Quaternary Research 82 (2014) 462–472

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Neotectonic evolution of the Brazilian northeastern continental margin based on sedimentary facies and ichnology☆,☆☆

Rosana Gandini [a,*], Dilce de Fátima Rossetti [b], Renata Guimarães Netto [c], Francisco Hilário Rego Bezerra [d], Ana Maria Góes [a]

[a] Institute of Geosciences, University of São Paulo—USP, São Paulo, SP, Brazil
[b] Division of Remote Sensing, Brazilian National Institute for Space Research—INPE, São José dos Campos, SP, Brazil
[c] Graduate School of Geology, University of Rio dos Sinos—UNISINOS, São Leopoldo, RS, Brazil
[d] Departament of Geology, Federal University of Rio Grande do Norte—UFRN, Natal, Brazil

ARTICLE INFO

Article history:
Received 6 December 2013
Available online 12 August 2014

Keywords:
Ichnology
Thalassinoides
Quaternary
South American passive margin
Tectonic reactivation

ABSTRACT

Quaternary post-Barreiras sediments are widespread along Brazil's passive margin. These deposits are well exposed in the onshore Paraíba Basin, which is one of the rift basins formed during the Pangean continental breakup. In this area, the post-Barreiras sediments consist of sandstones with abundant soft-sediment deformation structures related to seismicity contemporaneous with deposition. The trace fossils *Thalassinoides* and *Psilonichnus* are found up to 38 m above modern sea level in sandstones dated between 60.0 (±1.4) and 15.1 (±1.8) ka. The integration of ichnological and sedimentary facies suggests nearshore paleoenvironments. Such deposits could not be related to eustatic sea-level rise, as this time coincides with the last glaciation. Hence, an uplift of 0.63 mm/yr, or 1.97 mm/yr if sea level was 80 m lower in the last glaciation, would have been required to ascend the post-Barreiras sediments several meters above the present-day sea level during the last 60 ka. This would suggest that the post-rift stage of the South American eastern passive margin may have experienced tectonic reactivation more intense than generally recognized. Although more complete data are still needed, the information presented herein may play an important role in studies aiming to decipher the Quaternary evolution of this passive margin.

Introduction

Neogene and Quaternary deposits are geographically widespread along the northern and northeastern continental passive margins of Brazil, where they occur as thin sedimentary successions known as the Barreiras Formation (Miocene) and post-Barreiras sediments (late Quaternary) (Rossetti et al., 2012). The latter deposits, initially included in the Barreiras Formation, have been the focus of increasing scientific interest, given their importance for reconstructing the tectono-sedimentary evolution of the Brazilian continental margin (Bezerra et al., 2008; Rossetti et al., 2011a, b, 2012; Balsamo et al., 2013). Despite this relevance, the post-Barreiras sediments remain poorly known. For instance, details of the depositional environments have not been presented, which is partly due to their overall massive sandy nature. In general, these strata have been more commonly attributed to aeolian environments (Rossetti et al., 2001). However, most of these deposits are poorly sorted and highly bioturbated, which do not conform to deposition entirely by aeolian processes. It is probable that the post-Barreiras sediments include deposits formed in a wide variety of environments, which remain to be characterized in detail (Rossetti et al., 2011a,b).

The post-Barreiras sediments are particularly well represented in outcrops of the Paraíba Basin, an area of the northeastern Brazilian continental margin formed during the breakup of Pangea (Matos, 1992). In this region, such deposits contain an abundance of soft-sediment deformation structures related to tectonic activity contemporaneous with or shortly after deposition (Rossetti et al., 2011b). Rossetti et al. (2011b) attributed the post-Barreiras sediments exposed in the Paraíba Basin to intense seismic activity related to late Quaternary tectonic reactivation. This would have created space to accommodate sedimentation in areas that previously experienced long-term erosion. However, Rossetti et al. (2011b) focused solely on the description and interpretation of deformation structures, and questions remain about the environmental context in which these seismites were formed. There is no paleoenvironmental information concerning these deposits beyond a succinct reference to nearshore trace fossils made by Rossetti et al. (2011b).

☆ RRH: Neotectonic Evolution of the Brazilian Continental Margin.
☆☆ LRH: GANDINI et al.
* Corresponding author.
E-mail addresses: gandini.rosana@usp.br (R. Gandini), rossetti@dsr.inpe.br (D.F. Rossetti), nettorg@unisinos.br (R.G. Netto), bezerrafh@geologia.ufrn.br (F.H.R. Bezerra), goes@igc.usp.br (A.M. Góes).

http://dx.doi.org/10.1016/j.yqres.2014.07.003
0033-5894/

Although not investigated in detail, previous publications recorded highly bioturbated beds in the post-Barreiras sediments of Paraíba Basin (Rossetti et al., 2011a, b, 2012). Considering the generally scarce presence of physical sedimentary structures, trace fossils might be an important proxy to clarify the sedimentary environments of this unit, and discern its evolution within the context of sea-level fluctuations. Additionally, because these deposits contain seismites, they have the potential to help characterize tectonic events during the last stages of development of the Brazilian continental margin. This issue has been of increasing interest for investigation because, as opposed to the generally accepted model of post-rift stable passive margins, numerous studies have demonstrated that this region of Brazil recorded significant tectonic activity during the Neogene, which seems to have continued even into the Holocene (Bezerra and Vita-Finzi, 2000; Bezerra et al., 2008; Ferreira et al., 2008; Moura-Lima et al., 2011; Rossetti et al., 2011a, b, 2012; Balsamo et al., 2013). The precise timing and intensity of these events, however, are questions that remain to be answered.

Geological framework

The Paraíba Basin is the last marginal rift formed during the opening of the South Atlantic Ocean in Late Jurassic and Early Cretaceous time (Matos, 1992). Granite, migmatite and gneiss belonging to the Precambrian Borborema Province form the basement of this basin, which is

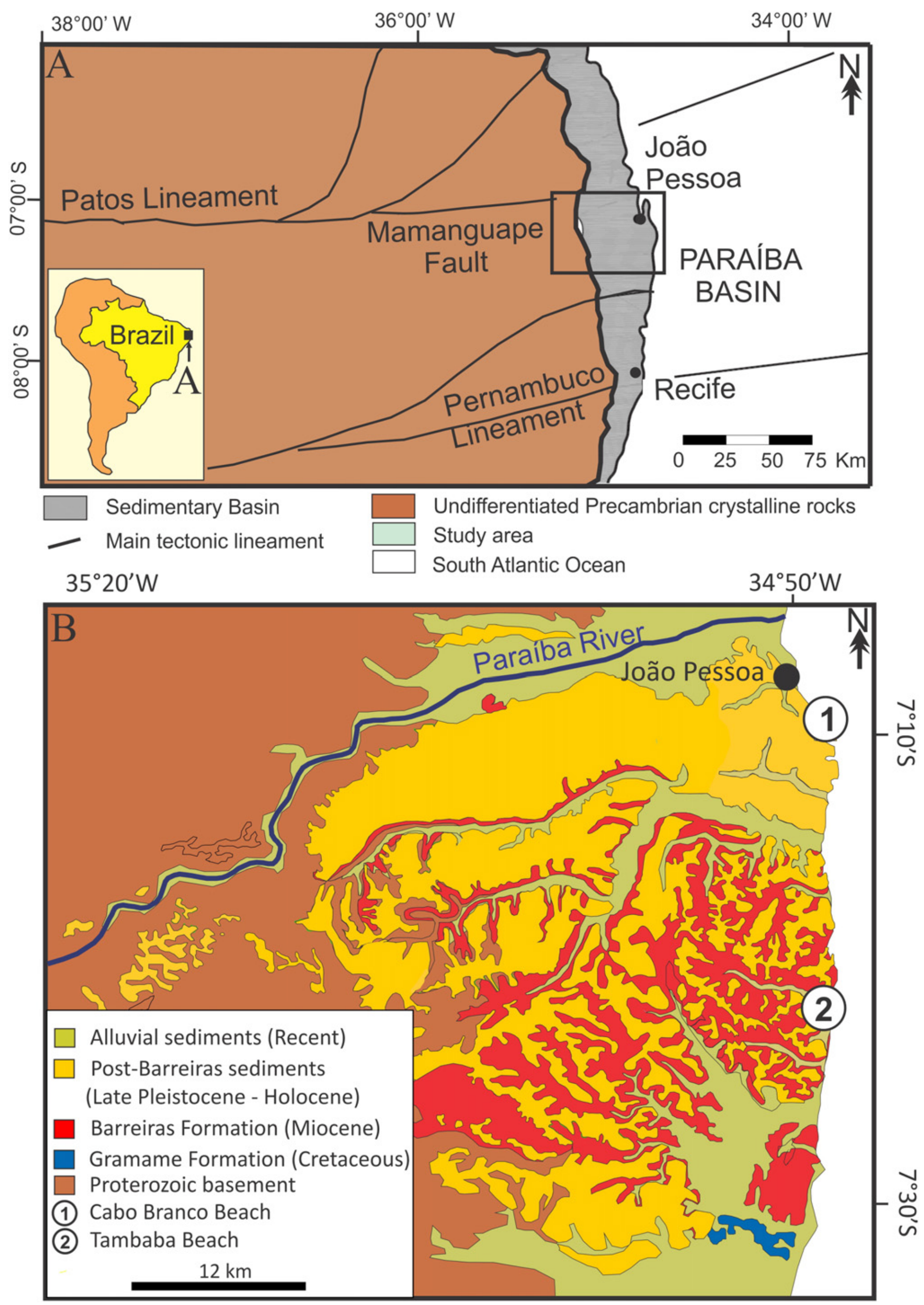

Figure 1. Location map of the study area in northeastern Brazil. A) Generalized geological map with location of the study area in the Paraíba Basin, between the Mamanguape and the Pernambuco tectonic lineaments. Box locates the study area. B) Detailed geological map with location of the studied sections (modified from Rossetti et al., 2011a).

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press

bounded by the Pernambuco Lineament to the south and Mamanguape Fault to the north (Fig. 1A). Several other faults are present in this basin, and they usually record reactivation of basement structures. Previous publications have documented that faulting continued up to the Neogene and even Quaternary in the Paraíba and other basins of this continental margin (e.g., Bezerra and Vita-Finzi, 2000; Bezerra et al., 2001, 2008; Rossetti et al., 2011a, b).

The sedimentary fill of Paraíba Basin starts with Coniacian–Santonian sandstones of the Beberibe Formation (Beurlen, 1967). These rocks are overlain by calcareous sandstones and siltstones of the Campanian Itamamaracá Formation. Sedimentation continued in the Maastrichtian, with the establishment of a carbonate platform represented by the Gramame Formation. Carbonate sedimentation continued up to the Paleogene, with deposition of the Maria Farinha Formation (Beurlen, 1967). After a prolonged period of subaerial erosion, siliciclastic deposition resumed giving rise to sandstones and mudstones of the Barreiras Formation in the Miocene (Rossetti, 2004). A renewed interval of non-deposition that extended up to the Quaternary resulted in an unconformity marked by a ferruginous lateritic soil horizon at the top of this stratigraphic unit (Rossetti et al., 2012, 2013). Sedimentation returned to the Paraíba Basin only in the late Quaternary, when the post-Barreiras sediments were formed (Rossetti et al., 2011b).

The post-Barreiras sediments, the focus of the present work, are geographically widespread in the central Paraíba Basin (Fig. 1B) and consist mostly of moderate to well-sorted fine- to medium-grained sandstones. These deposits are generally massive or have a variety of ductile and brittle synsedimentary deformation structures related to seismic activity contemporaneous with sediment deposition (Rossetti et al., 2011a, b, 2012). According to Rossetti et al. (2011a, b, 2012), the post-Barreiras sediments also include poorly consolidated or friable, fine-grained, well-sorted sands formed by aeolian processes. In addition, they established late Pleistocene to Holocene ages for the post-Barreiras sediments based on optically stimulated luminescence (OSL) dating.

Material and methods

This study was based on the analysis of two coastal cliffs, one at Cabo Branco Beach (7°8′45″S lat.; 34°58′08″W long.) in the city of João Pessoa, and the other located 30 km south at Tambaba Beach (7°21′57″S; 34°47′59″W) (Fig. 1B). The post-Barreiras sediments are well exposed in these cliffs, where they form a succession up to 15 m thick that unconformably overlies Miocene deposits of the Barreiras Formation. The base of the post-Barreiras sediments is at 12.2 m and 38 m above modern sea level in the Cabo Branco and Tambaba sections, respectively.

The methodological approach consisted of descriptions of sedimentary facies including parameters such as lithology, texture, sedimentary structure, and bed contact. Facies characteristics were documented in the field with the construction of lithostratigraphic profiles and recorded in photographs and photomosaics. This work was complemented by detailed descriptions of trace fossils and ichnofabric. The degree of bioturbation was measured using the method of Reineck (1963). Ichnofabric characterization considered ichnotaxobases (Bromley, 1996), ichnodiversity, burrow size, and inferred ethological patterns.

Sandstone ages were established on the basis of OSL dating of nine samples. Sampling procedure consisted of collecting sediments with 30-cm-long PVC plastic tubes 5 cm in diameter. The tubes, protected in both sides with caps, had no transparency in order to avoid renewed bleaching by sunlight. Samples were collected horizontally at the outcrops, which were previously cleaned from weathered material. The analyses were carried out at the Laboratory of Glasses and Dating of the *Faculdade de Tecnologia de São Paulo*, Brazil (FATEC–SP). OSL analysis of quartz grains was performed using a blue light (470 nm) and detection through a ~5-mm Hoya U-340 filter. OSL ages were based on the standardized growth curve (SGC) method (Roberts and Duller, 2004). For the SGC, the natural luminescence signal (L_n) and laboratory test dose (T_n) were measured. The ratio of both signals (L_n/T_n) was multiplied by the size of the test dose applied ($L_n/T_n \times Td$) in order to obtain the standardized OSL signal. In all cases, samples were preheated at 250°C for 10 s prior to measurements and at 200°C for 10 s after the test dose. The same thermal treatments were used during the single aliquot regeneration (SAR) protocol. Eight doses between 10 and 600 Gy were used to build the SGC, with five aliquots measured for each dose. To obtain the convenient equivalent dose (De) a regression curve using the equation $I(OSL) = I_{max}(1 - e^{-D/Do}) + k.D$ was fitted through the data. For calculation of dose rates (D_o), annual doses were calculated using U, Th, and K concentrations. The natural radioactive isotope contents in the samples were determined with gamma spectroscopy using an Inspector portable spectroscopy workstation, lead shield model 727, and a Canberra 802 NaI (TI) detector. Details of the methodology described above are found in Tatumi et al. (2001, 2008). The contributions of cosmic radiation and moisture content were taken into account to calculate the D_o. The contribution of cosmic rays varies according to the depth and geographical position of the sampling site (e.g., Prescott and Hutton, 1994). Hence, these parameters were also included in the calculation. Because interstitial moisture interferes in the radiation dose, the water contents of the samples were taken into account for D_o calculations by applying the appropriate attenuation factor for α, β and δ radiation according to the following equation (Aitken, 1985):

$$D = \frac{D\delta}{1 + 1.14 * F * w1} + \frac{D\beta}{1 + 1.25 * F * w1}$$

Where D = cosmic radiation and w = moisture contribution.

Results

Facies Description

The post-Barreiras sediments in the two studied sections consist chiefly of sandstones, which are described in terms of five facies: bioturbated sandstone/mudstone (facies Bs); massive sandstone (facies Ms); deformed sandstone (facies Ds); quartz and laterite pebble conglomerate (facies Cg); mud pebble conglomerate (facies Ic); and stratified sandstone (facies PCs). All these facies are interbedded and organized into three associations, designated as SH (upper shoreface), FS (foreshore), and AS (aeolian coastal dunes). The sections are pervasively affected by fractures, particularly at Tambaba section. Fracture surfaces are often highlighted by layers of iron oxides and hydroxides up to 5 cm thick.

Facies Association SH (upper shoreface)

This association is present in both of the studied sections. It is composed mostly of bioturbated sandstones/mudstones (Bs) that are alternated with quartz and laterite pebble conglomerate (facies Cg), mud-pebble conglomerate (facies Ic), massive sandstone (facies Ms) and deformed sandstone (facies Ds).

At Tambaba section (Figs. 2–4), facies Bs consists exclusively of a 3-m-thick sandstone package (Fig. 2A,B). Facies characteristics of this section are illustrated in Fig. 2. The corresponding lithostratigraphic profile, paleoenvironmental interpretation, ichnological features and OSL ages are shown in Fig. 3. Facies Bs at this locality consists mostly of very fine- to fine-grained and moderately sorted sandstone that alternates with facies Ms, Ds and Cg (Fig. 2A,B). Facies Ms and Ds consist generally of fine- to medium-grained sandstones with disperse quartz granules, which are either entirely massive or have convolute or contorted beddings, respectively. These facies can also form masses that are slightly disrupted to form blocks up to 1.5 m in diameter (see hatched lines in Fig. 2C). These blocks are usually highlighted by thin veneers of iron oxides and hydroxides. Facies Cg corresponds to conglomerate with pebbles up to 5 cm in diameter of laterite and quartz with a matrix of fine- to medium-grained sandstone (Figs. 2A, 3). All

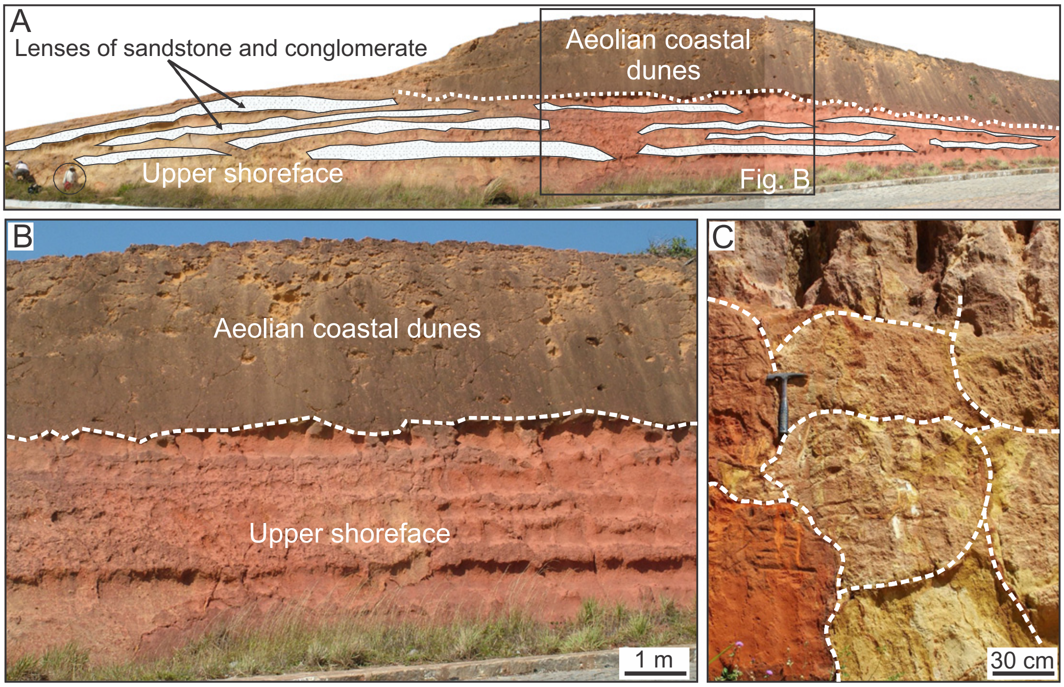

Figure 2. Post-Barreiras sediments at the Tambaba section (see Fig. 1 for location). A) General view of the outcrop showing upper shoreface deposits (facies association SH) with lenses of sandstone and quartz and laterite pebble conglomerate (facies Cg), unconformably overlain by aeolian coastal dune deposits (facies association As) (rectangle indicates location of figure B). B) Detail of A illustrating the lenticular nature of bioturbated sandstone (facies Bs). C) Decimeter-long clasts of massive sandstone (facies Ms in view profile).

these facies can occur as lenses up to 10 m long and averaging 20 cm in thicknesses.

Facies Bs displays a *Thalassinoides*-dominated ichnofabric (Fig. 4A–D) and locally *Psilonichnus* isp. (Fig. 4E). The *Thalassinoides* ichnofabric is monospecific and characterized by horizontal to inclined burrows with dichotomously branched tunnels (see Th in Fig. 4B and arrows in 4C). These display circular cross-sections and form complex networks (mazes and boxworks, sensu Frey et al., 1978). Burrows are unlined, smooth-walled; diameters vary from 2 to 4 cm. Burrow-wall ornamentation is lacking. Branches with Y- or T-shaped (Fig. 4C) bifurcations are dominant, with angles varying between 60° and 90°. Enlargements in bifurcation points (see El in Fig. 4C) are common, and some burrows may show turnarounds (see 1 and 2 in Fig. 4D). Sedimentary fills of these burrows is the same as the host material. The degree of bioturbation is moderate to high (according to scheme of Reineck, 1963) (Fig. 4A,B). The *Thalassinoides* burrows are in great part iron-cemented, although facies Bs also displays an abundance of non-cemented *Thalassinoides* trace fossils. *Psilonichnus* isp., the only burrow identified in association with *Thalassinoides*, is characterized by vertical, Y-shaped burrows with diameters varying from 1 to 3 cm and bifurcation angles from 60° to 90° (Fig. 4E). The burrow walls locally show scratch marks and the burrow fill is equivalent to the host rock. Burrows assigned to *Psilonichnus* isp. cut across the *Thalassinoides* ichnofabric.

In the Cabo Branco section (Figs. 5A,B, 6), facies association SH is more varied and consists of facies Bs (Fig. 5C), Ic (Fig. 5D), Ms and Ds. Facies Bs, which is finer-grained than in the Tambaba section, consists of thin (<1 m) layers of well to moderately sorted, very fine- to fine-grained sandstones and mudstones. These deposits are overlain by facies association FS (Fig. 5E, see below). The *Thalassinoides* ichnofabric is also present at this locality (see Th in Fig. 4F,G). Despite the relatively poor preservation, the same characteristics described for this ichnofabric in the Tambaba section are also observed at the Cabo Branco section. The majority of facies association SH in the Cabo Branco section consists of facies Ms and, secondarily, facies Ic. Facies Ms at this locality is finer-grained than in the Tambaba section, including very fine- to fine-grained massive sandstones and silty mudstones. Facies Ic consists of conglomerate with subrounded mud rip-up clasts, generally with a closed framework and a matrix of fine-grained sandstone (Fig. 5D). The thickness of facies association SH varies at the Cabo Branco section. At one end, the package is up to 12 m thick where it fills a concave-up depression nearly 200 m in width (Fig. 5C). These deposits thin laterally (to the right in Fig. 5A) as they overlie facies association FS, forming together a 5-m-thick tabular package.

Facies Association FS (foreshore)

This association was recorded only in the Cabo Branco section (see FS in Figs. 5A,E; 6), where it forms a package up to 2 m thick. It is laterally continuous for tens of meters, in part overlying unconformably the Barreiras Formation (Fig. 5A,B) and in part overlying facies association SH (Figs. 5E, 6). These deposits are composed of stratified sandstone (facies PCs), massive sandstone (facies Ms) and deformed sandstone (facies Ds). Facies PCs (Fig. 5F) consist of well-sorted, rounded to subrounded, fine-grained quartz sandstone with parallel stratification that grades vertically into low-angle cross-stratification. Parallel strata are arranged into low-angle truncating packages 20 to 30 cm thick. Medium-scale trough-cross stratification is most common and locally grades into tabular cross sets. Cross lamination may intergrade either with parallel- or cross-stratified strata, and they occur in sets with lower, either symmetrical or asymmetrical undulatory boundaries and common internal reactivation surfaces. Facies PCs is interbedded with facies Ds, the latter consisting of fine- to medium-grained and well- to moderately sorted sandstone averaging 1 m thick and internally characterized by either convolute or contorted bedding (Fig. 5G). Facies Ds grades into facies Ms, which in this association consists of entirely unstructured, well-sorted, fine-grained sandstone.

Facies Association AS (aeolian coastal dunes)

This association is recorded at the top of both cliffs overlying the other facies associations (Figs. 5A,B, 6). The basal bounding surface is sharp and locally undulatory. The deposits consist essentially of well-sorted, moderate to well rounded, fine- to medium-grained massive sandstone.

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press

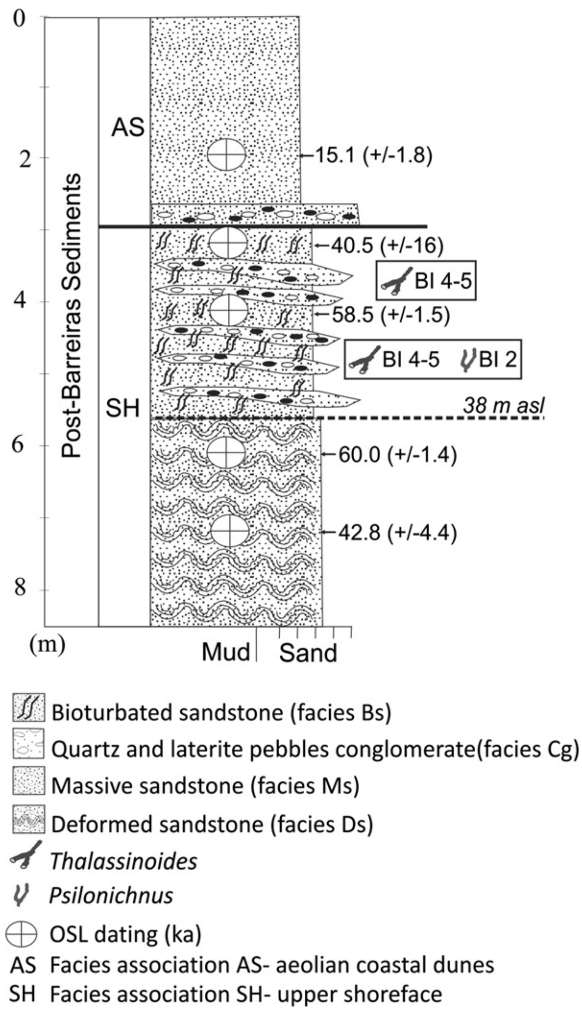

Figure 3. Lithostratigraphic profile at Tambaba section showing the vertical distribution of facies associations, ichnofossils, and OSL ages.

Chronology

Nine sandy samples of the post-Barreiras sediments have OSL ages ranging from 60.0 (±1.4) to 15.1 (±1.8) ka (Table 1). Five samples derive from the Tambaba section (Fig. 3). Three derive from other laterally correlated outcrops of the post-Barreiras sediments at the Tambaba Beach. One sample came from the top of the Cabo Branco section (Fig. 5A).

The OSL age distribution is generally consistent within the Tambaba section, with an upward progressive decrease. An exception occurs at the base of the profile, where an age inversion was recorded from a 42.8 (±4.4) ka sample located 1 m below a 60.0 (±1.4) ka sample. These two samples were collected from the deformed sandstone (facies Ds), and so this age inversion could have been due to sediment remobilization within this lithofacies during soft-sediment deformation, as explained in the following section. Two samples from the bioturbated sandstone provided ages of 58.5 (±1.5) and 40.5 (±1.6) ka for the lower and upper samples, respectively. However, a much younger age, namely 15.1 (±1.8) ka, was obtained for the massive sandstone from facies association AS at the top of the Tambaba section (Fig. 3).

Samples from outcrops having late Pleistocene deposits similar to the Tambaba section presented samples of the post-Barreiras sediments yielding ages from 23.2 (±2.1) ka to 37.6 (±7.0) ka. The single sample from the Cabo Branco section yielded an age of 46.8 (±3.1) ka.

Discussion

Paleoenvironmental setting

Sedimentologic characteristics integrated with ichnofabric observations and OSL dating lead us to conclude that the post-Barreiras sediments in the studied sections were deposited in marine-influenced settings during the late Pleistocene. Facies association SH records a marine environment, as suggested by the *Thalassinoides* ichnofabric. The morphological characteristics of the observed trace fossils, consisting of a complex network of horizontal to inclined and dichotomously branched tunnels with Y- or T-shapes, leave no doubts on their attribution to this ichnogenus. This represents a feeding–dwelling burrow system of decapod crustaceans (mostly thalassinidean and callianassidean shrimps) that inhabit coastal to shallow to deep-marine environments (e.g., Bromley and Frey, 1974; Ekdale et al., 1984; Bromley and Ekdale, 1986; Ekdale and Bromley, 1991; Myrow, 1995; Bromley, 1996; Buatois et al., 2011). There is only one presumable record of *Thalassinoides* in continental deposits (Kim and Pickerill, 2002), but the morphological characteristics described by these authors can be compared to crayfish burrows (*Loloichnus*) of continental environments (Bedatou et al., 2008).

Thalassinideans crustaceans can be regarded as a strategist organism, particularly in shallow marine settings, because they modify their environment, favoring the occupation of new ecological niches as a result of intense burrowing activity and high-density populations (Gibert et al., 2006). Taking this into account, the presence almost exclusive of thalassinidean burrows and the moderate to high degree of bioturbation in facies association SH are suggestive of shallow marine settings that are located above fair-weather base and undergo the influence of high-energy processes and normal to near-normal salinity conditions (e.g., Frey et al., 1978; Pollard et al., 1993; Gibert et al., 2006; Gingras et al., 2007). In such settings, wave and current action promotes frequent erosion, which destroys ichnofabrics produced by shallow tier organisms (e.g., Bromley and Ekdale, 1986; Bromley, 1996; Gingras et al., 2007, 2011; MacEachern et al., 2007a). Storm surges also promote extensive erosion and rapid sedimentation, which favor the preservation only of mid- and deep-tier organisms and, in general, only deeply penetrating structures are preserved (Howard and Frey, 1984).

The expressive occurrence of *Thalassinoides* suggests a climax of ecological conditions during the establishment of this trace fossil suite. The burrow size (i.e., >2 cm in diameter) and the intricate burrow architecture are consistent with colonization under stable marine salinity conditions. Burrows with simpler architecture and smaller sizes would be more characteristic of environments with stress generated by salinity fluctuations (e.g., Pemberton and Whightman, 1992; Pemberton et al., 2001; Savrda and Nanson, 2003; Buatois et al., 2005; Gingras et al., 2007, 2011; MacEachern et al., 2007a). Additionally, similar burrows can be found in modern tropical coastal environments, such as estuaries and lagoons (e.g., Curran and Martin, 2003). However, in such environments these burrows do not show the complex bifurcation and turnaround patterns recorded in the studied *Thalassinoides* ichnofabric. The density of these similar traces can be high, but they do not display the same morphologic and complex pattern with bifurcations and turnarounds, and normal sizes of burrows as in the *Thalassinoides* ichnofabric recorded in the study area. This favors a shallow marine environment, rather than an estuarine or other coastal depositional system, as the most likely in this instance. Taking this into account, then the most likely is to attribute facies association SH to an upper shoreface setting.

The *Psilonichnus* isp. in facies Bs of Tambaba section records subaerial coastal environments. This is because this dwelling burrow of decapod crustaceans, mainly ocypodiid crabs, has been recorded only in subaerial coastal deposits (e.g., Frey et al., 1984; Gingras et al., 2000; MacEachern et al., 2007b; Netto and Grangeiro, 2009). In addition, modern *Psilonichnus*-like burrows in the Atlantic Ocean coast are mostly attributed to the ghost crab *Ocypode quadrata* found in backshore areas (i.e., uppermost foreshore, aeolian dunes) (Rosa and Borzone, 2008).

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press

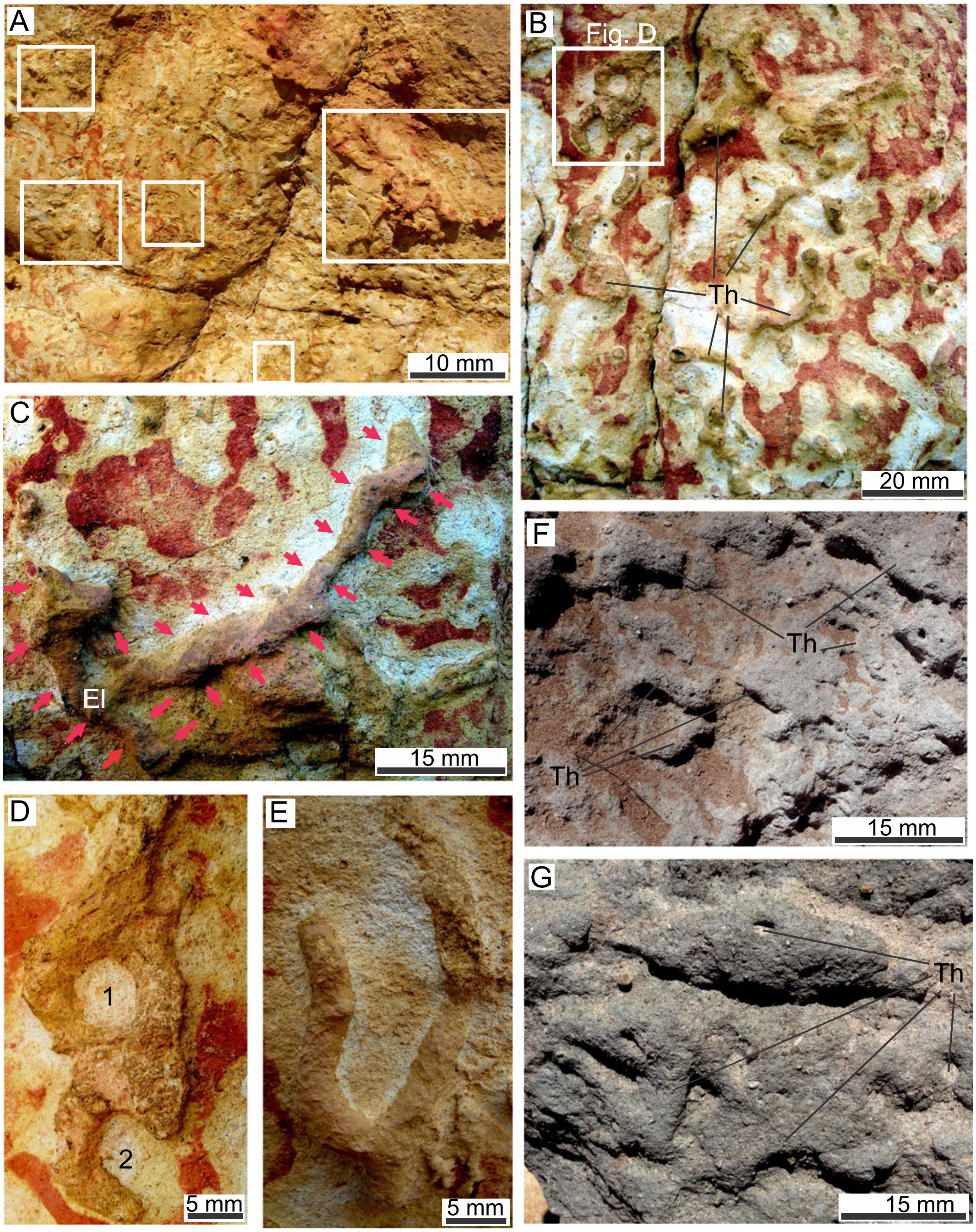

Figure 4. Icnofabrics observed at Tambaba (A–E) and Cabo Branco (F,G) sections. A) Bioturbated sandstone (facies Bs) at Tambaba section illustrating *Thalassinoides* ichnofabric with moderate to high degree of bioturbation (Reineck's scale 4–5) (squares delineate individual *Thalassinoides* traces or groups of traces). B and C) Networks of cylindrical dichotomously branched shafts (Th in B and arrows in C) of *Thalassinoides* (El in C indicates enlarged bifurcation point). D) Detail of B showing turnarounds (1 and 2) in *Thalassinoides*. E) Y-shaped in *Psilonichnus* isp. F,G) Bioturbated sandstone (facies Bs) at Cabo Branco section, characterized by *Thalassinoides* (Th) ichnofabric. (A–E = profile view or vertical to bedding; F,G = plain view or parallel to bedding).

For this reason, the *Psilonichnus* ichnofacies generally has low ichnodiversity and abundance, which results in its rare preservation in the sedimentary record (MacEachern et al., 2007b; Pemberton et al., 2001). The superposition of *Psilonichnus* isp. on the *Thalassinoides* ichnofabric in facies association SH is perhaps due to an eventual shallowing, which allowed the *Psilonichnus* tracemakers to colonize upper shoreface substrates that were subaerially exposed. This composite ichnofabric requires a change from subaqueous to subaerial, probably backshore conditions, where the Y-shaped burrows produced by *Psilonichnus* tracemakers were formed. Indeed, *Psilonichnus* has been considered as a good proxy for sea-level oscillation (Curran, 2007; Netto and Grangeiro, 2009).

The sandy nature of facies association SH in Tambaba section conforms to the upper shoreface interpretation indicated by the ichnological data. The genetic association of sandstone facies with quartz and laterite pebble conglomerate (facies Cg) in this association indicates episodic higher energy flows. This is because quartz pebbles and laterite concretions are present in association with a paleosol horizon that marks the top of the Barreiras Formation in this area (Rossetti et al., 2012). High-energy longshore currents, storm currents and/or river flooding events could have reworked these materials, and redeposited them in the upper shoreface as lenses of conglomerates.

The characteristics of the *Thalassinoides* ichnofabric of facies Bs in Cabo Branco section are similar to the one recorded in Tambaba section.

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press

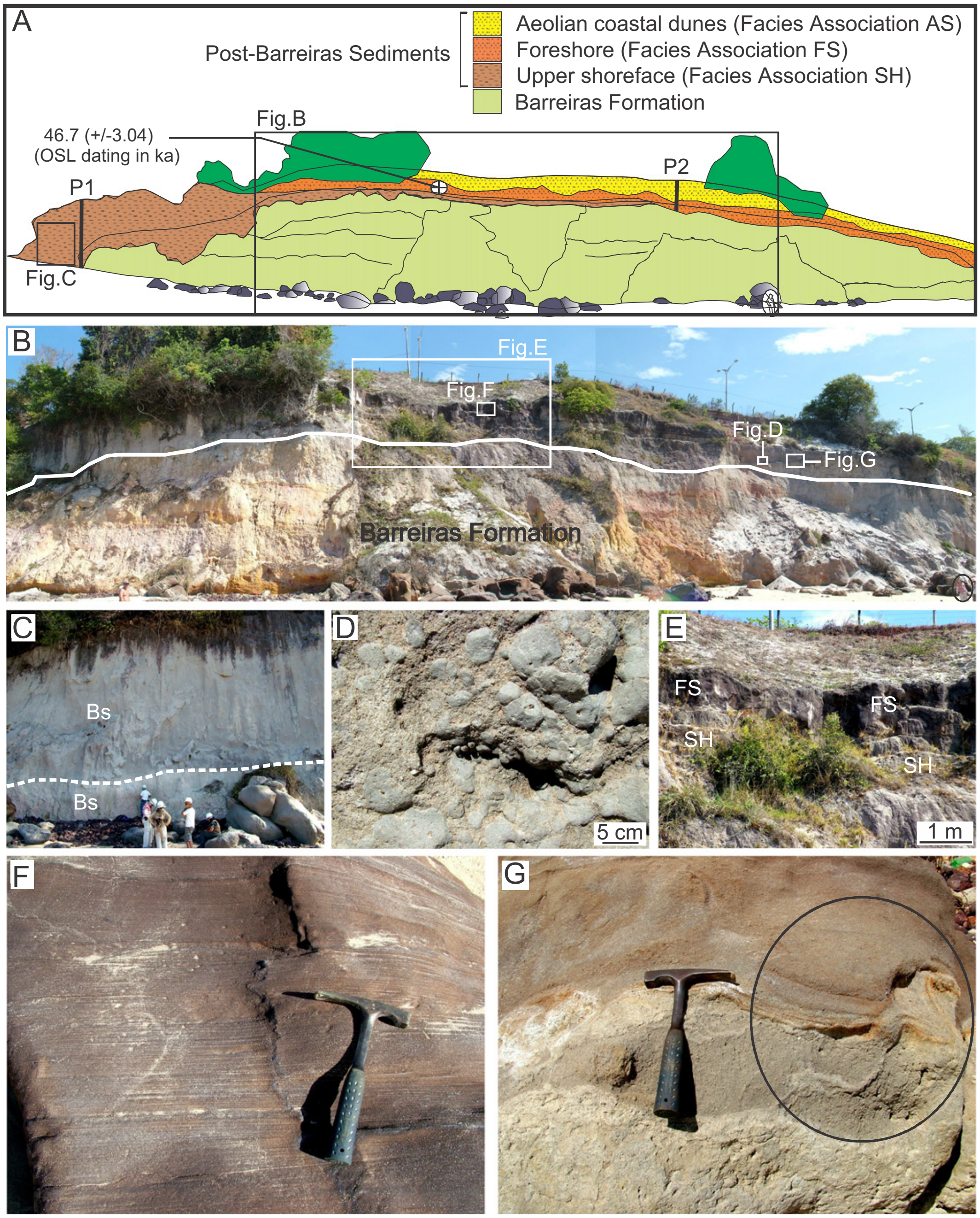

Figure 5. Post-Barreiras sediments at the Cabo Branco section. A) Geological section drawn over a photomosaic with plot of one OSL age acquired in the foreshore facies association (rectangles locate figures B and C; P1 and P2 are the stratigraphic profiles depicted in Fig. 6). B) View of part of the cliff shown in A with locations of figures D through H. C) Bioturbated sandstone/mudstones (facies Bs) attributed to shoreface (facies association SH). White line = sharp discontinuity surface. D) Conglomerate of muddy pebbles (facies Ic) from facies association SH (plain view). E) Foreshore deposits (facies association FS) in contact with shoreface deposits (facies association SH). F) Cross-stratified sandstone with parallel-stratification that grades into low-angle cross-stratification (facies PCs) of facies association FS. G) Detailed view of the sharp contact between bioturbated sandstone/mudstones (facies Bs) of facies association SH and deformed sandstone (Ds; circle indicates contorted bedding) of facies association FS. (Person for scale in A and B is 1.7 m tall; hammer for scale in F and G is 35 m long).

Therefore, facies Bs in Cabo Branco section was also related to a shallow marine environment located above the fair-weather base line, probably also in an upper shoreface setting. However, the muddier nature of facies Bs in this instance suggests lower energy conditions in this area, although facies Ic may have formed by reworking of these deposits within tidal channels.

The attribution of facies association SH to the upper shoreface environment is consistent with the transition of these deposits to facies association FS (as observed in Cabo Branco section). The latter is related to the foreshore setting based mainly on the occurrence of laterally continuous packages of parallel-stratified to low-angle cross-stratified sandstone (facies PCs). These packages are compatible with deposition under upper flow regime conditions and shallow water at the transition to or above fair-weather wave base, as typical of beach faces (e.g., Clifton et al., 1971; Driese et al., 1991). The parallel-stratified to low angle cross-stratified sandstone (facies PCs) is consistent with frequent changes in the beach-face profile. Truncation was also promoted by action of flows with fluctuating energy probably due to the swash–backwash action on beaches (e.g., Reinson, 1984). The cross lamination with highly undulatory, either symmetrically or asymmetrically low set boundaries and frequent internal reactivation surfaces in facies PCs attests combined flows. These features were possibly produced by the

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press

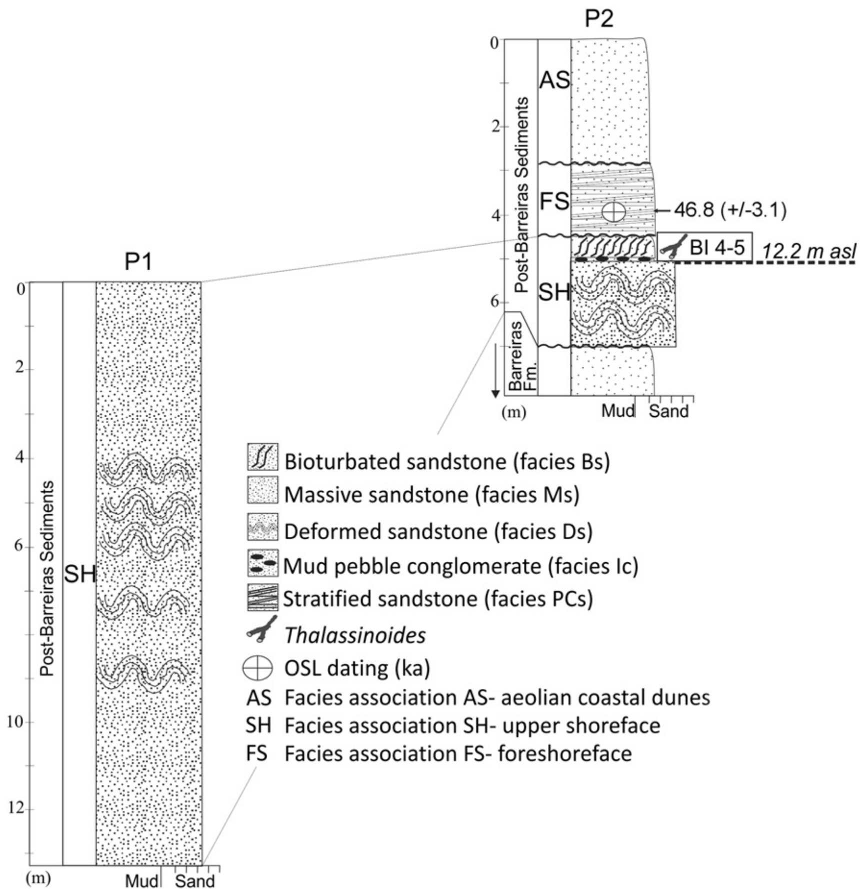

Figure 6. Stratigraphic profiles at Cabo Branco section, displaying the vertical distribution of facies associations, ichnofossils, and OSL age.

combination of fair-weather waves with littoral currents or tides (de Raaf et al., 1977). The tabular- and trough-cross strata in this facies association record areas where flow energy decreased and promoted the development of 2D- and 3D-bedforms, respectively. The absence of bioturbation in facies association FS is compatible with a high-energy setting, as typical of beaches. The deformed sandstones (facies Ds) suggest deformation while the sediment was still in an unconsolidated or semi-consolidated state. Its association with facies Ms led to interpret that the latter may also have been a consequence from deformation, probably recording areas submitted to more intense stress, which culminated with a complete loss of structure due to fluidification and/or liquefaction. The limited exposures do not allow to better understand the cause (s) of such soft-sediment deformation, but similar deposits previously reported in the post-Barreiras sediments of this basin were related to seismites (Rossetti et al., 2011a, b).

The massive and monotonous nature of facies association AS precludes the detailed interpretation of its depositional setting. In part, the massive nature of these deposits may result from pedogenesis associated with the present subaerial exposure. However, the preferred interpretation is that association AS constitutes the record of a distinctive depositional episode subsequent to the formation of the upper shoreface/foreshore associations. The presence of a well-defined discontinuity surface at the base of association AS (see Figs. 2A and 5A) and the age contrast (i.e., more than 25 ka) with respect to the underlying foreshore/shoreface deposits support this interpretation. In addition, the sandy nature, fine to medium grain size, and well-sorted

Table 1
Ages of the post-Barreiras sediments obtained by optically stimulated luminescence (OSL) dating.

Location	Sample	U (ppm)	Th (ppm)	K (%)	Accumulated dose (Gy)	Annual dose rate (μGy/year)	Age (ka)
Cabo Branco Beach	PB 114.7	0.72	1.41	b.d.l.	75 ± 4	1.604 ± 60	46.8 ± 3.1
	PB 113.2[b]	3.93	18.26	0.90	53.0	3506 ± 240	15.1 ± 1.8
	PB 113.5[b]	3.64	19.44	0.46	131.3	3068 ± 159	42.8 ± 4.4
	PB 113.11	4.96	12.44	b.d.l.	144.2	2.450 ± 500	58.5 ± 1.5
Tambaba Beach	PB 113.12	4.58	16.46	b.d.l.	160.7	2.670 ± 500	60.0 ± 1.4
	PB 113.13	4.94	14.28	b.d.l.	105.9	2.600 ± 900	40.5 ± 1.6
	PB 113.15[a]	7.08	33.67	1.04	156.3	5.550 ± 490	28.2 ± 3.9
	PB 113.16[a]	5.71	32.54	0.58	107.8	4.640 ± 190	23.2 ± 2.1
	PB 113.17[a]	7.13	32.97	1.85	177.8	6.290 ± 750	28.28 ± 4.8
	PB 113.18[a]	4.43	19.85	0.61	128.8	3.420 ± 460	37.65 ± 7.0

b.d.l. = below detection limi.
[a] Samples from outcrops of the Post-Barreiras Sediments located laterally to the lithostratigraphic profile shown in Fig. 3.
[b] Data from Rossetti et al. (2011b, 2012).

moderately to well-rounded grains suggest that association AS was possibly formed by aeolian deposition in coastal dunes.

Shallow marine deposition in the context of sea level

Unfortunately, body fossils that could support the proposed marine interpretation have not been found in the studied deposits yet. These strata are mostly sandy and oxidized, and have low potential for fossil preservation. In such instances, trace fossils are particularly valuable in making facies interpretations. Despite the lack of body fossils, a shallow marine environment seems to be the most likely interpretation that can explain both the described sedimentary facies and the ichnological assemblage dominated by *Thalassinoides*.

Under the assumption that the proposed marine interpretation is correct, the location of these deposits ca. 38 m above modern sea level must be explained. This altitudinal position conflicts with the fact that the global sea level during the post-Barreiras sedimentation was trending to a fall as a result of the last glaciation (Fig. 7). The estimate is that sea level reached nearly 120 m (Clark et al., 2009; Fairbanks, 1989) or at least 80 m (e.g., Cutler et al., 2003) below modern sea level during the maximum of this glaciation episode, i.e., between circa 23 and 18 ka (e.g., Crowley and North, 1991). Subsequently, in the Holocene, sea level rose to the present mean sea level. Sea-level reconstruction along the Brazilian coast agrees with this global pattern, indicating a drop during the last glaciation (Barreto et al., 2002; Suguio et al., 2011), with a rise occurring only in the mid-Holocene, but with sea level having reached a maximum of only 5 m above the present one (Dominguez et al., 1992; Bezerra et al., 2003; Martin et al., 2003; Caldas et al., 2006; Suguio et al., 2013). If deposition of the post-Barreiras sediments occurred between 60.0 ($\pm$1.4) and 15.1 ($\pm$1.8) ka (Fig. 7), as suggested by the OSL ages provided herein, then the current elevation of shallow marine deposits in the Tambaba and Cabo Branco sections at 38 and 12.2 m, respectively, is inconsistent with the history of late Pleistocene sea-level oscillation.

The apparent conflict between sediment deposition and sea-level history potentially could be related to limitations of the OSL methodology. Age accuracy depends on the rate of bleaching due to exposure to daylight. In general, the OSL signal of clean quartz sand can reset within a few seconds when exposed to the sunlight, but grains in natural settings commonly have iron and manganese oxide coatings (Murray and Olley, 2002). Under this condition, bleaching requires longer exposure to daylight, with this rate varying according to the transportion process. More complete bleaching occurs in aeolian deposits, while this process may vary in subaqueous environments depending on flow behavior. Incomplete bleaching provides overestimated ages inherited from previous depositional sites. Tests in aeolian, fluvial, lacustrine and shallow marine settings have provided accurate ages (Murray and Olley, 2002). According to these authors, sand reworked in shallow marine settings might reach complete bleaching and provide precise OSL ages. Thus, the potential for complete bleaching of the studied quartz grains is high considering their deposition above fair-weather base line. Characteristics in favor of the proposed deposition of the post-Barreiras sediments during the last glacial lowering of sea level are: (i) the consistent OSL ages from a set of 10 samples distributed within a relatively short time range of a few thousand years; and (ii) the general progressive age increase with depth in the instance of Tambaba section. In addition, these ages are in agreement with those obtained from other deposits of the post-Barreiras sediments in other areas of Paraíba Basin (e.g., Rossetti et al., 2011a). Based on these arguments, the studied shallow marine deposits could not be associated with any episode of eustatic sea-level rise that would justify their position several meters above modern sea level.

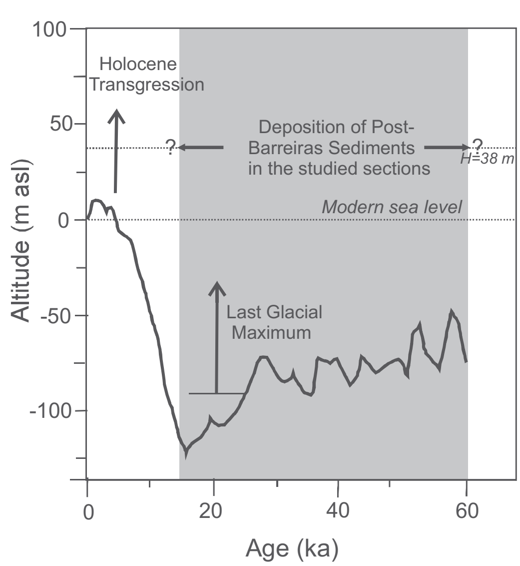

Figure 7. Global sea-level curve during the last glaciation based on marine oxygen isotopes from Shackleton (1988), with indication of the time for deposition of the post-Barreiras sediments recorded in the studied sections. Note that sediment deposition occurred during a time when eustatic sea level was several meters below the modern sea level.

The hypothesis of a tectonic uplift

If we assume that the marine attribution and the OSL ages for the studied strata are correct, then tectonic uplift must be invoked as the most plausible hypothesis to explain the altitudinal position of the studied strata several meters above modern sea level. This hypothesis is significant considering the location of the Brazilian coast in a passive margin that presumably has been stable since the main continental rifting. However, if one disregards an origin related to a sea-level rise, as previously discussed, then the tectonic hypothesis appears as the most suitable explanation for the high elevation of these marine deposits.

Notably, Bezerra et al. (2014) have proposed that the passive margin of South America remained active long after the continental breakup. This conclusion was based on an increasing number of publications reporting Neogene and Quaternary tectonic reactivations of Precambrian basement structures affecting both the sedimentary and morphological evolutions of several areas in northeastern Brazil (e.g., Bittencourt et al., 1999; Moraes-Neto and Alkimin, 2001; Lopes et al., 2010), including the Paraíba Basin (e.g. Balsamo et al., 2013; Bezerra et al., 2008, 2014; Rossetti et al., 2009, 2011a, b, 2012). In addition to the studied sections, the latter authors described numerous outcrops with normal and reverse faults, as well as folds, related to E–W compression and N–S oriented extension within a strike-slip deformational regime in the Neogene and Quaternary. Although the age of faulting was not quantitatively established by those authors, Balsamo et al. (2013) argued that faulting was very recent (i.e., $<$100 ka) based on growth wedge geometry of the post-Barreiras sediments and fault-related diagenetic alterations.

Therefore, despite being in a passive margin, the studied shallow marine deposits occur in a region with records of neotectonic structures, with faults and folds previously documented in the studied sections. This tectonic context should be taken into account when attempting to explain the studied strata above the modern sea level. Hence, the recent transpressive kinematics documented in the Paraíba Basin may have induced, at least locally, the vertical uplift of shallow marine deposits of the post-Barreiras sediments to their present-day topographic position.

The record of neotectonic activity on the passive margin of the South America plate should not be regarded as improbable, as other passive continental margins worldwide have experienced, polyphased evolution, with common post-rift tectonic reactivation (e.g., Dendith and Featherstone, 2003; Japsen et al., 2003, 2006; Faccenna et al., 2008). In addition, Pedoja et al. (2011) suggest that the coasts of many continents have been uplifting since the last interglaciation period by compression due to long-term continental accretion related to plate tectonics. The eastern Brazilian passive margin is currently under compression due to the effect of E–W and N–S oriented strike-slip deformation (Ferreira et al., 2008). Such recent tectonic activity is in agreement with the fact that seismicity in northeastern Brazil remains active today, as shown by earthquakes up to 5.2 mb body-wave magnitude and VII MMI (Modified Mercalli Intensity scale) (Ferreira et al., 2008). These seismic events have recurred through time (Bezerra et al., 2011) and have influenced sediment deposition in northeastern Brazil during the late Pleistocene and Holocene (e.g., Bezerra et al., 2008; Moura-Lima et al., 2011; Rossetti et al., 2011a, b, 2012).

Uplift rate

Although the studied deposits are in a region with a tectonic context that could justify their position above the modern sea level, the estimated uplift rate appears to be much higher than expected. Pedoja et al. (2011) proposed an uplift rate of only 0.1 mm/yr for this passive margin. If the proposed tectonic hypothesis is correct, a rise of 38 m in the last 60 ka would result in an uplift rate of 0.63 mm/yr. However, if the sea level at this time was 80 m below the present sea level as claimed by some authors (e.g., Cutler et al., 2003), then an estimated uplift of up to 1.97 mm/yr would be have required to lift the post-Barreiras sediments to an altitude of 38 m during the last 60 ka. This would place the passive margin of Brazil within an area of high uplift, being compared to Andean areas where uplift rates range from 0.6 to 9.6 mm/yr (e.g., Gregory-Wodzicki, 2000; Saillard et al., 2009; Hervé and Ota, 1993).

The uplift estimate for the study area would require vertical slip rates along faults that are much higher than the reported for passive continental margins. In part, the rate of uplift recorded here could be tentatively justified by the location of Paraíba Basin in one of the most seismically active areas in intraplate South America (e.g., Ferreira et al., 2008). Indeed, the number and styles of tectonic structures recorded in Neogene and Quaternary strata of this basin cannot be compared to those found thus far from any other sedimentary basins of northeastern Brazil. However, the limited nature of our data and the estimated high uplift rate raise a word of caution in applying our interpretations in future studies. The information presented herein should be evaluated in the light of a larger volume of structural data. This will be necessary to formulate a geotectonic model that better explains the evolution of the Brazilian passive margin, an issue still open for debate.

Conclusions

The integrated ichnological and sedimentological studies presented here provide valuable information on the neotectonics of Paraíba Basin. The post-Barreiras sediments presumably formed in shallow marine environments are now exposed at an altitude up to 38 m above the present-day sea level. The occurrence of such marine deposits at this altitude cannot be associated with any known rise in sea level. This is because at the time of deposition during the last glaciation sea level remained lower than the present during most of the last glaciation, with a rise of only ~5 m during the mid-Holocene transgression. Thus, terrain uplift is suggested as the most likely hypothesis responsible for the altitudinal displacement of the post-Barreiras sediments in the study area. Taking into account that these strata were formed in the last 60 ka, an estimated uplift rate of about 0,63 mm/yr, or 1,97 mm/yr (considering that sea level was 80 m below the present sea level to this last one) would be required during this period. If the uplift hypothesis is correct, then tectonic deformation along this margin during the Quaternary time might have been even more intense than previously anticipated. However, further studies integrating additional sedimentological, chronological and tectonic data are recommended to fully test the proposed uplift hypothesis presented here.

Acknowledgments

This work was supported by FAPESP Project # 2012/06010-5 and CNPq Project 303443/2009-0. All authors hold research grants from CNPq (302189/2011-4 and 305208/2010-1) and CAPES Foundation (BEX 18881/12-2). The authors are grateful to the contributions of Dr. Luis A. Buatois and Dra. Maria Gabriela Mángano, for their ichnological discussions. Editor-in-Chief Dr. Derek B. Booth, Associate Editor Dr. Dan Muhs, Dr. Fabrizio Balsamo, and two anonymous reviewers provided numerous suggestions and corrections that helped us to significantly improve an earlier version of this manuscript.

References

Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London (359 pp.).

Balsamo, F., Bezerra, F.H.R., Vieira, M.M., Storti, F., 2013. Structural control on the formation of iron oxide concretions and Liesegang bands in faulted, poorly lithified Cenozoic sandstones of the Paraíba Basin, Brazil. Geological Society of America Bulletin 125, 913–931.

Barreto, A.M.F., Bezerra, F.H.R., Suguio, K., Tatumi, S.H., Yee, M., Paiva, R., Munita, C.S., 2002. Late Pleistone marine terrace deposits in northeastern Brazil: sea-level change and tectonic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 179, 57–69.

Bedatou, E., Melchor, R.N., Bellosi, E., Genise, J.F., 2008. Crayfish burrows from late Jurassic–Late Cretaceous continental deposits of Patagonia: Argentina. Their palaeoecological, palaeoclimatic and palaeobiogeographical significance. Palaeogeography, Palaeoclimatology, Palaeoecology 257, 169–184.

Beurlen, K., 1967. Estratigrafia da faixa sedimentar costeira Recife–João Pessoa. Boletim de Geociências 16, 43–53.

Bezerra, F.H.R., Vita-Finzi, C., 2000. How active is a passive margin? Paleoseismicity in northeastern Brazil. Geology 28, 591–594.

Bezerra, F.H.R., Barreto, A.M.F., Suguio, K., 2003. Holocene sea level history on the Rio Grande do Norte State coast, Brazil. Marine Geology 196, 73–89.

Bezerra, F.H.R., Amaro, V.E., Vitafinzi, C., Saadi, A., 2001. Pliocene–Quaternary fault control of sedimentation and coastal plain morphology in NE Brazil. Journal of South American Earth Sciences 14, 61–75.

Bezerra, F.H.R., Neves, B.B.B., Correa, A.C.B., Barreto, A.M.F., Suguio, K., 2008. Late Pleistocene tectonic-geomorphological development within a passive margin–the Cariatá trough, northeastern Brazil. Geomorphology 97, 555–582.

Bezerra, F.H.R., Nascimento, A.F., Ferreira, J.M., Nogueira, F.C.C., Fuck, R.A., Neves, B.B.B., Souza, M.O.L., 2011. Review of active faults in the Borborema Province, Intraplate South America integration of seismological and paleoseismological data. Tectonophysics 510, 269–290.

Bezerra, F.H.R., Rossetti, D.F., Oliveira, R.G., Medeiros, W.E., Brito-Neves, B.B., Balsama, F., Nogueira, F.C.C., Dantas, E.L., Andrades-Filho, C.O., Góes, A.M., 2014. Neotectonic reactivation of shear zones and implications for faulting style and geometry in the continental margin of NE Brazil. Tectonophysics 614, 78–90.

Bittencourt, A.C.S.P., Dominguez, J.M.L., Ussami, N., 1999. Flexure as a tectonic control on the large scale geomorphic characteristics of the eastern Brazil coastal zone. Journal of Coastal Research 15, 505–519.

Bromley, R.G., 1996. Trace Fossils: Biology, Taphonomy and Applications, 2nd edition. Chapman and Hall, London (361 pp.).

Bromley, R.G., Frey, R.W., 1974. Redescription of the trace fossil *Gyrolithes* and taxonomic evaluation of *Thalassinoides*, *Ophiomorpha* and *Spongeliomorpha*. Bulletin of the Geological Society of Denmark 23, 311–335.

Bromley, R.G., Ekdale, A.A., 1986. Composite ichnofabrics and tiering of burrows. Geological Magazine 123, 59–65.

Buatois, L.A., Gringas, M.K., MacEachern, J., Mángano, M.G., Zonneveld, J.P., Pemberton, S.G., Netto, R.G., Martin, A.J., 2005. Colonization of brackish-water systems through time: evidence from the trace-fossil record. Palaios 20, 321–347.

Buatois, L.A., Santiago, N., Herrera, M., Plink-Björklund, P., Steels, R., Espin, M., Parra, K., 2011. Sedimentological and ichnological signatures of changes in wave, river and tidal influence along a Neogene tropical deltaic shoreline. Sedimentary Geology 59, 1568–1612.

Caldas, L.H.O., Stattegger, K., Vital, H., 2006. Holocene sea-level history: evidence from coastal sediments of the northern Rio Grande do Norte coast, NE Brazil. Marine Geology 228, 39–53.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCABE, M., 2009. The last glacial maximum. Science 325, 710–714.

Clifton, H.E., Hunter, R.E., Phillips, R.L., 1971. Depositional structures and processes in the non-barred high energy nearshore. Journal of Sedimentary Petrology 41, 651–670.

Crowley, T.J., North, G.R., 1991. Paleoclimatology. Oxford University Press, Oxford New York (339 pp.).

Curran, H.A., 2007. Ichnofacies, ichnocoenoses and ichnofabrics of Quaternary shallow-marine to dunal tropical carbonates: a model and implications. In: Miller, W. (Ed.), Trace Fossils: Concepts, Problems, Prospects. Elsevier, Amsterdam, pp. 232–247.

Curran, H.A., Martin, A.J., 2003. Complex decapods burrows and ecological relationships in modern and Pleistocene intertidal carbonate environments. San Salvador Island, Bahamas, Palaeogeography, Palaeoclimatology, Palaeoecology 192, 229–245.
Cutler, K.B., Edwards, R.L., Taylor, F.W., Cheng, H., Adkins, J., Gallup, C.D., Cutler, P.M., Burr, G. S., Bloom, A.L., 2003. Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth and Planetary Science Letters 206, 253–271.
Dendith, M.C., Featherstone, W.E., 2003. Controls on intra-plate seismicity in southwestern Australia. Tectonophysics 376, 167–184.
Dominguez, J.M.L., Bittencourt, A.C.S.P., Martin, L., 1992. Controls on Quaternary coastal evolution of the east-northeastern coast of Brazil: roles of sea-level history, trade winds and climate. Sedimentary Geology 80, 213–232.
Driese, S.G., Fischer, M.W., Easthouse, K.A., Marks, G.T., Gogola, A.R., Schoner, A.E., 1991. Model for genesis of shoreface and shelf sandstone sequences, southern Appalachians: paleoenvironmental reconstruction of an Early Silurian shelf system. In: Swift, D.J.P., Oertel, G.F., Tillman, R.W., Thome, J.A. (Eds.), Shelf Sand and Sandstone Bodies: Geometry, Facies and Sequence Stratigraphy. International Association of Sedimentologists, Amsterdam, Special Publication, 14, pp. 309–338.
Ekdale, A.A., Bromley, R.G., 1991. Analysis of composite ichnofabrics: an example in Uppermost Cretaceous Chalk of Denmark. Palaios 6, 232–249.
Ekdale, A.A., Bromley, R.G., Pemberton, S.G., 1984. Ichnology. The Use of Trace Fossils in Sedimentology and StratigraphySociety of Economic Paleontologists and Mineralogists, Tulsa (371 pp.).
Faccenna, C., Rossetti, F., Becker, T.W., Danesi, S., Morelli, A., 2008. Recent extension driven by mantle upwelling beneath the Admiralty Mountains (East Antarctica). Tectonics 27, 1–15.
Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.
Ferreira, J.M., Bezerra, F.H.R., Sousa, M.O.L., Nascimento, A.F., Sá, J.M., França, G.S., 2008. The role of Precambrian mylonitic belts and present-day stress field in the coseismic reactivation of the Precambrian lineament, Brazil. Tectonophysics 456, 111–126.
Frey, R., Howard, J.D., Pryor, W.A., 1978. *Ophiomorpha*: its morphologic, taxonomic, and environmental significance. Palaeogeography, Palaeoclimatology, Palaeoecology 23, 199–229.
Frey, R.W., Curran, H.A., Pemberton, S.G., 1984. Tracemaking activities of crabs and their environmental significance: the ichnogenus *Psilonichnus*. Journal of Paleontology 58, 333–350.
de Gibert, J.M., Netto, R.G., Tognoli, F.M.W., Grangeiro, M.E., 2006. Commensal worm traces and possible juvenile thalassinidean burrows associated with *Ophiomorpha nodosa*, Pleistocene, southern Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology 230, 70–84.
Gingras, M.K., Hubbard, S.M., Pemberton, S.G., Saunders, T., 2000. The significance of Pleistocene *Psilonichnus* at Willapa Bay, Washington. Palaios 15, 142–151.
Gingras, M.K., Bann, K.L., MacEachern, J.A., Waldron, J., Pemberton, S.G., 2007. A conceptual framework for the application of trace fossils. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied ichnology. Society of Economic Paleontologists and Mineralogists, Tulsa, Short Course Notes, 52, pp. 1–25.
Gingras, M.K., MacEachern, J.A., Dashtgard, S.A., 2011. Process ichnology and the elucidation of physical–chemical stress. Sedimentary Geology 237, 115–134.
Gregory-Wodzicki, K.M., 2000. Uplift history of the Central and Northern Andes: A review. GSA Bulletin 112, 1091–1105.
Hervé, F., Ota, Y., 1993. Fast Holocene uplift rates at the Andes of Chiloé, southern Chile. Revista Geológica del Chile 20 (1), 15–23.
Howard, J.D., Frey, R.W., 1984. Characteristic trace fossils in nearshore to offshores sequences, Upper Cretaceous of east-central Utah. Canadian Journal Earth Sciences 21, 200–219.
Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., Lidmar-Bergström, K., 2006. Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland: Earth and Planetary Science Letters 248, 330–339. http://dx.doi.org/10.1016/j.epsl.2006.05.036.
Kim, J.Y., Pickerill, R.K., 2002. Cretaceous nonmarine trace fossils from Hasadong and Jinju formations of the Namhae Area, Kyongsangnamdo, Southeast Korea. Ichnos: an International Journal for Plant and Animal Traces 9, 41–60.
Lopes, A.E.V., Assumpção, M., do Nascimento, A.F., Ferreira, J.M., Menezes, E.A.S., Barbosa, J. R., 2010. Intraplate earthquake swarm in Belo Jardim, NE Brazil: reactivation of a major Neoproterozoic shear zone (Pernambuco Lineament). Geophysical Journal International 180, 1303–1312.
MacEachern, J.A., Pemberton, S.G., Bann, K.L., Gingras, M.K., 2007a. Departures from the archetypal ichnofacies: effective recognition of physicchemical stresses in the rock record. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied ichnology. Society for Sedimentary Geology, Tulsa, Short Course Notes, 52, pp. 65–93.
MacEachern, J.A., Bann, K.L., Pemberton, S.G., Gingras, M.K., 2007b. The ichnofacies paradigm: high resolution palaeoenvironmental interpretation of the rock record. In: MacEachern, J.A., Bann, L.K., Gingras, M.K., Pemberton, S.G. (Eds.), Applied ichnology. Society of Economic Paleontologists and Mineralogists Tulsa, Short Course Notes, 52, pp. 27–64.
Martin, L., Dominguez, J.M.L., Bittencourt, A.C.S.P., 2003. Fluctuating Holocene sea levels is eastern and southeastern Brazil: evidence from a multiple fossil and geometric indicators. Journal of Coastal Research 19, 101–124.
Matos, R.M.D., 1992. The northeastern Brazilian rift systems. Tectonics 11, 766–791.
Myrow, P.M., 1995. *Thalassinoides* and the enigma of Early Palaeozoic open-framework burrows system. Palaios 10, 58–79.
Moraes-Neto, J.M., Alkimim, F.F., 2001. A deformação das coberturas terciárias do planalto da Borborema (PB–RN) e seu significado tectônico. Revista Brasileira de Geociencias 31, 95–106.
Moura-Lima, E.N., Bezerra, F.H.R., Lima-Filho, F.P., Castro, D.L., Sousa, M.O.L., Fonseca, V.P., Aquino, M.R., 2011. 3-D geometry and luminescence chronology of Quaternary soft-sediment deformation structures in gravels, northeastern Brazil. Sedimentary Geology 235, 160–171.
Murray, A.S., Olley, J., 2002. Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. Geochronometria-Journal on Methods and Applications of Absolute Chronology 21, 1–16.
Netto, R.G., Grangeiro, M.E., 2009. Neoichnology of the seaward side of Peixe Lagoon in Mostardas, southernmost Brazil: the *Psilonichnus* ichnocoenosis revisited. Revista Brasileira de Paleontologia 12, 211–224.
Pedoja, K., Husson, L., Regard, V., Cobbold, P.R., Ostanciaux, E., Johnson, M.E., Kershaw, S., Saillard, M., Martinod, J., Furgerot, L., Weill, P., Delcaillau, B., 2011. Relative sea-level fall since the last interglacial stage: are coasts uplifting worldwide? Earth-Science Reviews 108, 1–15.
Pemberton, S.G., Whightman, D.M., 1992. Ichnological characteristics of brackish water deposits. In: Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration: A Core Workshop. Society for Sedimentary Geology, Tulsa, Core Workshop, 17, pp. 141–167.
Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., Maceachern, J.A., Robbins, D., Sinclair, I. K., 2001. Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne D'Arc Basin. Geological Association of Canada, Short Course 15, 343.
Pollard, J.E., Goldring, R., Buck, S.G., 1993. Ichnofabrics containing Ophiomorpha: significance in shallow-water facies interpretation. Journal of the Geological Society 150, 149–164.
Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Radiation Measurements 23, 497–500.
Raaf, J.M.F., Boersma, J.R., Van Gelder, A., 1977. Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland. Sedimentology 24, 451–483.
Reineck, H.-E., 1963. Sedimentgefüge im Bereichder südlichen Nordsee. Abhandlungen der Senckenbergische Naturforschende Gesellschaft 505, 1–138.
Reinson, G.E., 1984. Barrier-island and associated strand-plain systems. In: Walker, R.G. (Ed.), Facies models. Geological Association of Canada, St. John's, pp. 119–140.
Roberts, H.M., Duller, G.A.T., 2004. Standardized growth curves for optical dating of sediment using multiple-grain aliquots. Radiation Measurements 38, 241–252.
Rosa, L.C., Borzone, C.A., 2008. Spatial distribution of *Ocypode quadrata* (Crustacea: Ocypodidae) along estuarine environments in the Paranaguá Bay Complex, Southern Brazil. Revista Brasileira de Zoologia 25, 383–388.
Rossetti, D.F., 2004. Paleosurfaces from northeastern Amazonia as a key for reconstructing paleolandscapes and understanding weathering products. Sedimentary Geology 169, 151–174.
Rossetti, D.F., Goés, A.M., Souza, S.B.L., 2001. Estratigrafia da Sucessão Sedimentar Pós-Barreiras (Zona Bragantina, Pará) com base em radar de penetração no solo. Brazilian Journal of Geophysics 19, 113–130.
Rossetti, D.F., Valeriano, M.M., Bezerra, F.H.R., Brito-Neves, B.B., Góes, A.M., 2009. Caracterização morfológica da porção sul da Sub-bacia de Alhandra, Bacia Paraíba, com base em dados SRTM: contribuição na compreensão do arcabouço estrutural. Anais XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil, pp. 3325–3332.
Rossetti, D.F., Bezerra, F.H.R., Góes, A.M., Valeriano, M.M., Andrades Filho, C.O., Mittani, J.C.R., Tatumi, S.H., Brito-Neves, B.B., 2011a. Late Quaternary sedimentation in the Paraíba Basin, northeastern Brazil: implications for the interplay among landform, sea level and tectonics in Eastern South America passive margin. Palaeogeography, Palaeoclimatology, Palaeoecology 300, 191–204.
Rossetti, D.F., Bezerra, F.H.R., Góes, A.M., Brito-Neves, B.B., 2011b. Sediment deformation in Miocene and post-Miocene strata, northeastern Brazil: evidence for paleoseismicity in a passive margin. Sedimentary Geology 235, 172–187.
Rossetti, D.F., Góes, A.M., Bezerrra, F.H.R., Valeriano, M.M., Brito-Neves, B.B., Ochoa, F.L., 2012. Contribution to the stratigraphy of the onshore Paraíba Basin, Brazil. Anais da Academia Brasileira de Ciências 84, 187–207.
Rossetti, D.F., Bezerra, F.H.B., Dominguez, J.M.L., 2013. Late Oligocene-Miocene transgressions along the equatorial and eastern margins of Brazil. Earth-Science Reviews 123, 87–112.
Saillard, M., Hall, S.R., Audin, L., Farber, D.L., Hérail, G., Martinod, J., Regard, V., Finkel, R.C., Bondoux, F., 2009. Non-steady long-term uplift rates and Pleistocene marine terrace development along the Andean margin of Chile (31ºS) inferred from 10 Be dating. Earth and Planetary Science Letters 277, 50–63. http://dx.doi.org/10.1016/j.epsl.2008.09.039.
Savrda, C.E., Nanson, L.L., 2003. Ichnology of fair–weather and storm deposits in an Upper Cretaceous estuary (Eutaw Formation, western Georgia, USA). Palaeogeography, Palaeogeography, Palaeoclimatology, Palaeoecology 202, 67–83.
Shackleton, N.J., 1988. Oxygen isotopes, ice volume, and sea level. Quaternary Science Reviews 6, 183–190.
Suguio, K., Bezerra, F.H.R., Barreto, A.M.F., 2011. Luminescence dated Late Pleistocene wave-built terraces in northeastern Brazil. Anais da Academia Brasileira de Ciências 83, 907–920.
Suguio, K., Barreto, A.M.F., Oliveira, P.E., Bezerra, F.H.R., Lilela, M.C.S.H., 2013. Indicators of Holocene sea-level changes along the coast of the States of Pernambuco and Paraíba, Brazil. Geologia USP–Série Científica 13, 141–152.
Tatumi, S.H., Kowata, E.A., Gozzi, G., Kassab, L.R.P., Suguio, K., Barreto, A.M.F., Bezerra, F.H.R., 2001. Optical dating results of beachrock, eolic dunes and sediments applied to sea-level changes study. Journal of Luminescence 102–103, 562–565.
Tatumi, S.H., Silva, L.P., Pires, E.L., Rossetti, D.F., Góes, A.M., Munita, C.S., 2008. Datação de sedimentos Pós-Barreiras no Norte do Brasil: implicações paleogeográficas. Revista Brasileira de Geociencias 38, 514–524.

https://doi.org/10.1016/j.yqres.2014.07.003 Published online by Cambridge University Press