southeast at the Canopus Bank (H1 in Fig. 6). This horizon is very clear due to the contrast between seismic patterns and indicates the end of the half-grabens main activity.

Unit U2 presents a semi-parallel seismic facies with low continuity (Fig. 4). This unit predominantly contains carbonate rocks that interfinger with shale and sparse thin sandstone layers. Unit U2 presents buried submarine canyons and slump deposits in proximal areas, which generate great variations in thickness, inclined reflectors, and sparse chaotic patterns. The horizon on the top displays moderate continuity (H2 in Figs. 6 and 7) and is slightly concordant locally, whereas it is frequently cut by submarine canyons and affected by fault reactivation. In distal areas, this unit overlays the fossil ridge, where clinoforms occur associated with inclined depositional surfaces (Fig. 4). Moreover, the reflectors are plane-parallel and exhibit a consistent aggradation pattern of deposition in a distal area of the fossil ridge (Figs. 4 and 7(a), (c)).

Unit U3 displays an abrupt contact with the volcanic body of the Canopus Bank (Fig. 4), which implies that it was deposited after a magmatic event occurred in the region. Horizon H2 was mapped as a reflector well concordant with the top of the magmatic body. This unit displays mainly plane-parallel seismic patterns with lateral variations between low- to moderate-amplitude signals. However, similar to unit U2 in the proximal area, unit U3 presents several submarine canyons (dotted lines in Figs. 4, 6, and 7). Unit U3 also exhibits a decrease in carbonates and an increase in clay sediments (Fig. 3).

The volcanic body of the Canopus Bank was mapped in the subsurface using the boundary between semi-parallel seismic patterns of the drift sedimentary cover onlapping on the volcanic complex that displays an internal chaotic pattern (Fig. 4). At depth, the boundary between the sedimentary layers and the Canopus Bank is gradual due to thermal influences (Fig. 4). Moreover, volcanic activity generated chimney structures, which may be related to gas exhumation or dike intrusions (Fig. 4).

Geomorphology of the Ceará Terrace

The modern relief of the Ceará Terrace displays an asymmetric ridge between depths of 2000 and 3500 m. This structure
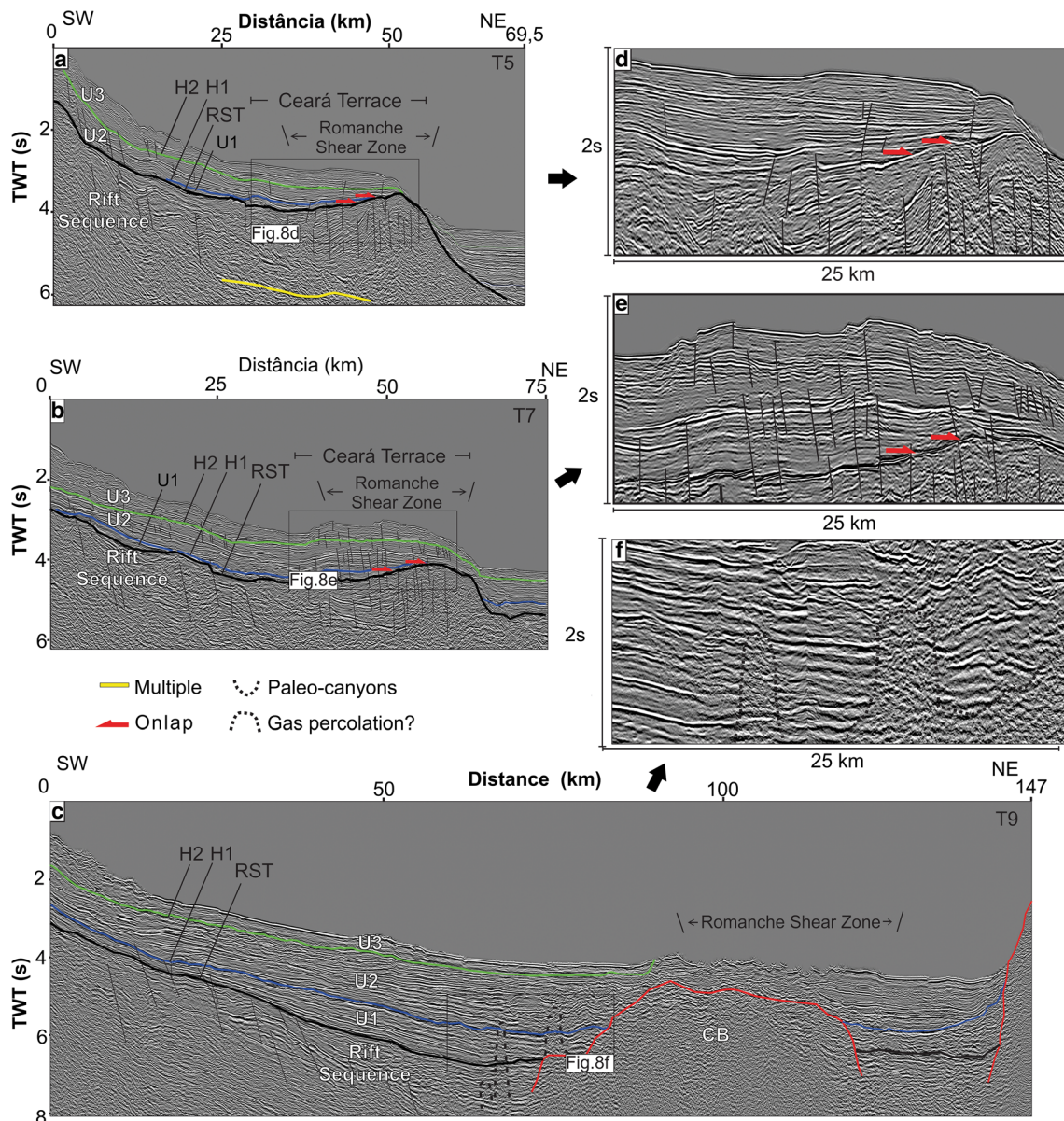
Fig. 8 Seismic lines T5, T7, and T9 transversal to the coastline. Location in Fig. 2

represents the boundary of the divergent segment and the transform segment of the margin, which is bounded to the north by the Romanche Fracture Zone (Fig. 1(B)). The contact between the Ceará Terrace and the Romanche Fracture Zone is approximately 100 km long, and it forms an accentuated slope with a bathymetric step of greater than 850 m. This E-W-trending slope represents an extension of the continental slope (Fig. 1(B)). The southern and southeastern slopes of the Ceará Terrace have gentle gradients, which gradually deepen towards the Mundaú Basin as far as the Canopus Bank. The continental slope of the Ceará Basin is the northeastern limit of the Ceará Terrace.

Submarine canyons cut the shelf edge, the continental slope, and the Ceará Terrace in different directions ((a), (b), (c), and (d) in Fig. 1(B)). The regional bathymetry

and the first reflector of seismic data revealed the presence of two large canyons that are more than 5 km wide. The N-S-trending canyon cuts across the Romanche Fracture Zone, and the ENE-WSW-trending canyon is almost parallel to the Romanche Fracture Zone ((a) and (b) in Fig. 1(B)). Two other large submarine canyons, which are ~ 5 km wide and ~ 400 m deep, occur at the shelf edge of the Icaraí Basin ((c) and (d) in Fig. 1(B)). These canyons define the southeastern limit of the Ceará Terrace and are aligned with its major faults F1 and F2 (Fig. 1(B); F1 and F2 in Fig. 6(a), (d)). Several minor-scale submarine canyons were recognized only through the first reflection of the seismic profiles (P1 and P2 in Fig. 6(a), (d)). These canyons are abundant on the continental slope and on the edges of the Ceará Terrace.

The subsurface morphology of the Ceará Terrace is represented by the horizon of the rift sequence top (RST in Fig. 3; colored surface in Fig. 5). This morphology exhibits strong concordance to the Ceará Terrace seafloor expression, which is consistent with the fact that the sedimentary deposition of the drift sequence is coeval to the fossil marginal ridge. The relief of the buried ridge varies from approximately 5.0 s in the southern limit of the Ceará Terrace to less than 4.0 s close to the Romance Fracture Zone (Fig. 5). Similar to the modern relief of the Ceará Terrace, the fossil ridge is bounded by the continental slope in the northwestern region of the study area and by the Romanche Fracture Zone in the northern region of the study area (Fig. 5). The southeastern boundary is defined by two half-grabens (F1 and F2 in Fig. 5). The topographic depressions generated by the half-grabens and the faults probably controlled the canyon development. The fossil ridge was buried by units U1 and U2, where it is possible to recognize the onlap terminations near the Romanche Fracture Zone (Figs. 7(a), (c), and 8(g), (h)). Furthermore, the concordance of the spatial limits of the Ceará Terrace on the seafloor surface and the buried fossil ridge in the subsurface strongly supports the long-term depositional processes associated with F1 and F2 reactivation and the uplift process.

Submarine canyons appear widespread on the Ceará Terrace, cutting mainly the top of unit U3 (the local the seafloor). Moreover, many canyons may occur inside units U2 and U3. On the uplifted area of the marginal ridge, aside from the fracture zone, the canyons incised through the entire drift sequence, reaching and exposing the top of the rift sequence (northwestern part of profiles P1 and P2 in Fig. 6(a), (d)). The strong erosion and consequent canyon widespread distribution may be associated with events of exhumation of the drift units related to faults observed in the ridge area. Furthermore, the main structures (e.g., F1 and F2 in Fig. 6) controlled the major canyon development since rifting till affected modern seafloor expression.

Tectonic framework

The most prominent tectonic structures displayed in the seismic lines are two half-grabens associated with extensive faults (F1 and F2 in Figs. 5 and 6). The half-graben faults strike NE-SW and dip to the SE. These structures are linear features parallel to the Transbrasiliano Lineament (SSZ and FSZ in Fig. 1(B)) in the continent, suggesting that these faults could reflect the brittle reactivation of these ductile shear zones. These structures affected the rift sequence, generated steps almost half a second high, and created morphological constraints to unit U1 deposition (Figs. 5, 6(a), (d), and 7(a), (c)). Therefore, the reactivation event may have been associated with a second rift event.

The seismic sections display another half-graben northwest of the NE-SW-trending half-grabens, with a significant

displacement of 0.2 s in the base of the continental slope (F0 in Figs. 5 and 6(a), (d)). This structure was only recognized in two lines (P1 and P2 in Fig. 5) and is controlled by an E-W-oriented fault, dipping to the S (Fig. 6(a), (d)).

The F1 fault was mapped for approximately 35 km along the entire set of seismic sections (F1 in Figs. 6 and 7). This fault bounds a half-graben from line P1 to line P6 (Figs. 6 and 7). Unit U1 caps the half-graben associated with this fault (Figs. 6(a), (d), and 7(a), (c)). This unit presents variations in thickness across F1, indicating that it is a growth fault. Above the F1 fault, unit U1 presents a chaotic pattern (seismic lines P5 and P6 in Fig. 7(a), (c)), which may reflect the result of the reactivation of the fault after the deposition of unit U1. This reactivation could be associated with the subsidence of the divergent margin segment.

The F2 fault is displayed in seismic lines P1 to P5 (Figs. 6(a) and 7(a)) and is ~ 30 km long. In seismic lines P1 and P2, this fault has a displacement of more than 0.5 s (Fig. 6(a), (d)). However, in seismic line P5, it represents a subvertical structure that has a small offset but exhibits significant discontinuity in its seismic reflections (F2 in P5 in Fig. 7(a)). The geometry of this fault suggests an oblique fault and shear movement. The interpretation of the F2 fault in seismic line P6 is not obvious due to the lower seismic resolution and the great depth of investigation in this seismic line. Notably, the F2 fault is well aligned with the Forquilha strike-slip shear zone (FSZ) in the continental shelf (Fig. 1(B)).

Another set of normal faults can be observed in the seismic lines transversal to the continental margin (T5, T7, and T9 in Fig. 8(a), (b), and (c)). These faults are NW-SE-striking and dip to the NE. The orientation and dip of these faults indicate that their generation was related to the normal faults of the Mundaú Basin in the shelf border (Fig. 1(B)). Thus, this set of faults is related to the rift phase of the basin and its possible reactivation during subsidence.

A dense set of strike-slip faults is located in the Romanche Fracture Zone (RFZ region in Figs. 4, 6(a), (d), and 7(a), (c)). These faults are apparently deep-seated in the basement and are practically restrict to the rift sequence. However, despite the difficult recognition due to the local erosive characteristics (i.e., several submarine canyons and paleo-canyons), faults cross the top of the rift sequence affecting the drift sequence (Figs. 6, 7, and 8).

Folds and complex compressional features were recognized only in the northeastern part of the study area, extending approximately 100 km within the syn-rift unit between the Romanche Fracture Zone and F2 faults (Figs. 6(a), (d) and 7(a), (c)). Seismic lines P1 and P2 display folds between the chaotic seismic facies, which were affected by a set of normal faults (Fig. 6(a–d)). The throw of the F2 fault decreases towards offshore, and the terminations of the F1 and F2 faults and this fault approximate to the fracture zone bounding and narrowing the fossil ridge (approximately 60 km wide) at the

northeast of the Ceará Terrace (P5 and P6 in Fig. 7(a), (c)). These complex folds were only observed in the seismic lines parallel to the continental margin. Although it is not possible to correlate the fold axes in two or more seismic lines, it is reasonable to infer approximately the NE-SW directions of these axes. These folds are restricted to the rift sequence of the fossil ridge, and there are no records of similar compressional structures in the deposits of the drift sequence; therefore, they were formed prior to the deposition of the drift sequence.

A complex set of fault geometries cuts across all units of the drift sequence (Figs. 6, 7, and 8). In the seismic lines transversal to the shelf edge, in the vicinity of the Romanche Fracture Zone (Fig. 8(a), (b), (d) and (e)), the faults present subvertical geometries and minimum displacement (Fig. 8(e)). In these lines, normal faults were recognized in the continental slope (T5 and T7 in Fig. 8(a), (b)). Faults with *en echelon* geometry occur in distal regions (P6 in Fig. 7(c), (d)), which are commonly related to transtensional tectonics. In the drift sequence, these faults affected and controlled the morphology of the seafloor. The active canyons on the seafloor and buried paleo-canyons in the drift sequence are clearly constrained by the faults mapped in the seismic lines (Fig. 6(a), (d)). In the distal region, without the presence of canyons, the faults directly affected the seafloor, generating the discontinuities shown in lines P6 and T5 (Figs. 7(c), (d), (b) and 8(e)). The presence of these faults represents evidence of Cenozoic neotectonic activity in the Ceará Terrace area. Additionally, their geometry and proximity to the fracture zone suggest that the transform activity affected all the drift units during the Cenozoic.

Magmatism

The bathymetric expressions of the volcanic bodies are nearly concentric and aligned in the SSW direction (Fig. 1(B)). The most prominent volcanic body is the Canopus Bank. Seismic data indicate that the small seamounts in the southern portion of the Canopus Bank (Fig. 1(B)) represent the broad extension of a unique volcanic body in the subsurface (Fig. 5). Seismic profiles display large regions dominated by volcanic features, which were mapped based on the transition from the plane-parallel seismic facies to the chaotic facies (Fig. 4). Vertical structures with chaotic seismic facies, which are associated with magmatic units, were recognized in the drift sequence (Figs. 4, and 8(c), (f)). These features are related to dike and sill intrusions represented by the vertical to subvertical chaotic seismic facies (Figs. 4 and 8(f)). Other vertical structures cut across the sediment layers and form small domes. These structures are associated with the gas exhumation generated by the thermal effects of volcanic intrusions (Fig. 4).

The CS0111B well, which is located on the tail of the Canopus Bank ((d) in Fig. 2), shows layers of the basalt and dolerite of the Macau Formation (Oligocene) within the marine shales of the Ubarana Formation. We associate these dikes and sills with other volcanic structures identified in other seismic lines and interpret them as belonging to the same Macau Formation (Figs. 7(a), (c) and 8(c)). However, it is possible to recognize a dolerite layer above the basalt in the CS0111B well, indicating that more than one magmatic event occurred. The volcanic bodies affected most of the layers of units U1 and U2 of the drift sequence (Figs. 7(a), (c) and 8(c)). However, abrupt oblique reflectors indicate that the deposition of unit U3 occurred after the magmatic event. These volcanic bodies cut across the ~ 1.0-s-TWT-thick sediment layers in line P2 to the 0.5-s-TWT-thick layers in P5, which represent Oligocene to Holocene sedimentary deposits (Figs. 6(d) and 7(a)).

Discussion

The fossil ridge composed of the rift sequence, its internal geometry, and spatial location with respect to the Romanche Fracture Zone and the continental margin indicates that the Ceará Terrace represents a marginal ridge developed in the evolutionary setting of a transform margin. The marginal ridge in the Brazilian Equatorial Margin represents the conjugate structure of the Ivory-Ghana ridge in west Africa. They were both developed in the context of the Romanche Fracture Zone.

There is a remarkable morpho-stratigraphic resemblance between the Ceará Terrace and the Ivory Coast-Ghana Ridge (ICGR; Figs. 1(A) and 9). First, seismic data reveal fossil marginal ridges in both tips of the Romanche Fracture Zone, whose top is represented by a high-amplitude reflector. The scientific drilling campaign of the Ocean Drilling Program in the Ivory-Cost Ghana Margin (ODP Leg 159) showed that this unconformity occurs atop a sedimentary layer deposited during the Lower Cretaceous, which mainly comprises sandstones of the syn-rift sequence. Similarly, the analysis of boreholes in the Ceará Terrace indicates that the lithology of the fossil ridge comprises Lower Cretaceous sedimentary rocks of the rift sequence.

Although the ODP 159 Leg boreholes did not reach the basement, seismic data indicate that the basement is located close to the unconformity (Pletsch et al. 2001; Nemčok et al. 2013). The boreholes in the Brazilian margin also did not reach the basement. In contrast to its African counterpart, the rift sequence in the Brazilian margin is more than 1500 m thick (Fig. 3). This thicker sedimentary sequence can be explained by the higher rates of sedimentation and subsidence in the small, new basins (Manscle and Blarez 1987) generated at both ends of the Romanche Fracture Zone in the Lower Cretaceous. The arched relief of the fossil ridge is associated with uplift due to the transpressional characteristics of the fracture zone, flexural uplift, the passage of the ocean

Fig. 9 Comparison between the marginal ridges through seismic lines in the Ivory Coast Ghana Ridge (left; source, Blarez and Mascle 1988) and in the Ceará Terrace (right; P6 line)
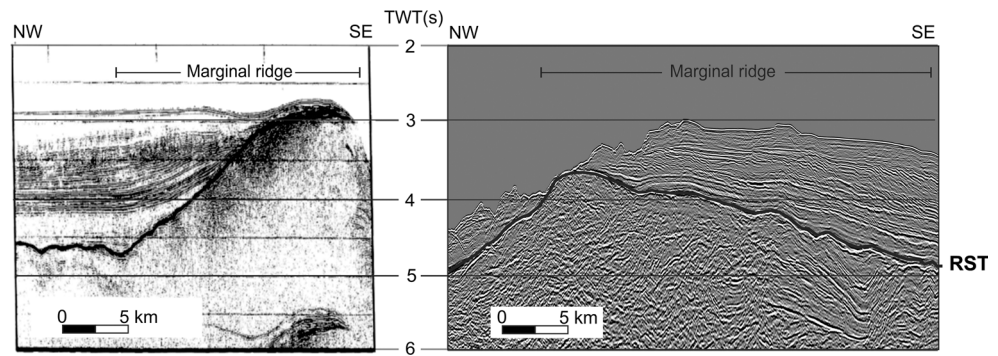
spreading center, and erosion during three stages of the evolution of the margin.

Continent-continent shear stage

The presence of folds in the rift sequence in the continental slope indicates that a compressional regime affected the Ceará Terrace. When both the African and South American continental crusts were in contact, the Romanche shear zone was active and generated syn-sedimentary compressional deformation (Fig. 10(a); Zalan et al. 1985; Manscle and Blarez 1987; Davison et al. 2016). Several studies have suggested that the uplift in the Ivory Coast-Ghana Ridge started at this time (Manscle and Blarez 1987; Pletsch et al. 2001; Attoh et al. 2004; Nemčok et al. 2013). Although some studies have proposed that uplift occurred due to thermal exchange during the passage of the spreading center through the marginal ridges, the tectonic unconformity in the Lower Cretaceous

Fig. 10 Evolutionary model of the Ceará Terrace. (a) Transpression generating folds and reactivation of the Transbrasiliano Lineament during the Late Albian to Cenomanian. (b) Erosion and flexural uplift during the Turonian to Coniacian. (c) Thermal uplift during the Santonian to Campanian. (d) Emersion of the Canopus Bank (CB)

layers formed on top of the fossil ridge before thermal exchange, indicating that uplift predated thermal exchange (Attoh et al. 2004).

The set of strike-slip faults in the Romanche Fracture Zone probably contributes to the uplift in the northwestern portion of the Ceará Terrace. The restriction of most faults to the rift sequence indicates its origin during the continent-continent shear stage. Similar fault sets were recognized in transform boundary of the Exmouth Plateau (Lorenzo et al. 1991). The compressional regime in the Romanche Fracture Zone was related to changes in the plate movement vectors of the South American and African continents in the Late Albian (Zalan et al. 1985; Azevedo 1991). This shift in plate movement generated transpressional stress during the Late Albian to Cenomanian in a large area close to the main shear zone of the Romanche Fracture Zone, which was 500 km long and 50 km wide (Davison et al. 2016), and it may have affected other oceanic fracture zones (Dailly 2000). In the Brazilian Equatorial Margin, this transpressional regime generated uplift, regional erosion, and folds in the Barrerinhas, Piauí-Camocim, Icaraí, and Acaraú Basins (Zalan et al. 1985; Azevedo 1991; Castro 1992; Davison et al. 2016). In the African margin, the same event also generated uplift, regional erosion, and folds (Attoh et al. 2004). Furthermore, the folds in the Ceará Terrace exhibit axes trending ~NE-SW, which are consistent with the NW-SE-oriented main compressional stress during the transpressional tectonic phase in the Romanche Fracture Zone (Davison et al. 2016). Therefore, we suggest that the onsets of the uplifts of both the Ceará Terrace and Ivory Coast-Ghana Ridge were synchronous during this transpressional event (Fig. 10(a)).

The seismic data reveal two NE-SW-striking faults (F1 and F2 in Fig. 6), which can be related to the preexisting tectonic fabric. The changes in the plate movement vectors in the Late Albian probably led to the reactivation of the shear zones of the Brasiliano-Pan African orogeny (Destro et al. 1994) (Fig. 10(a)). Studies of the northeastern part of the Transbrasiliano Lineament have indicated that the dextral reactivation of faults occurred during this period (Destro et al. 1994). Therefore, we also suggest that these changes in plate movement reactivated weakness zones, such as the
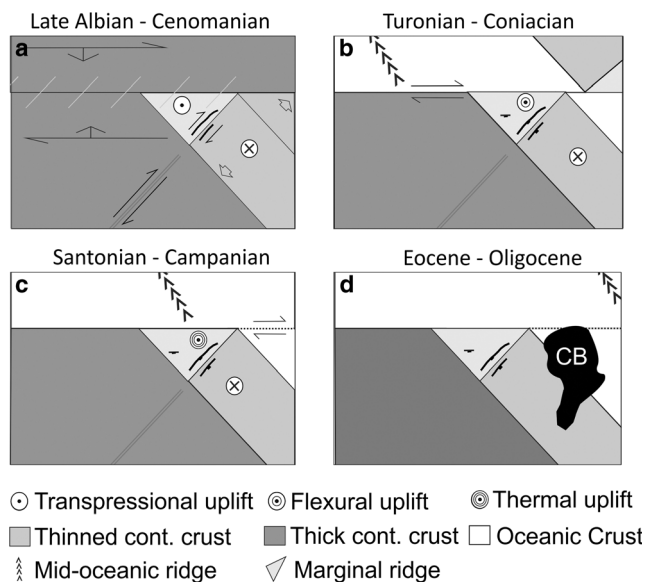
Transbrasiliano Lineament, and affected the Ceará Terrace, generating the NE-SW-striking faults (Fig. 10(a)). This can be observed in the seismic sections (P1, P2, P5, and P6 in Figs. 6(a), (d) and 7(a), (c)), in which the faults in the continent are aligned with the Transbrasiliano Lineament.

The results show that the compressional structures of the rift sequence are limited to the northwestern part of the F2 fault in the Ceará Terrace (Figs. 6(a), (d), and 7(a), (c)). This indicates that shear movement limited the transpressional environment in the Ceará Terrace in the Late Albian-Cenomanian in the transform segment margin basins (Barreirinhas, Piauí-Camocim, Acaraú, and Icaraí) to the transtensional tectonics in the divergent segment of the Mundaú Basin (Fig. 1(B)) along the Forquilha Fault. A compilation of structural data in the equatorial margin (Davison et al. 2016) shows that the compressional features in the continental shelf are concentrated to the northwest of the Forquilha Fault, corroborating this hypothesis. Additionally, previous studies of the Mundaú Basin provide evidence of a tectonic event generating normal/oblique faults that mainly affected the Paracuru and Mundaú formations (Antunes et al. 2008). These characteristics were not recognized in the Ivory Coast-Ghana Ridge, which appears not to have been influenced by preexisting structures due to its location on the West African Craton. The prolongation of the Transbrasiliano Lineament in the African continent, i.e., the Kandi Lineament, is located more than 300 km east of the ridge (Caby 1989; de Castro et al. 2011).

Oceanic-continent shear stage

The seismic and well data in the Brazilian margin indicate an unconformity related to strong erosion on top of the rift sequence that generated a high-amplitude reflector, which is cut by rift faults. A coeval erosional event was also recognized in the Ivory Coast-Ghana Ridge (Manscle and Blarez 1987; Basile et al. 1993; Antobreh et al. 2009). Erosion started in the Ceará Terrace during the Cenomanian due to tectonic uplift when the continents were together. Thus, in the Turonian, the separation of the continental crusts and the end of the active boundary between the plates led to the formation of a high topographic step between the thick continental crust and the new thin oceanic crust (Basile and Allemand 2002). From the Turonian to the Coniacian, the topographic step was eroded, shaping the marginal ridges and followed by a new phase of uplift due flexural compensation (Fig. 10(b); Basile and Allemand 2002). In general, flexural uplift is no more than 55% of the step height for subaerial cases (Basile and Allemand 2002). Therefore, the total uplift generated by flexural compensation in Ceará Terrace is less than 0.5 km, which is approximately 55% of the estimated step height.

This erosional event generated a tectonic unconformity that may be related to the post-breakup unconformity of divergent rifted margins (Manscle and Blarez 1987). Most likely, the resulting tectonic unconformity occurred synchronously in both marginal ridges, as they represented the last contact of the South American and African continental crusts and probably interacted with each other. This hypothesis is corroborated by the location of this unconformity within sedimentary layers of the same age in both marginal ridges.

During the oceanic-continent shear stage, both marginal ridges were subjected to thermal exchanges from Santorian to Campanian, amplifying the uplift (Fig. 10(c)). Models of uplift due to thermal conduction and viscous coupling predict uplifts of approximately 0.5 to 1.0 km (Vågnes 1997). The exact time of the passage of the spreading centers through the marginal ridges is not well known due to the lack of magnetic data during the Cretaceous Quiet Magnetic Zone (Zalan et al. 1985). However, studies of thermal exchange in the Ivory Coast-Ghana transform margin indicate a possible Santorian to Campanian time (Sage et al. 2000; Nemčok et al. 2013).

The uplift amplitude differed between the Ceará Terrace and the Ivory Coast-Ghana Ridge (Fig. 9) because each marginal ridge was subjected to thermal exchange with different spreading centers. To the south of the Romanche Fracture Zone, close to the Ghana margin, oceanic fracture ridges were recognized (Edwards et al. 1997), indicating the complex geometry of the spreading centers. Furthermore, the structural interpretation of the transform boundary geometry in the Ivory-Cost Ghana Margin suggests the existence of two spreading centers affecting the African margin (Antobreh et al. 2009). On the other hand, to the north of the Romanche Fracture Zone, only one spreading center affecting the Brazilian Equatorial Margin was identified, which may explain the lower uplift amplitude in the Ceará Terrace.

During this time, the formation of the half-grabens balanced the uplift of the Ceará Terrace with the subsidence of the Mundaú Basin, which limited the fossil ridge. The deposition of unit U1 probably started during the flexural uplift concentrated in the deepest regions of the Ceará Basin (Figs. 6(a), (d) and 7(a), (c)). This unit is part of the Ubarana Formation, classified as a drift sequence due to its marine sedimentation. However, the drift stage started after the passage of the ocean spreading center and unit U1 deposition during the ocean-continent shear stage. Additionally, results indicate that U1 filled the half-grabens, as seen in the seismic lines (Figs. 6(a), (d), 7(a), and 7). Therefore, this unit may be associated with a syn-rift II sequence. In the Ceará Terrace, the uplift was followed by the deposition of unit U2, which caped the fossil ridge, as indicated by onlap terminations and sigmoidal patterns (Figs. 7(a), (d) and 8(d), (e)).

Drift stage

During the drift stage of the equatorial margin, magmatic events occurred in the Paleogene period (Fig. 10(d)).

Magmatic association with transform margin evolution has been reported in other studies (Lorenzo et al. 1991; Lorenzo 1997; Berndt et al. 2001). However, the ages of the volcanic rocks in the Ceará Basin range from Eocene (44 My) close to the Ceará High to Oligocene (32 My) close to the Fortaleza High (Fig. 1(B); Almeida et al. 1988; Mizusaki et al. 2002; Condé et al. 2007) associated with the drift stage. Close to the Canopus Bank, well data show intercalations of magmatic rocks in the drift sequence, associated with Macau magmatism. Therefore, we theorize that the Canopus Bank volcanic body emerged in the Neo-Oligocene synchronously with an important pulse of Macau magmatism. However, the CS0111B well reveals dolerite in the upper sedimentary layers above basaltic rocks, indicating that the Canopus Bank was formed by more than one magmatic event. Most likely, these magmatic events are correlated with Cenozoic tectonic activity in deep-water regions. These magmatic events generated chimney structures and semi-chaotic patterns from the rift sequence to unit U2. The younger unit U3 was probably deposited after the formation of the Canopus Bank due to the lack of these structures and the abrupt boundary between the volcanic body and this unit.

Furthermore, the presence of faults in all units of the drift sequence indicates that tectonic activity occurred during the Cenozoic and may have occurred in all evolutionary stages of the Ceará Basin. The normal faults in the slope are related to the gravitational effects of the margin. On the other hand, the *en echelon* faults are related to transtensional tectonism. In addition, the concentration of faults affecting the drift sequence in the vicinity of the Romanche Fracture Zone in lines T5 and T7 (Fig. 8(a), (b)) and the few strike-slip faults that cross the top of the rift sequence are probably related to the shear movement of the Fracture Zone and suggest that this structure is still active. However, the wide variety of the faults in this sequence implies complex tectonic activity.

The faults in the drift sequence play an important role in the morphology of the seafloor. The topographic depressions generated by these faults are conduits of gravitational flux from the continental slope and the incised canyons. Where there are no submarine canyons, these faults generate discontinuities and directly affect the seafloor. The faults' activity in Romanche shear zone that affected the drift sequence possibly contributed to the strong erosion in the northwestern region. This demonstrates that this portion of the continental margin is still tectonically active.

Conclusions

The Ceará Terrace is the first marginal ridge recognized in the Brazilian Equatorial Margin, which was predicted in evolutionary models of transform margins. The remarkable resemblance of the Ceará Terrace to the Ivory Coast Ghana Ridge helps reveal its tectonic evolution. The uplift of both marginal ridges started during the Late Albian to Cenomanian transpression in the Romanche Fracture Zone; their acoustic basements comprise Cretaceous sedimentary layers. The differences in the uplift amplitudes of both marginal ridges can be related to their interactions with different spreading centers during the drift stage.

The reactivation of basement fabrics is indicated by the alignment of normal faults mapped in the Ceará Terrace with the Precambrian Transbrasiliano shear zone. The fault reactivation that occurred in the Late Albian is most likely related to the same change in plate movement that apparently separated the transform margin segment in the western side of the study area from the divergent margin segment in the eastern side of the study area. The faults evolved to half-grabens balanced the uplift at NW region with the subsidence in SE region and may be associated with a rift II phase.

Furthermore, evidence of Cenozoic tectonic activity is recorded in the drift sequence, which displays faults associated with shear movements. During the Paleogene, magmatic events occurred, generating large seamounts and the Canopus Bank close to the Ceará Terrace, which may be associated with Cenozoic tectonic activity in the region. The faults in the drift sequence display *en echelon* geometry and are associated with shear movements and were probably controlled by the crustal heritage of the Transbrasiliano Lineament and the Romanche Fracture Zone. These faults control the morphology of the seafloor, where submarine canyons are located.

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