Geomorphology 203 (2013) 46–59

Contents lists available at ScienceDirect

Geomorphology

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

The narrow, shallow, low-accommodation shelf of central Brazil: Sedimentology, evolution, and human uses

José Maria Landim Dominguez [a,*], Rian Pereira da Silva [a], Alina Sá Nunes [a,b], Antonio Fernando Menezes Freire [a,c]

[a] IGEO-UFBA, Universidade Federal da Bahia, Brazil
[b] UFS, Universidade Federal de Sergipe, Brazil
[c] Cenpes-Petrobras, Brazil

ARTICLE INFO

Article history:
Received 3 April 2012
Received in revised form 25 June 2013
Accepted 5 July 2013
Available online 12 July 2013

Keywords:
Foramol
Rhodoalgal
Narrow shelf
Eastern Brazil
Incised valleys
Mud depocenters

ABSTRACT

The continental shelf off the coast of central Brazil, extending from 10 to 16°S, is unusually narrow (~20 km) and rests on the São Francisco craton. The shelf break is located between the 45 and 50 m isobaths and coincides with major hinge-lines of the marginal basins. The shelf was exposed for most of the Quaternary period, particularly during the last 1 my, when the average sea level was −62 m. Submarine geomorphology is strongly influenced by this extended sub-aerial exposure and reduced subsidence, resulting in widespread incisions on the shelf. During the limited episodes of shelf inundation, as is the case today, a few meters of non-framework grain assemblages dominated by coralline algae accumulated on the outer shelf, while quartz sands were restricted to water depths of less than 10–15 m. Mud accumulation on this unusually shallow shelf is aided by additional accommodation space provided by incisions and canyon heads indenting the shelf. Artisanal fisheries, targeting high-value commercial species associated with hard bottoms located on the outer shelf and shelf break, are the most important human use of this shelf. Data used in this study have been compiled from theses and previously conducted surveys and consist of four piston cores, 509 km of chirp subbottom profiles and side scan recordings, and 711 bottom grab samples that have been analyzed for various textural and compositional aspects.

1. Introduction

Narrow, shallow continental shelves are relatively rare in passive margin settings. The continental shelf of central Brazil is extremely narrow and shallow compared to the global average width of 78 km (Shepard, 1963). Other narrow shelves have been recently documented in the literature, such as those of Durban, South Africa (Cawthra et al., 2012) and NW Iberia (Lantzsch et al., 2009), but these shelves are characterized by high-gradients with the shelf break located at depths greater than 100 m. At the narrow shelf of central Brazil, however, the shelf break is located at a depth between 45 and 60 m, which coincides with major hinge lines of offshore sedimentary basins. In these basins, major sediment depocenters are located on the slope and continental rise (Ferreira et al., 2009). The existence of such a narrow shelf has usually been attributed to the fact that it is located entirely on the São Francisco craton (Alkmim et al., 2001) (Fig. 1). Consequently, the shelf has experienced very limited subsidence since the Mesozoic continental break-up. This lack of accommodation space, in conjunction with the fact that during the Quaternary period, particularly during the last 1 million years (my), the average sea-level position was −62 m (Lea et al., 2002; Waelbroeck et al., 2002; Berger, 2008; Blum and Hattier-Womack, 2009) implies that the shelf was exposed sub-aerially almost continuously during this time or that there was no shelf at all during most of the Quaternary period. A major implication of this extended sub-aerial exposure and reduced subsidence is that the submarine geomorphology of the shelf is determined by long-term erosional processes as opposed to sedimentation. Many structural features dating back to the continental break-up period still have a topographic expression on the shelf today and exert control on sedimentation and on the shelf seascape, and thus on human uses and exploitation of its natural resources, particularly fisheries.

These unique characteristics (long exposure, limited subsidence) also provide an opportunity to develop a facies template for tropical narrow-shallow shelves, which has a broad application in deriving distributions of natural resources and predicting the fate of land-derived contaminants.

There is also a substantial lack of information about the tropical shelf of Brazil and its sediments. For example, a recent compilation published by Harris and Baker (2011) on seafloor geomorphology and benthic habitats does not include any contribution from the South Atlantic. In fact, since the REMAC (Brazilian Continental Margin Global Reconnaissance Program) project (Milliman and Summerhayes,

* Corresponding author at: Inst. Geociências, UFBA, Rua Barão de Jeremoabo, s/n, Campus Universitário de Ondina, 40170-115 Salvador-BA, Brazil. Tel.: +55 71 91195484 (cell), +55 71 3283 8605 (office).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.07.004

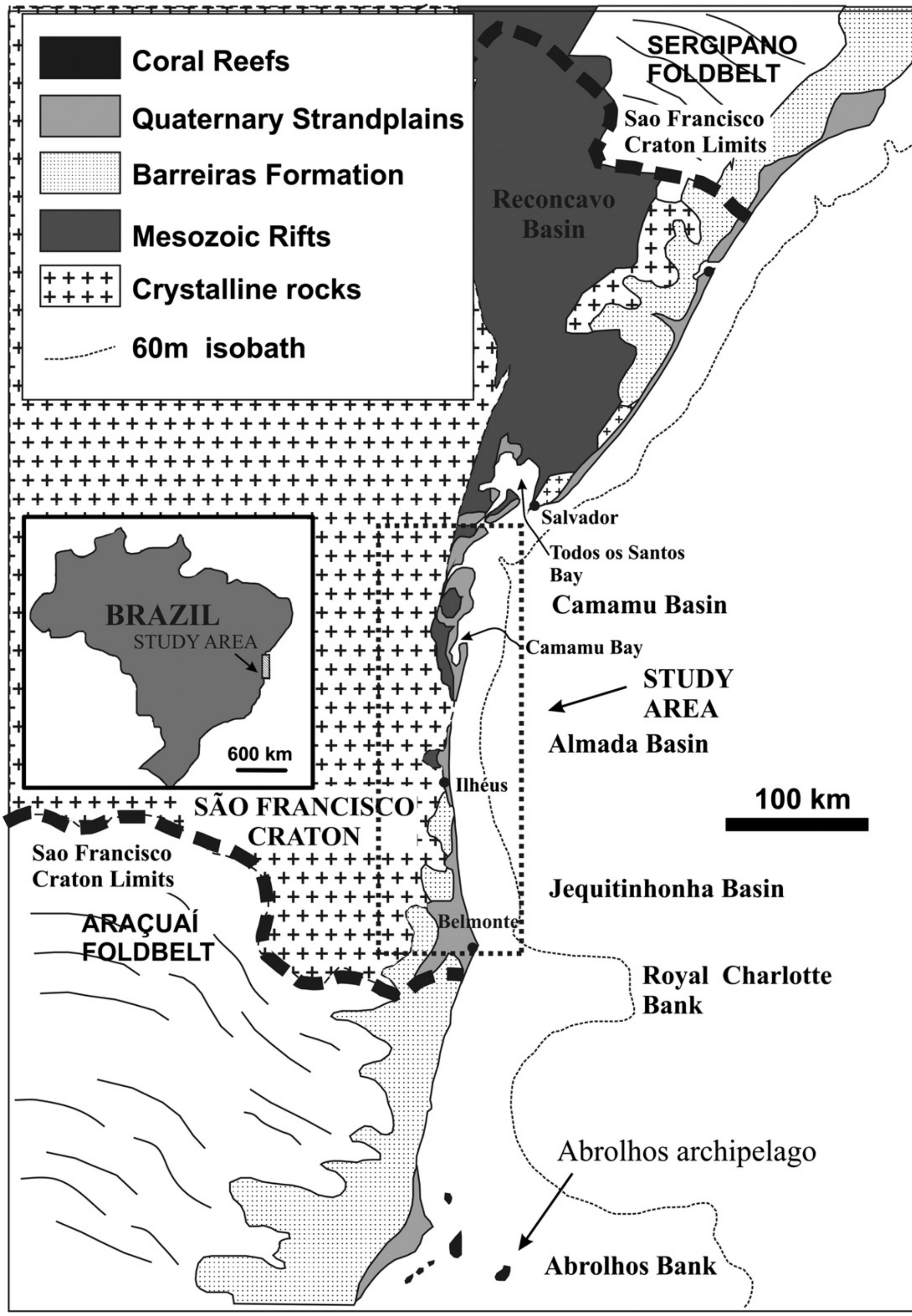

Fig. 1. Location of study area. Also showing simplified geology, and major geotectonic elements discussed in text.

1975), no major synthesis has been published about this area, with the exception of Carannante et al. (1988). However, their paper, although extensively cited in the international literature, presents very limited hard data about the region.

The present paper presents a compilation of the sedimentologic data currently available for the shallow, narrow shelf of central Brazil and discusses how the characteristics mentioned above (long term exposure and limited subsidence) controlled the characteristics of the Holocene sedimentation, the distribution of the seascapes and the human uses of this area, particularly fisheries. We hope that this compilation will help to bridge the information gap about shelf sedimentation in the Tropical Western South Atlantic area.

2. Datasets

The datasets used in the production of this compilation include (Fig. 2): (a) 711 surficial sediment grab samples collected in the shelf area; (b) 509 km of side-scan (EdgeTech model 272-TD — 100 kHz and 500 kHz operating frequencies) and sub-bottom chirp recordings (EdgeTech model SB-216S — 2 to 16 kHz operating frequencies); and (c) 4 piston-cores collected from the outer shelf. Most of the CHIRP recordings exhibit very poor penetration because of the sandy–gravelly nature of the shelf sediments. The best results were obtained from mud depocenters, of which the most important is associated with the Almada incised valley (Fig. 2).

The grab samples were analyzed for texture (dry sieving; 1 phi interval) and composition. The compositional analysis consisted of identifying 100 grains of each class of Wentworth's scale (Wentworth, 1922) (from gravel to medium sand) under a binocular microscope. The results were weighted by the percentage of each sediment class in the total sample using the methodology described in Ginsburg (1956) and Purdy (1963). Grains were identified using Milliman's identification key (Milliman, 1974). Only 315 samples of a total of 711 were analyzed this way. The percentages of gravel, sand, mud, bioclasts, quartz, coralline algae, mollusks, forams and bryozoans determined for each sample were used to prepare maps showing the spatial distributions of these sediments. Values in between the samples were interpolated using the Inverse Distance Weight method.

All data were collected during the last 10 years under supervision of the senior author and were compiled from theses, dissertations and unpublished reports produced at the Institute of Geosciences at the Federal University of Bahia, Brazil. The data presented herein have not yet been published in the international literature. The datasets used in this paper are included in the supplementary material.

3. Background information

3.1. Geological setting

The continental shelf of central Brazil rests shoreward of the major hinge lines of the Camamu, Almada, and Jequitinhonha maritime sedimentary basins (see Mohriak et al., 2008, for a brief account on the evolution of the Brazilian continental margin) (Figs. 1 and 3).

Two major large-scale tectonic features apparently exert direct control over the shelf morphology (Fig. 1): (i) the Archaean–Paleoproterozoic São Francisco craton and (ii) the Araçuaí Neoproterozoic foldbelt. The craton affected the South America–Africa break-up, forcing it to occur along a very narrow band, which resulted in a narrow,

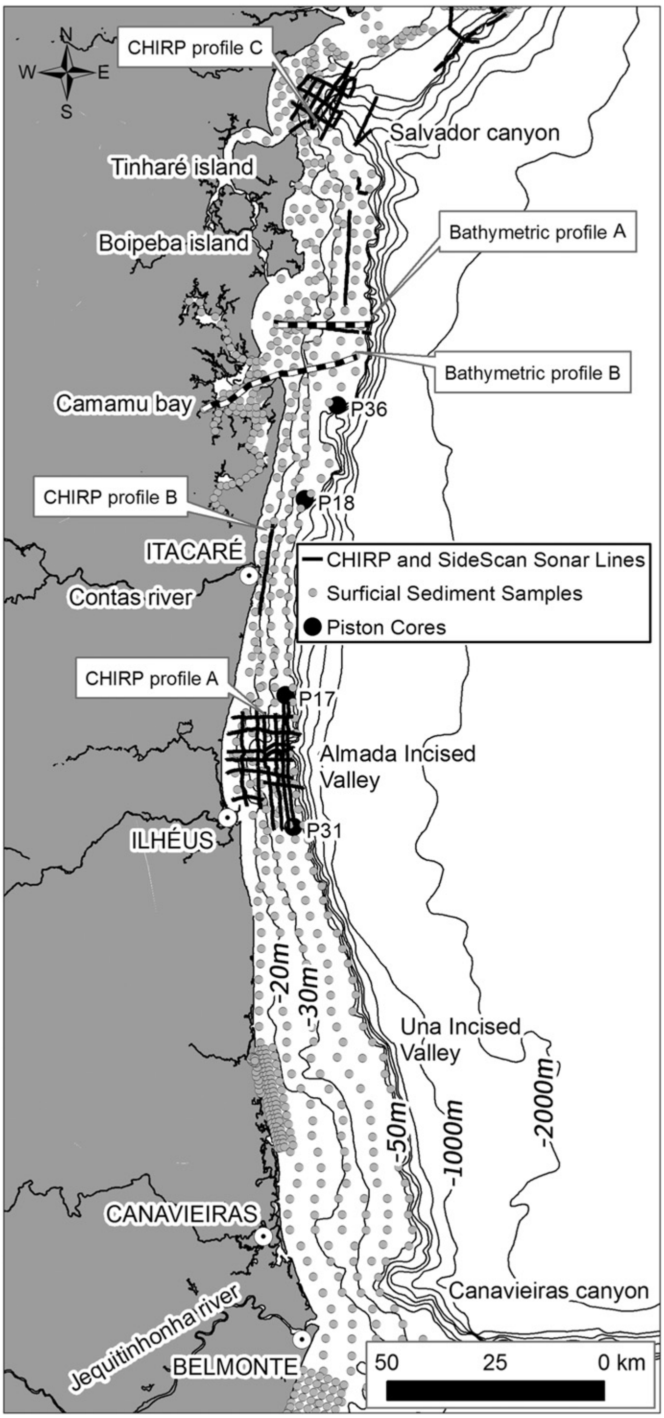

Fig. 2. Distribution and nature of datasets used in this compilation. Coordinates, texture and composition of grab samples are available in supplementary material.

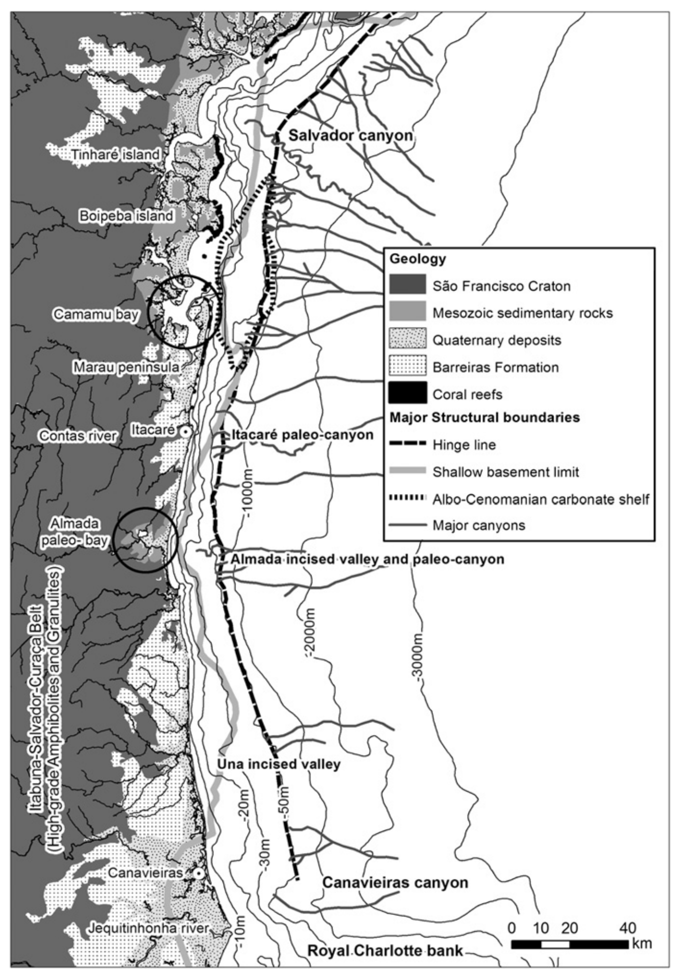

Fig. 3. Major geologic provinces and tectonic elements of the study area and adjacent coastal zone.

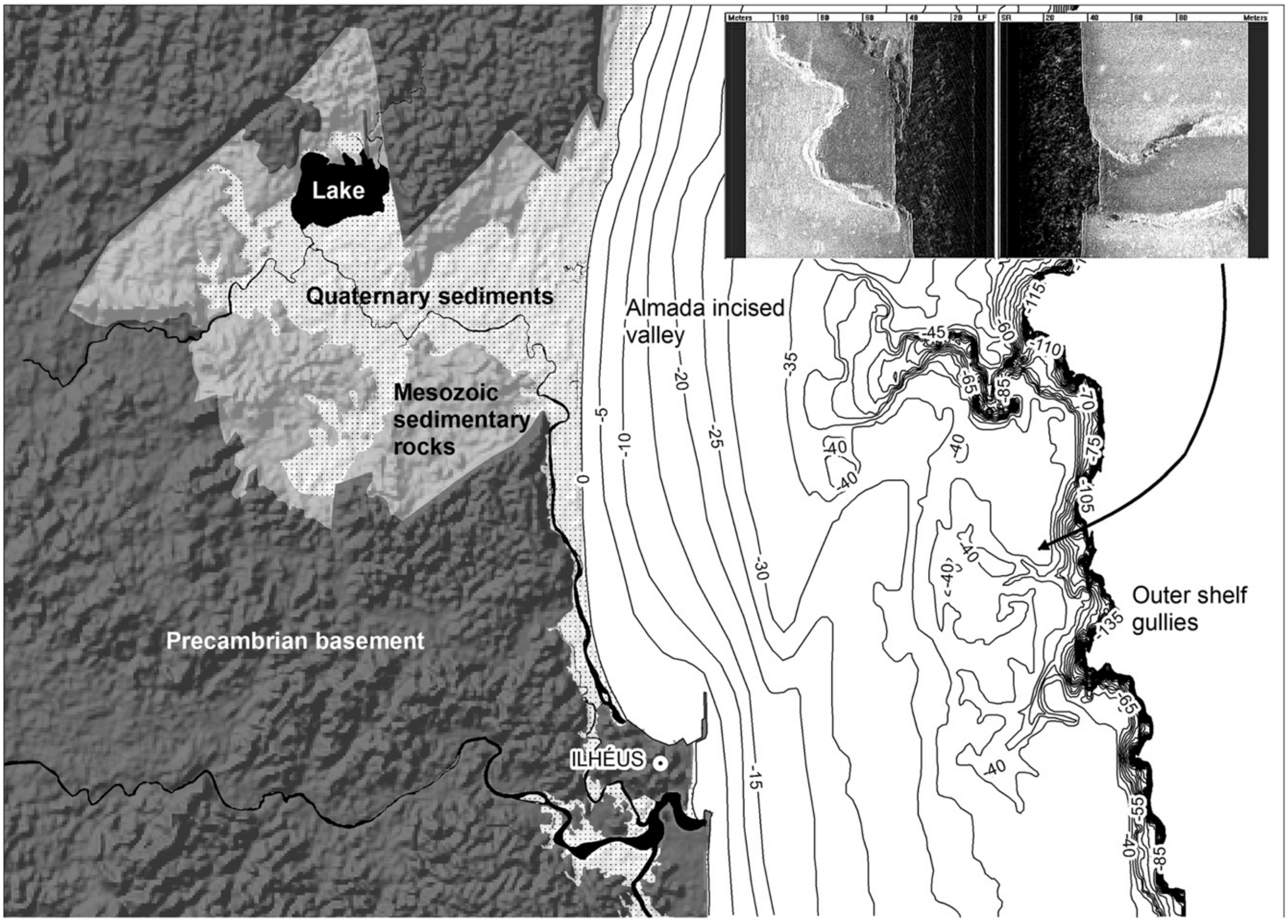

Fig. 4. Detailed bathymetry showing the unfilled Almada incised valley, and gullies dissecting the outer shelf. The inset in the upper right corner shows a sidescan record of one of those gullies. The Mesozoic sedimentary rocks of the Almada sedimentary basin outcrop in the coastal zone. The small lake depicted in the figure is a remnant of a large bay that existed in the region during the maximum of the Holocene highstand.

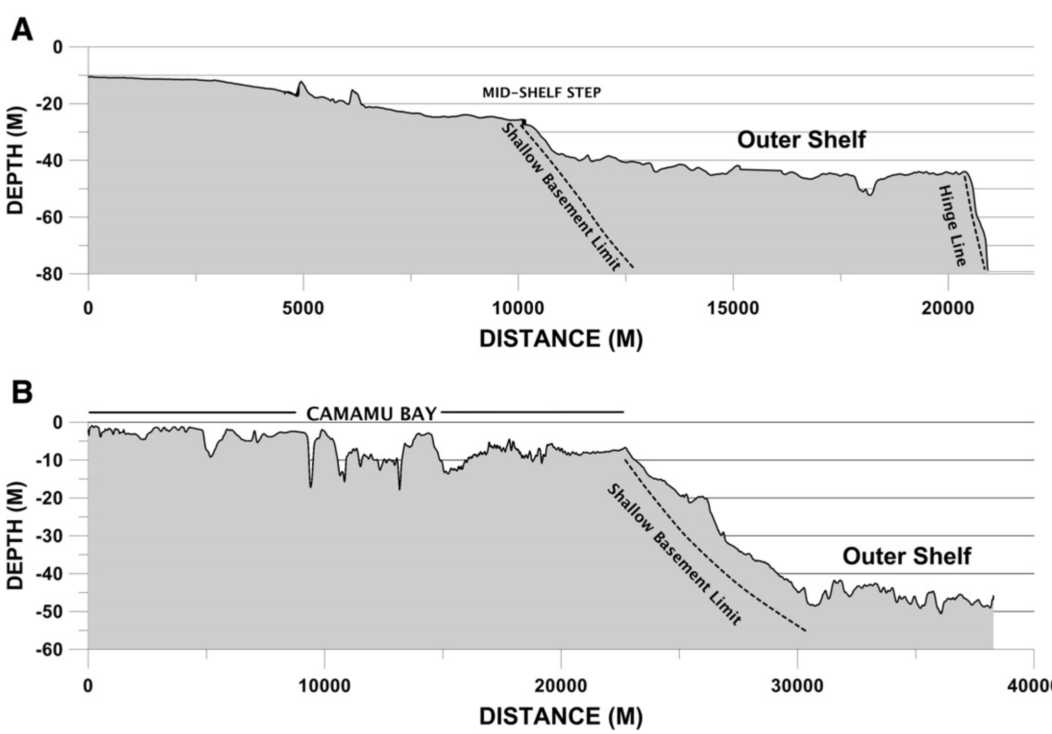

Fig. 5. A: Bathymetric profile extending from the inner shelf to the shelf break. B: Bathymetric profile extending from the inner portion of the Camamu bay to the outer shelf (see Fig. 2 for location).

low accommodation shelf that continues to influence modern sedimentation trends (Alkmim et al., 2001). In front of the Araçuaí foldbelt, the shelf widens due to the presence of the Royal Charlotte and Abrolhos banks (Fig. 1). These two dominant features formed as a result of volcanic activity in the early Tertiary (40–60 Ma) (Mohriak, 2006; Sobreira and França, 2006) and associated sediment damming by the volcanic build-ups. These volcanic rocks crop out at the Abrolhos archipelago in association with littoral deltaic siliciclastic sediments (Mohriak, 2006; Santos Filho, 2009). Mohriak et al. (2003) also suggested that the archipelago has experienced Neogene uplift resulting from compressional salt migration and associated tectonics. Cobbold et al. (2010), using vitrinite reflectance data, concluded that an uplift on the order of 2–3 km affected the continental shelf at the Camamu basin (Fig. 1) during the Cenozoic.

The most important geological unit bordering the coastline is the Itabuna–Salvador–Curaçá belt of Paleoproterozoic age (included in the São Francisco craton), which is composed of high-grade amphibolites and granulite facies (Barbosa and Sabaté, 2004) (Fig. 3). On top of this unit, Mesozoic sediments dating from the earlier stages of the continental break-up crop out discontinuously along the coastal zone (Fig. 3). During the early–middle Miocene transgression, the Barreiras formation was deposited, onlapping the Precambrian basement and the Mesozoic rocks (Rossetti et al., 2013) (Fig. 3). The drop in sea level since the middle-Miocene highstand enhanced the differential erosion between the Mesozoic sedimentary rocks (less resistant) and the Precambrian high-grade metamorphic rocks (more resistant). This caused topographic lowering of the areas occupied by these basins, which were intermittently flooded during the Late Quaternary highstands, such as the present one (MIS 1). While the Almada paleo-bay is already infilled because of its smaller size (Dominguez et al., 2009), the Camamu Bay still contains some unfilled accommodation space (Fig. 3). Bordering the present day shoreline, beach-ridge deposits associated with the MIS 5e and MIS 1 occur. Modern fringing reefs developed on top of abrasion terraces carved into the Mesozoic rocks. These reefs are more prominent off the Boipeba and Tinharé islands and along the Maraú Peninsula (Leão et al., 2003) (Fig. 3).

The origins of the Camamu and Almada bays (Fig. 3) are related to differential erosion between the Mesozoic sedimentary rocks and the more resistant surrounding crystalline basement rocks. This erosion was favored by the prolonged drop decrease in sea level since the mid-Miocene highstand (Dominguez, 2007, 2009; Dominguez and Bittencourt, 2009; Dominguez et al., 2009) and the humid climate characteristics of the area.

The Almada paleo-bay, located near Ilhéus City, was completely filled in the youngest ca. 6000 years, i.e. since eustatic sea-level rise has ended (Almeida, 2006; Dominguez et al., 2009). It contains a typical example of a highstand bay infill, with siliciclastic sands passing offshore into a large, partially mud-filled incised-valley fill (Fig. 4). A major wave-dominated delta is present at the mouth of the Jequitinhonha river (Dominguez et al., 2009) (Fig. 3).

3.2. Oceanographic aspects

The wave climate at the study area is characterized by average heights and periods ranging from 1 to 2 m and 6 to 8 s, respectively (Pianca et al., 2010). Because of the shallow depth of the continental shelf in our study area, waves with heights between 2.5 and 3 m and periods between 9 and 13 s, common during the austral winter, are able to mobilize the majority of the surficial shelf sediments (Campos and Dominguez, 2010). Shelf water temperatures and salinities average 24–26 °C and 37.7, respectively (Amorim, 2005).

Tides are semidiurnal with maximum a spring range on the order of 2.6 m. Tidal currents are not normally an important element in the shelf circulation at the study area. The only exception is the entrance of the Camamu Bay (44.5 cm/s — M2 component) (Amorim et al., 2011). The velocity fields of these currents are oriented essentially perpendicular to the general shoreline orientation. This tidal circulation interacting with longitudinal sediment transport has resulted in the accumulation of large sand deposits at the entrance of Camamu Bay, with the outer limits of the ebb-tidal delta reaching the inner shelf.

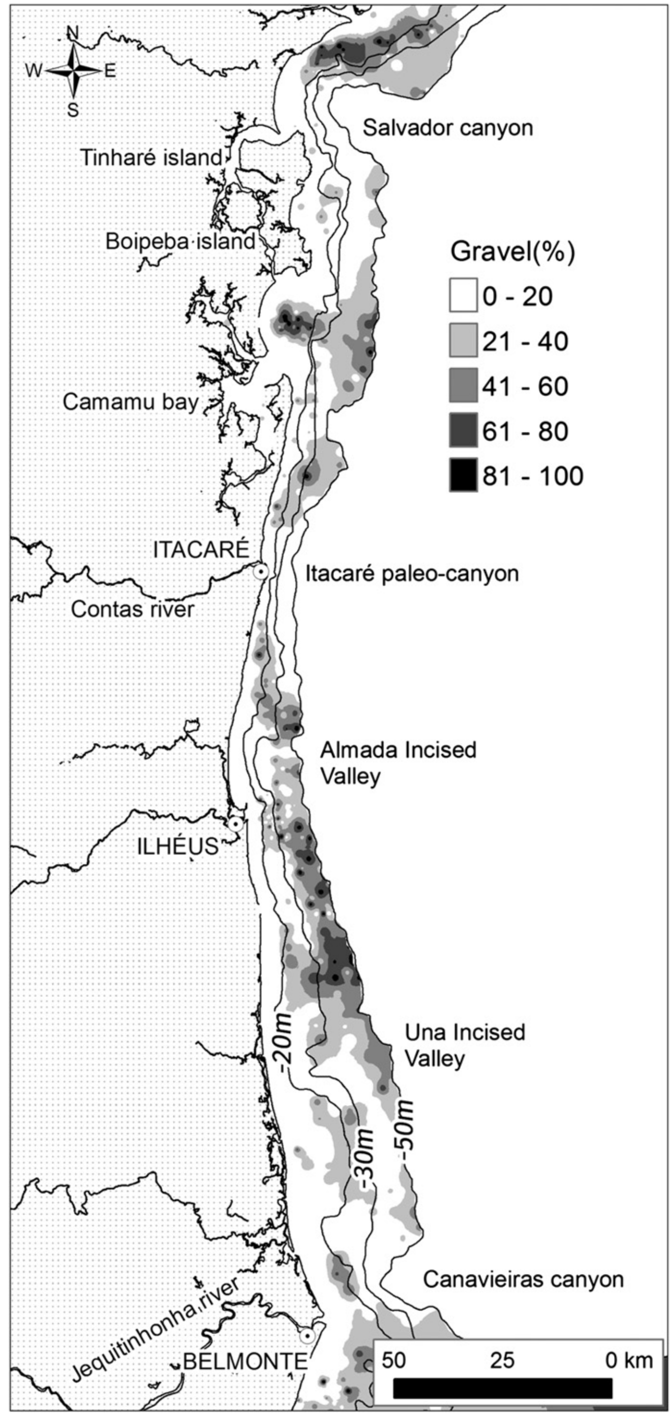

Fig. 6. Percentage of gravel in the surficial shelf sediment. Gravelly sediments are restricted to the outer shelf, and comprise exclusively bioclasts. The so-called bull's eye effect present in this and following figures is an artifact common in the interpolation method used (inversion distance weight).

Wind-generated currents are the major circulation mechanism at the studied area. These currents rapidly react to changes in the wind field and are oriented longitudinal to the shoreline (Lessa and Cirano, 2006; Lima, 2008; Amorim et al., 2011). Southerly currents dominate during austral fall and winter, whereas northerly currents

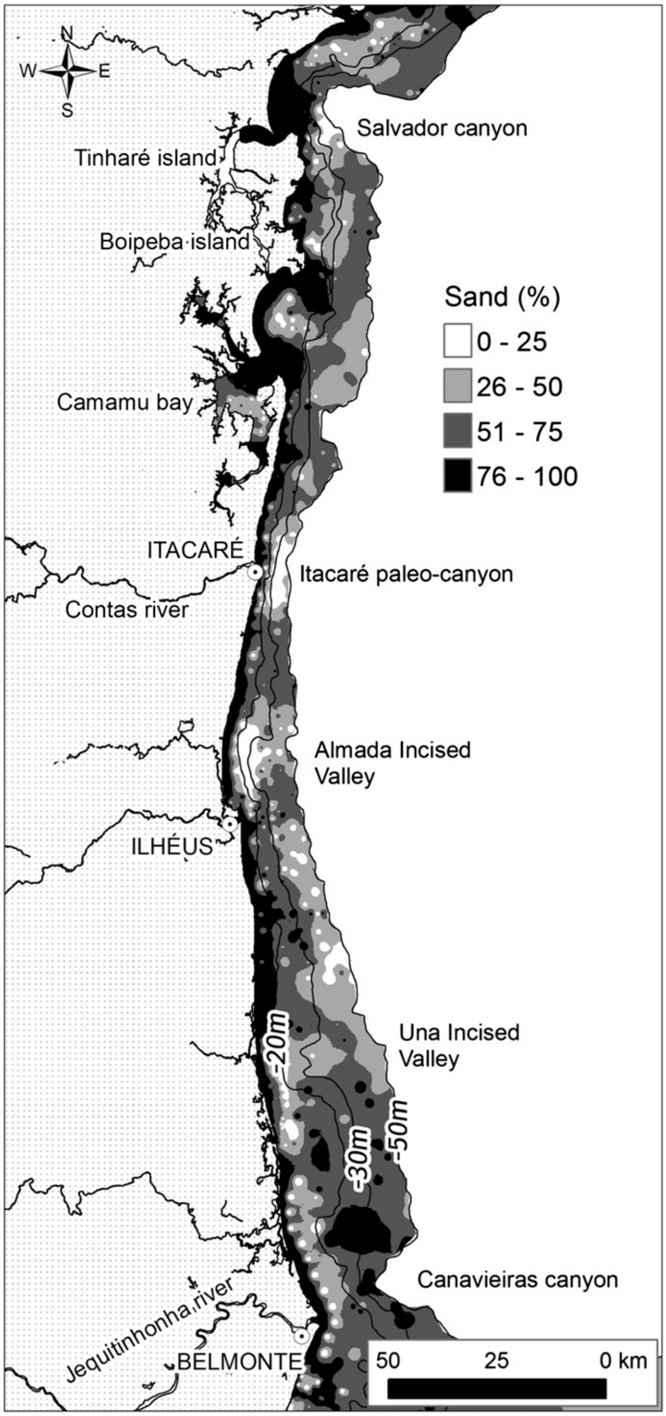

Fig. 7. Percentage of sand in the surficial shelf sediment. Sand content is greater in a narrow belt bordering the shoreline, where it is dominantly siliciclastic. On the rest of the shelf the sand fraction has a bioclastic origin. Please compare with Figs. 9 and 10.

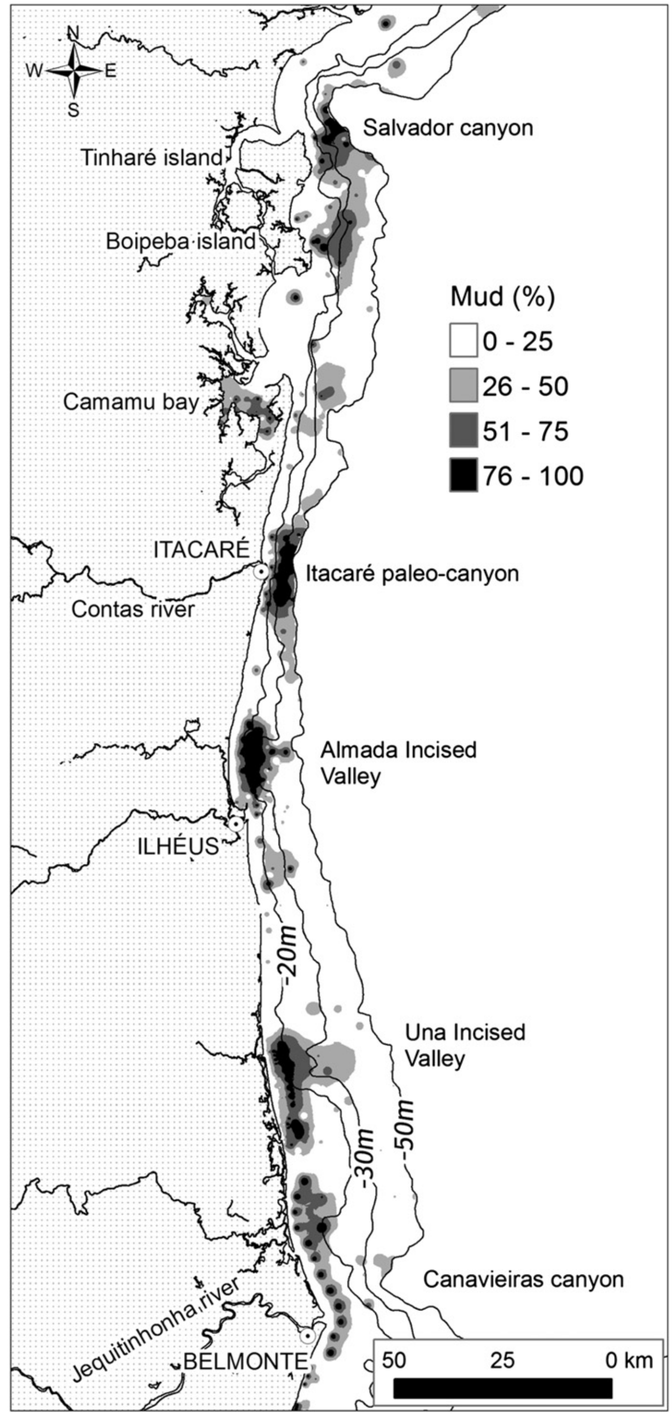

Fig. 8. Percentage of mud in the surficial shelf sediment. Mud depocenters are associated with unfilled incised valleys, canyon heads, the mid-shelf step and major river mouths.

dominate during the austral spring–summer months (residual currents: 22–15 cm/s at the surface and 2–5 cm/s at the bottom) (Amorim, 2005).

The north and south geostrophic Brazil currents, although flowing essentially along the continental slope, sometimes overflow the shelf break, flooding the outer shelf. These two currents originate from the bifurcation of the South Equatorial current when it reaches South America. The position of this bifurcation varies from approximately 13°S (November) to 17°S (July) (Rodrigues et al., 2007).

3.3. Climate and sediment supply

The climate in the hinterland is very humid with annual precipitation reaching more than 2000 mm along the coast, decreasing to less than 1000 mm/year in more interior areas.

The most important river emptying into the study area is the Jequitinhonha (drainage basin: 70,315 km^2; mean discharge: 464 m^3/s; solid discharge: 7.89×10^6 t/year). This river has constructed a large wave-dominated delta (Dominguez et al., 2009) (Fig. 2). All other rivers are considerably smaller and may contribute a limited sediment load to the coastal zone, although no direct measurements are available.

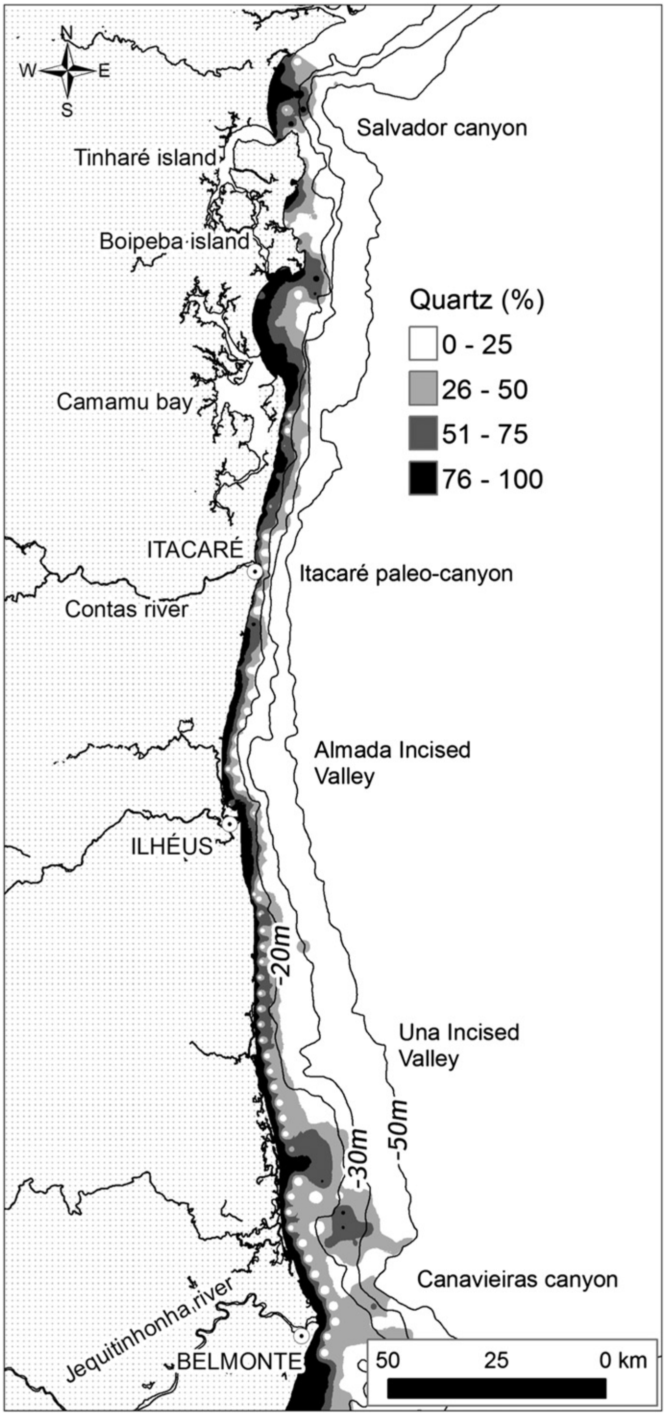

Fig. 9. Percentage of quartz in the coarser fraction (gravel to medium sand) of the surficial shelf sediment. Quartz grains are restricted to a narrow belt bordering the shoreline. Please compare with Fig. 7.

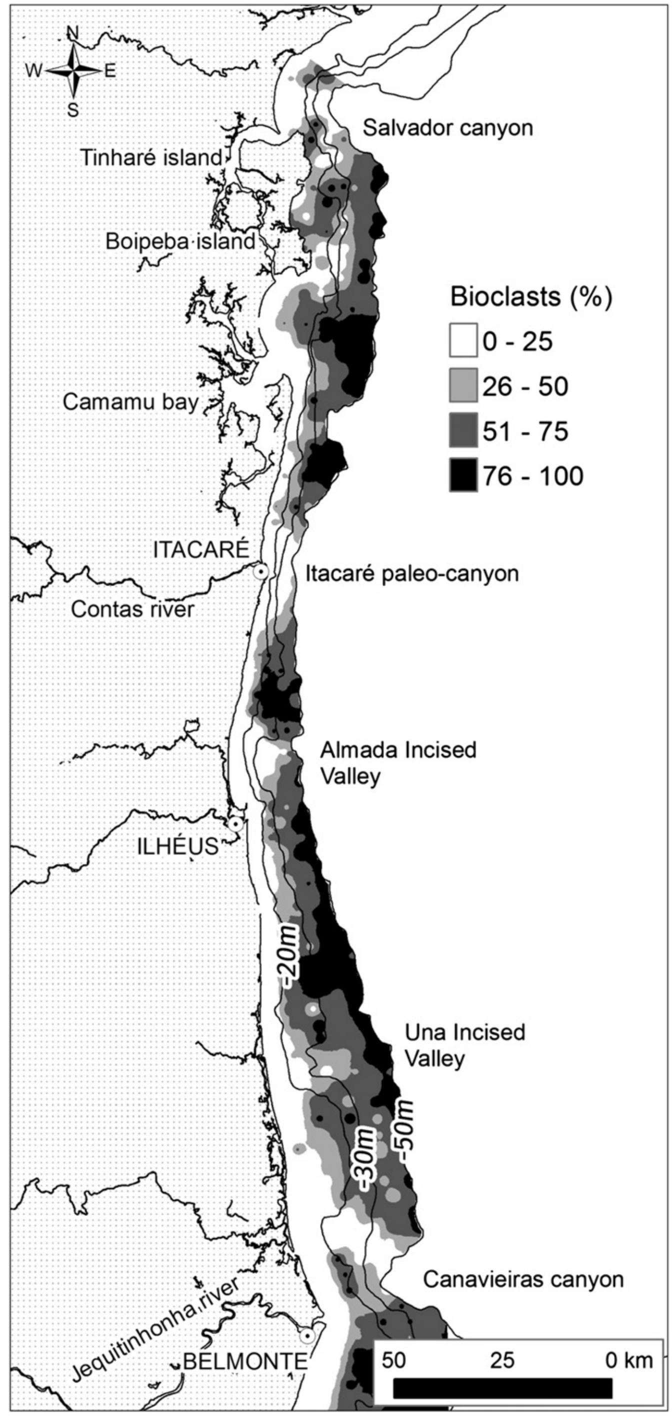

Fig. 10. Bioclast content in the coarser fraction (gravel to medium sand) of the surficial shelf sediment.

3.4. Bathymetry

The average shelf width at our study area is 20 km, with the maximum and minimum values found in front of Canavieiras (32 km) and Itacaré (7 km), respectively (Fig. 2). Many of the physiographic features present on the shelf are controlled by the structural framework of the marginal basins (Fig. 3). The outer shelf is usually separated from the inner shelf by a high-gradient step located between 20 and 30 m, which, in many sectors, coincides with the limit of the shallow basement (Figs. 3 and 5). In front of Camamu Bay, where the shelf is wider, its limits are coincident with those of an Albo-Cenomanian carbonate platform (Fig. 3). Several canyons dissect the slope at the study area. The most important canyons are the Salvador and the Canavieiras, both indenting the continental shelf (Fig. 3). Some of these canyons exhibit a structure inherited from the framework of the marginal basins. This is the case for the Salvador canyon, which is controlled by the Salvador transfer zone (ZTS), where a marked change in the original continental margin orientation occurs (from N–S to NE–SW) (Ferreira et al., 2009). The Salvador canyon has been active since the Paleocene and represents an important conduit for coarse sediments transfer to the deep basin (Ferreira et al., 2009). Two other paleocanyons, the Itacaré and Almada, both date from the Cretaceous (Coniacian—90 Ma) (D'Avila et al., 2004; Karam, 2005).

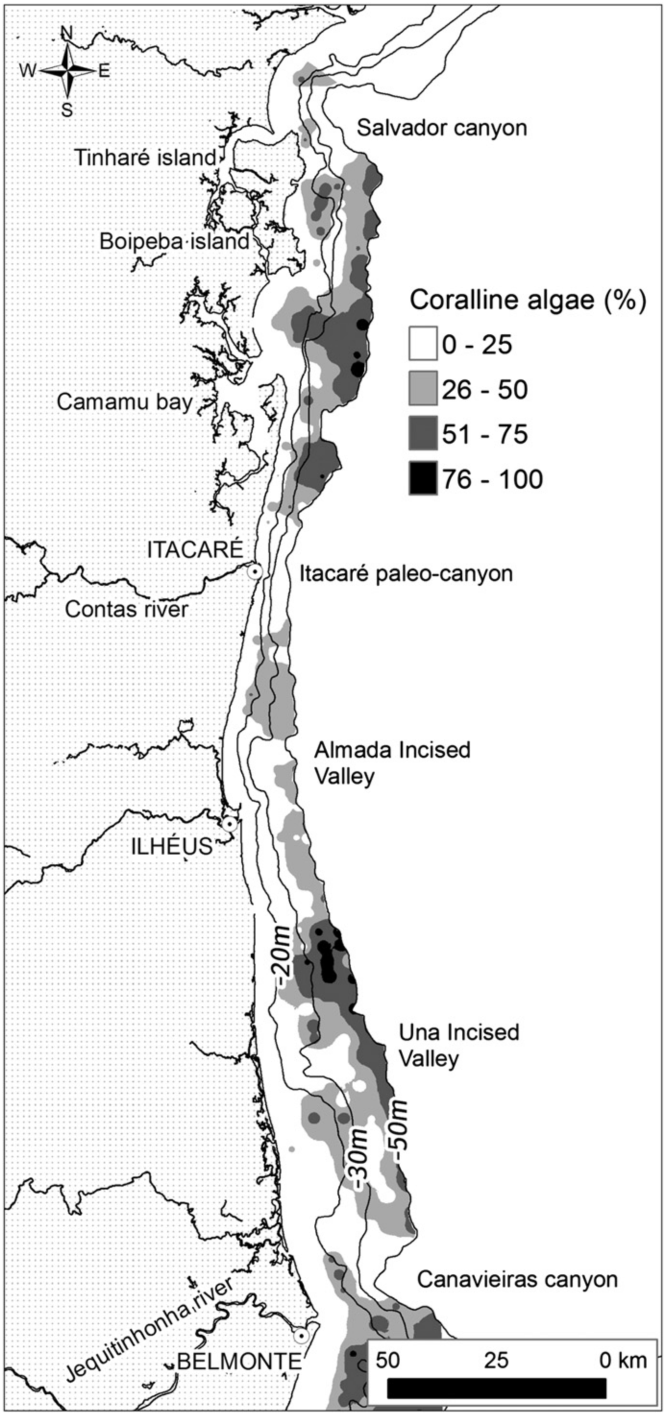

Fig. 11. Percentage of fragments of incrusting coralline algae in the coarser fraction (gravel to medium sand) of the surficial shelf sediment. Coralline algae is a major constituent of the shelf sediments in the outer shelf, particularly close to the shelf break due to a higher availability of hard substrates in this region.

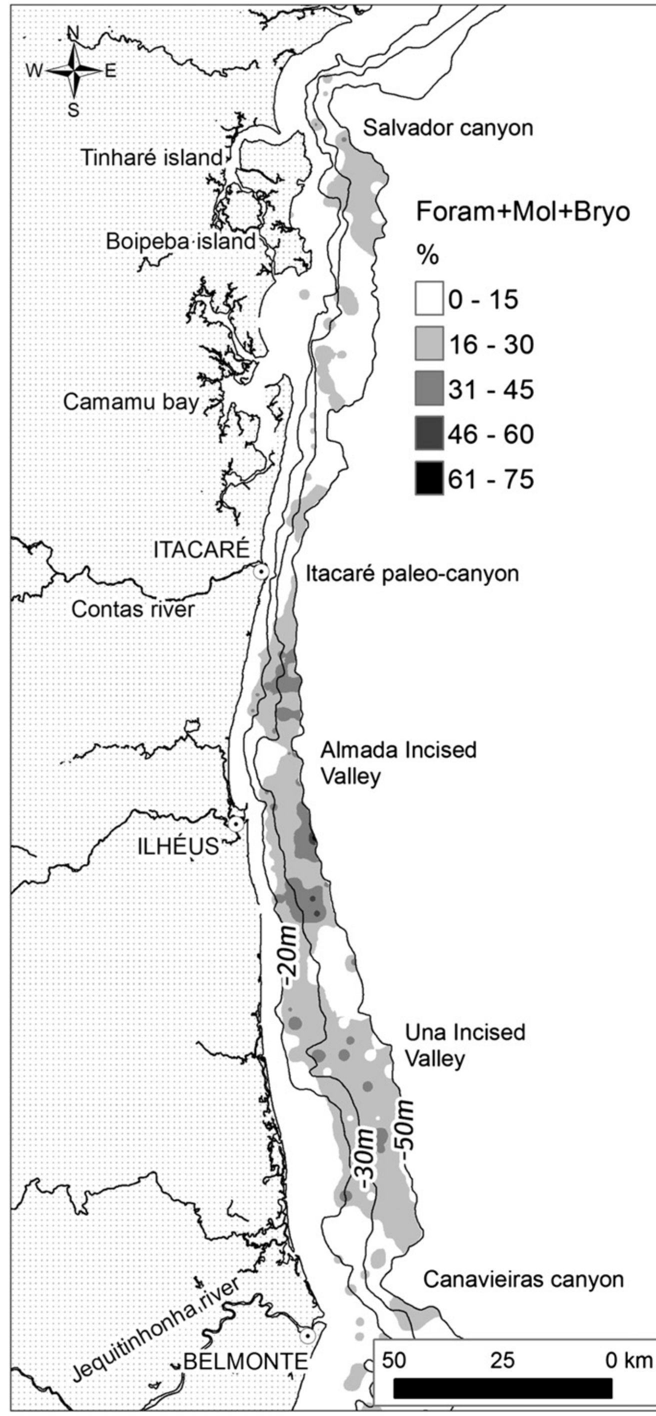

Fig. 12. Combined percentage of fragments of foraminifera, molluscs and bryozoans in the coarser fraction (gravel to medium sand) of the surficial shelf sediment.

Although these paleocanyons are considerably smaller today, they still control the characteristics of sedimentation on the continental shelf (Almeida, 2006), by creating high-gradient areas which favors deposition of fine-grained sediments.

Major hinge lines of the maritime sedimentary basins control the position of the shelf break (Figs. 3 and 5A). The outer shelf is virtually flat and dominated by hard substrates, as shown by the available bathymetric and side-scan records. It is locally dissected by small gullies (Fig. 4). Low-lying shelf areas are controlled by incised valleys (rivers Almada and Una), paleocanyons (rivers Itacaré and Almada) and canyon heads indenting the shelf (rivers Salvador and Canavieiras).

4. Results

4.1. Shelf sediments — texture and composition

Sandy sediments occur along the entire shelf area, with the highest percentages close to the shoreline. Figs. 6–8 show the spatial distributions of the gravel, sand and mud fractions of the surficial sediments, respectively (see supplementary material for the complete dataset used in preparing these maps). Quartz is the major sediment component

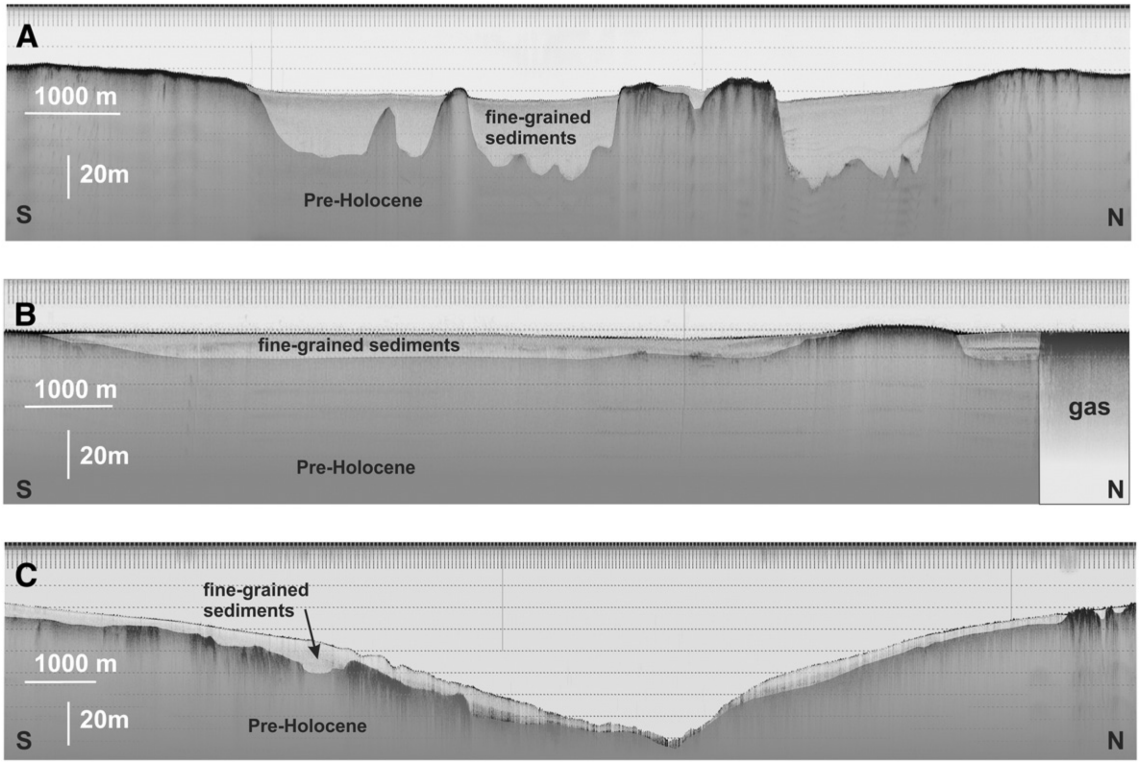

Fig. 13. Interpreted chirp records of major mud depocenters in the study area. A — Almada incised valley, B — Itacaré river mouth (Itacaré paleo-canyon), C — Salvador canyon (see Fig. 2 for location).

near the shoreline up to a depth of approximately 15–20 m, forming a narrow belt. Significant accumulations of quartz sands are present in front of Camamu Bay and neighboring tidal inlets, associated with ebb-tidal deltas (Fig. 9). In the remainder of the shelf, sandy sedimentation is essentially bioclastic with major constituents represented by incrusting coralline algae (Figs. 10 and 11), followed, in importance, by forams, mollusks and bryozoans (Fig. 12). Within Camamu Bay, bioclasts are scarce and represented mostly by molluscs and fecal pellets, and these bioclasts occur in the central bay area in association with fine-grained sediments.

Gravelly sediments are restricted to the outer shelf in waters usually deeper than 30 m (Fig. 6), especially close to the shelf edge. These gravelly sediments are exclusively bioclastic (Fig. 10), with major constituents including incrusting coralline algae and rhodoliths (Fig. 11), forams, mollusks and bryozoans (Fig. 12). These three last components are more common south of the Contas River, with major abundances found in the vicinity of the Almada incised valley. This carbonate sedimentation is most likely still active because in many of the grab samples, living rhodoliths and fragments of coralline algae were recovered.

Mud depocenters disrupt the above patterns and form distinct the mud distribution centers (Fig. 8): (i) the Salvador canyon head, (ii) in front of Boipeba island, (iii) the mouth of the Contas River, (iv) the incised valleys of Almada and Una, and (v) the mouth of the Jequitinhonha River. Mud percentages greater than 75% are characteristic of these depocenters. On the outer shelf, the mud content averages 10–20%. CHIRP records show that fine-grained sediments reach a thickness of up to 40 m at the Almada incised valley (Fig. 13A) and at least 10 m in front of the Contas River, at the 20 m isobath (Fig. 13B). At the Salvador canyon head, Holocene fine-grained sediments reach up to 15 m (Fig. 13C). No information about the composition of these fine sediments is available (e.g., carbonate vs. siliciclastic). Gas is present in some records of the Almada and Contas depocenters.

4.2. Radiocarbon ages

Whereas there an abundance of radiocarbon dates of the Quaternary deposits and coral build ups in the coastal zone exists (Suguio et al., 1985; Martin et al., 1996; and references therein), datings of shelf sediments are limited to just four piston cores collected in the area (Fig. 2), presented in Table 1. All cores were composed of a packstone/wackstone facies dominated by encrusting coralline algae, rhodoliths, mollusks and forams. Sediment accumulation rates of 0.3–0.4 mm/year are estimated for the carbonate sediments at the shelf edge based on these dates. The datings further show carbonate sedimentation to have began 10,000 years ago, coincident with transgressive shelf inundation.

Table 1
Radiocarbon ages of piston-core samples. For location see Fig. 2.

Piston-core	Total penetration	Position of sample below sediment–water interface	Material dated	Conventional	AMS ^{14}C date (2 sigma calibration)	Beta Analytic Inc. Number
P36	290 cm	250 cm	Rhodolith	8160 ± 40 BP	Cal BP 8760 to 8440	Beta-298207
P18	210 cm	200 cm	Rhodolith	9430 ± 40 BP	Cal BP 10,380 to 10,140	Beta-298205
P17	310 cm	300 cm	Coralline Algae	8030 ± 40 BP	CAL BP 8570 to 8340	Beta-298204
P31	400 cm	390 cm	Coralline Algae	9500 ± 40 BP	Cal BP 10,480 to 10,190	Beta-298206

Calibration database IntCal04. Samples dated at Beta Analytic Inc., Florida, USA.

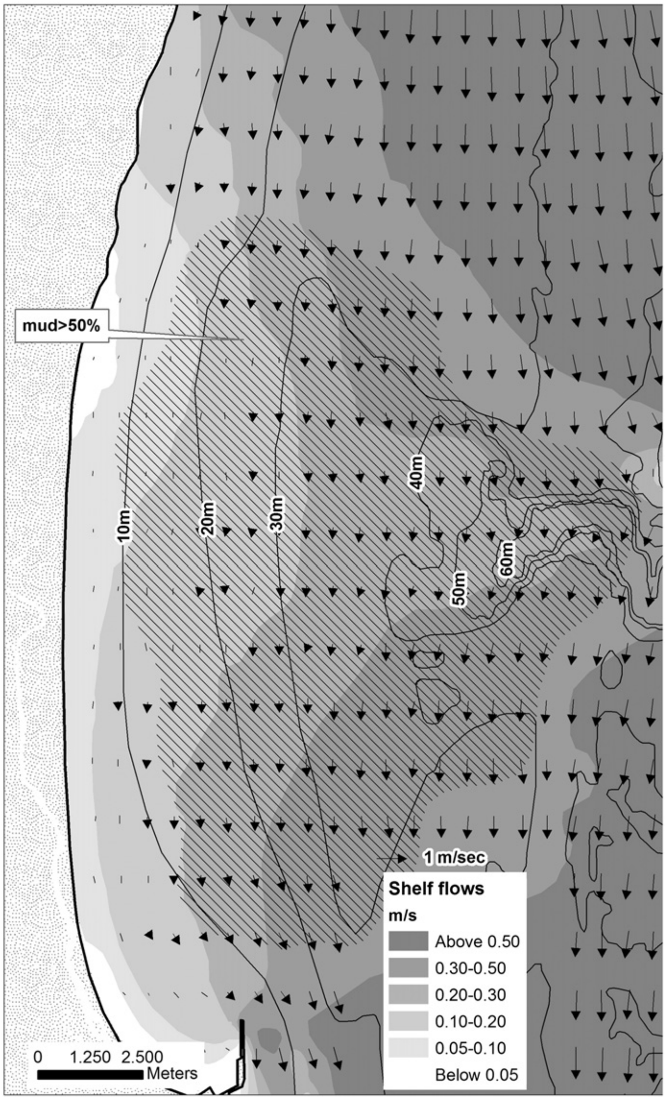

Fig. 14. Present continental shelf flows at the Almada incised valley, illustrating the decelerating effect of these low-lying areas, inducing fine grained sediment deposition. Modified from Hydros-Orienta-Derba (2011).

5. Discussion

5.1. Nature of grain assemblages

Sedimentation at the narrow, shallow shelf of central Brazil is dominantly carbonatic and occurs under humid tropical climate conditions. From the perspective of the grain assemblages, the dominant carbonate lithofacies at our study area is the Rhodoalgal (sensu Carannante et al., 1988), also known as Foramol (sensu Lees and Buller, 1972). Surprisingly, this type of grain assemblage is commonly believed to be characteristic of warm temperate zones in the transition between a cold temperate (molechfor lithofacies) and a tropical zone (chlorozoan and chloralgal lithofacies) (Carannante et al., 1988).

More recently, Wilson and Vecsei (2005) performed an extensive literature review and found that carbonate sedimentation in tropical low-latitude shelves in SE Asia and Australia is characterized by non-framework building light-dependent biota (benthic foraminifera and coralline algae), typical of the foramol assemblage. Wilson (2012) has reported that many features of warm-water carbonate systems from humid equatorial systems show similarities to carbonate systems formed in cooler waters, in contrast with the better-studied arid tropical carbonate systems. This misperception was attributed partly to a general lack of published data from tropical humid regions. The characteristics of the central Brazil shelf allow us to classify it as a platform dominated by a deep oligophotic interior with minimal areas of very shallow water (10 m or less) and non-existent to very minor framework development (Wilson and Vecsei, 2005). These authors state that in this type of platform, the major factor controlling the distribution of grain assemblages is water depth. At the better-known tropical shelves of SE Asia and Australia, biota changes occur at approximately 20 m of depth (Wilson and Vecsei, 2005). These changes are related to different wavelength light components. Coral and their simbionts absorb light predominantly in the violet-blue and red wavelengths (Falkowski et al., 1990), characteristic of shallow to moderate depths of the euphotic zone, whereas coralline algae have photosynthetic pigments that are attenuated to blue and green wavelength light, characteristic of the oligophotic zone (Wilson and Vecsei, 2005).

The decrease in available light at approximately 20 m in tropical shelves could be because tropical humid areas usually present major levels of suspended sediments and nutrients and consequently less light penetration, thus reducing the limits of the euphotic zone and inhibiting the development of corals (Wilson and Vecsei, 2005). Although our results fit well in this picture, it should be noted that those factors alone are not sufficient to explain the absence of widespread framework builders in central Brazil. Coral growth is not inhibited at our study area, even under such humid conditions. We believe that a lack of suitable shallow hard substrates in the shelf interior is also a contributing factor. In fact, at the study area, framework builders are present in very shallow areas bordering the shoreline, growing on top of abrasion terraces carved into Mesozoic rocks. In these shallow areas, fringing reefs occur. Halimeda is an important component of the reef flat and lagoon (Leão et al., 2003; Rebouças et al., 2011), i.e. of the so-called Photozoan or Chlorozoan communities (sensu Lees and Buller, 1972; James, 1997, respectively). The presence of these Chlorozoan communities is directly reflected in the composition of the nearby beach sands, such as on the Tinharé and Boipeba islands (Rebouças et al., 2011).

The most important coral buildups of the western South Atlantic are located south of our study area, at the Abrolhos bank (Leão et al., 2003) (Fig. 1). Even there, the distributions of major reef buildups are controlled by the availability of areas shallower than 20 m, which are associated with salt tectonics and volcanic build-ups (Dominguez et al., 2012). These reef buildups are characterized by endemic species tolerant of high levels of suspended sediments (Leão et al., 2003). However, in the rest of the Abrolhos bank and the nearby Royal Charlotte bank, non-framework grain assemblages comprised of coralline algae dominate (Moura et al., in press). On the outer shelf, the low sediment accumulation rates are suggestive of the presence of “give-up” (sensu Neumann and Macintyre, 1985).

5.2. Factors controlling fine-grained sediment distribution

At the narrow shallow shelf of central Brazil, the distribution of mud depocenters is strongly controlled by shelf physiography, which in turn is a result of antecedent geology and extended subaerial exposure of the shelf during the Quaternary period. Low-lying areas on the shelf are associated with large unfilled incised valleys or canyon heads indenting the shelf. These low-lying areas promote deceleration of shelf currents, thus creating natural traps for fine-grained sediments (Fig. 14). In addition to decelerating the shelf flows, these areas also create additional accommodation space in this otherwise very shallow shelf. Thus, for example, the fine-grained sediment accumulation in front of the Contas River is considerably larger than at the Jequitinhonha because of the availability of a substantially larger accommodation space inherited from the Itacaré paleo-canyon (Figs. 3 and 8). In front of a major river such as the Jequitinhonha, mud accumulation is minimal and restricted to a narrow belt bordering the shoreline.

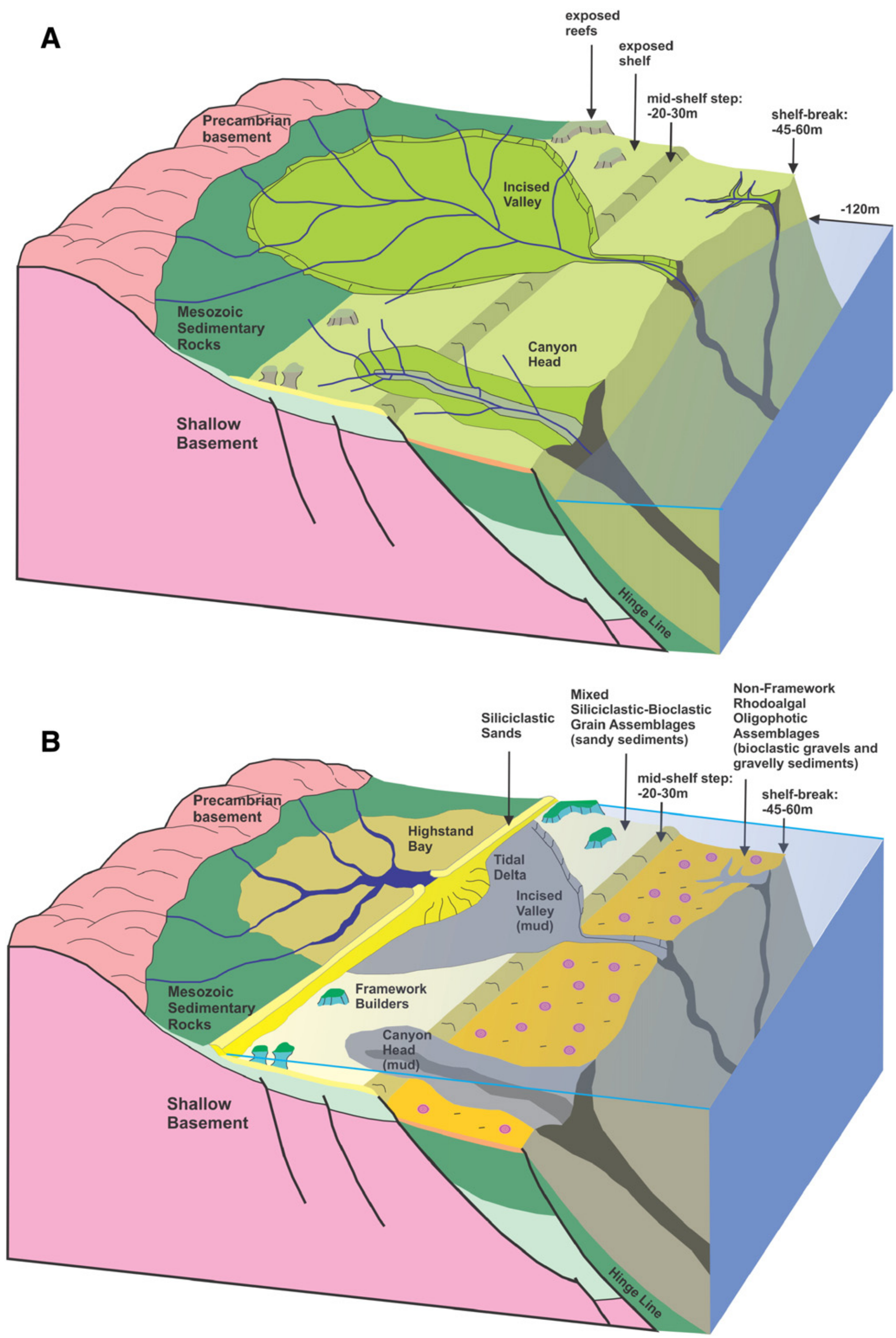

Fig. 15. Conceptual model for sedimentation in the narrow, shallow shelf off central Brazil. A — Lowstand sedimentation — because of the shallow shelf break, widespread erosion of the shelf and adjacent coastal zone dominated during most of the Quaternary. Differential erosion between Mesozoic and Precambrian rocks, locally favored the development of large incised valleys. B — Highstand sedimentation — during the few, brief highstand episodes, the shelf and coastal zone were flooded. Highstand coastal bays formed at the upstream end of incised valleys and were later infilled. On the shelf these incised valleys were partially infilled with fine-grained sediments. On the rest of the shelf, the reduced siliciclastic influx favored an essentially carbonate sedimentation, of non-framework rhodoalgal, oligophotic grain assemblages. Framework builders (hermatipic corals) developed on the very shallow areas bordering the coastline.

Just offshore of this mud belt, bioclastic sedimentation occurs. The mud depocenter of the Jequitinhonha river delta is displaced northward, where the Una-incised valley provides adequate accommodation space.

The role of antecedent geology in controlling the distribution of mud-depocenters on present-day shelves has not received adequate attention in the recent literature. Most studies of mud depocenters have placed too much emphasis on present day processes, ignoring the fundamental role of antecedent geology and inheritance (Phillips, 2007). For example, George and Hill (2008) evaluated the sand–mud transition, defined by greater than 25% mud, and using fifteen worldwide examples, concluded that this transition is controlled by the wave height. No significant correlation was found between the depth of this transition and the load of fluvial sediments or secondary parameters, such as shelf width and gradient. Walsh and Nittrouer (2009), based on a compilation of 105 worldwide fluvial systems (discharge, wave and tidal regime and shelf width), proposed a model for fine-grained sediment partitioning and dispersal that includes five basic types (estuarine accumulation dominated (EAD), canyon captured (CC), proximal accumulation dominated (PAD), marine dispersal dominated (MDD), and subaqueous delta clinoform (SDC)). These results are not consistent with our findings because in central Brazil, the most significant mud depocenters bear no direct relationship with major fluvial systems but are instead controlled by the availability of depressed areas on the shelf, usually related to unfilled incised valley systems. Processes such as wave and tidal regimes would act on top of this first-order control.

6. Quaternary evolution

During the younger part of the Quaternary, the average sea level position was approximately −65 m below present MSL (Blum and Hattier-Womack, 2009). Because of the shallow depth of the shelf break, the entire shelf of our study area was subaerially exposed for the majority of the last glacial cycles. This exposure favored extensive erosion of the shelf surface associated with the development of valley incisions. Incision most likely began as soon as the sea level dropped below 20–30 m, with the appearance of a nickpoint in the mid-shelf step (30 m). The landward migration of the nickpoint propagated the eustatic signal, particularly along the less resistant Mesozoic sedimentary rocks, embedding smaller drainage basins on top of the pre-existing ones and thus creating low-lying areas on the exposed shelf (Fig. 15A). Major processes operating during sea-level lowstands include widespread erosion and movement of sediment to the shelf edge (Dominguez et al., 2012). During the last deglaciation event, this landscape was rapidly drowned by rapidly rising sea levels (1–5 m/100 years) (Berger, 2008; Bard et al., 2010). Flooding of the shelf began approximately 10,000 years ago and was completed 3000 years later (Dominguez et al., 2012). Therefore, almost instantaneously, oligophotic conditions were created in the outer shelf, where non-framework carbonate sedimentation began (Fig. 15B).

Along the coastal zone, as soon as the eustatic sea-level stabilized, smaller estuaries and bays were rapidly infilled and siliciclastic sands accumulated along the shoreline, reaching high levels in the vicinities of tidal deltas and larger river mouths (Dominguez, 2009; Dominguez et al., 2009). Carbonate framework builders began developing on the shallow euphotic areas fringing the coastline, using the hard substrates available (e.g., abrasion terraces carved into the Mesozoic sedimentary rocks). The endemic coral fauna adapted to high-turbidity levels, allowing the development of framework buildups in those places (Leão et al., 2003). The low lying areas on the shelf surface, such as ancient incised valleys and canyon heads, trapped fine-grained sediments dispersed shelf-wide as a result of their decelerating effect on the shelf flows (Fig. 15B).

7. Economic uses of the continental shelf

The geologic inheritance upon which present day oceanographic processes act exerts a major influence on the shelf habitats and human uses of this region and should be considered in the environmental management of this area. Line-hook fishing is the most extensive human activity, although it is restricted to the outer shelf/shelf break (Fig. 16). This activity is typical of tropical countries with an artisanal fleet characterized by small wooden vessels 5 to 12 m long. Line-hook fishing targets highly commercial demersal species (snapper, grouper) associated with hard bottoms, such as those present in the outer shelf, incised valley walls, canyon heads, submarine gullies and rocky reefs. In decreasing order of importance, the most captured families are the Lutjanidae (demersal), Carangidae (pelagic), Scombridae (pelagic) and Serranidae (demersal) (Nunes, 2009; Olavo et al., 2011). In all of these families, the captured genera have carnivorous habits with a direct dependence on hard-ground benthic communities (small fish, crustaceans and polychaeta) (Nunes, 2009).

Limited trawling is practiced in a few of the mud depocenters, and it is precluded in the rest of the shelf by a lack of adequate substrates (Nunes, 2009). Other shelf uses include the disposal of dredged sediments from port facilities at Salvador and Ilheus. The dredged sediments are disposed of at two licensed sites offshore of the continental shelf edge (Fig. 16). A new port facility north of Ilhéus is planned to begin construction soon, which will involve the dredging of approximately 16 million cubic meters of sediment. This will certainly increase use conflicts with the artisanal fisheries.

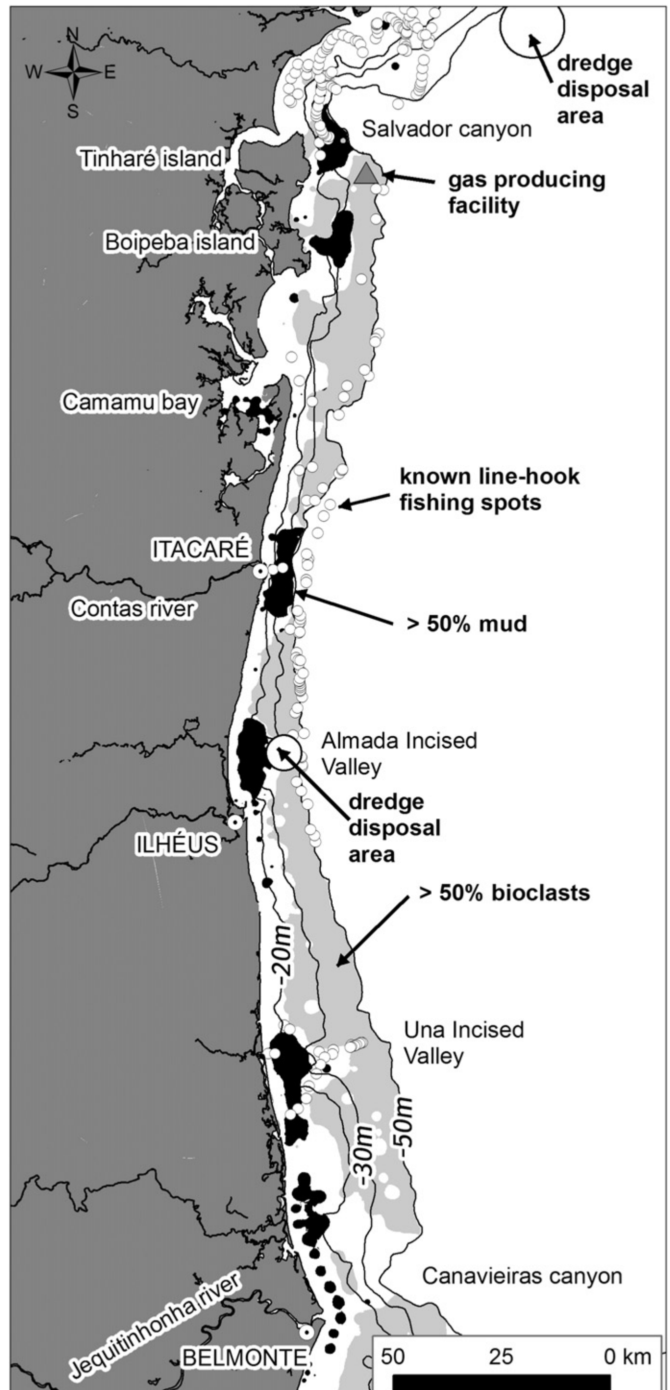

Fig. 16. Major human uses in the eastern narrow shelf off eastern Brazil. Fishing spot distribution are from Nunes (2009) and other unpublished data.

Oil exploration is still in its early stages compared, for example, with southern Brazil, where major reserves are located. Presently, there is only one gas-producing facility on the shelf with reserves of 72.5 billion BOE and a daily production of 6 million m^3 (http://www.mzweb.com.br/ref). Most oil exploration is focused on the slope, where most of the sediment accumulation has occurred since the South America–Africa break up (Ferreira et al., 2009). Therefore, this activity is not expected to expand over the shelf.

8. Conclusions

This paper presents a description of sedimentation in a narrow, shallow shelf located in a humid tropical area of the South Atlantic ocean. The main economic use of the shelf is artisanal line-hook fishing targeting high-value species associated with hard bottoms on the outer shelf. The physiography and sediment composition of the shelf was, however, poorly documented so far.

Collected seismic data and information on sediment grain assemblages show the seafloor geomorphology to result from the interaction between (i) a geologic inheritance influenced by a stable cratonic basement, (ii) extended exposure during most of the Quaternary period, (iii) limited sediment supply and (iii) lack of hard substrates shallower than 20 m. Sedimentation is characterized by non-framework grain assemblages dominated by encrusting coralline algae in the oligophotic outer shelf and limited framework builders fringing the shoreline. Mud depocenters are controlled by the accommodation space created by large incised valleys and canyon heads indenting the shelf.

Acknowledgments

This study is a contribution of inctAmbTropic — Brazilian National Institute of Science and Technology for Tropical Marine Environments, CNPq/FAPESB Grants: 565054/2010-4 and 8936/2011 and of IGCP Project 526. Financing for data acquisition over the last 10 years was provided by CBPM (Campanhia Baiana de Pesquisa Mineral) and CNPq (Conselho Nacional de Desenvolvimento Cientïfico e Tecnológico). JML Dominguez thanks CNPq for a Research Fellowship. This paper was greatly improved by the comments of Dr. Michael Scott Harris, another anonymous reviewer, and Dr. K.M. Cohen as special issue editor, for his patience and enthusiastic support.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geomorph.2013.07.004. These data include Google maps of the most important areas described in this article.

References

Alkmim, F.F., Marshak, S., Fonseca, M.A., 2001. Assembling West Gondwana in the Neoproterozoic: clues from the São Francisco craton region, Brazil. Geology 29, 319–322.

Almeida, A.B., 2006. História de Preenchimento do Vale Inciso da Lagoa Encantada – Ilhéus-B A – Durante o Quaternário. (M.Sc. Thesis) Universidade Federal da Bahia, Brazil (130 pp.).

Amorim, F.N., 2005. Caracterização Oceanográfica da Baía de Camamu e Ad-jacências e Mapeamento das Áreas de Risco à Derrames de Óleo. (M.Sc. Thesis) Universidade Federal da Bahia, Brazil (191 pp.).

Amorim, F.N., Cirano, M., Soares, I.D., Lentini, C.A.D., 2011. Coastal and shelf circulation in the vicinity of Camamu Bay (14S), Eastern Brazilian shelf. Continental Shelf Research 31, 108–119.

Barbosa, J.S.F., Sabaté, P., 2004. Archean and Paleoproterozoic crust of the São Francisco craton, Bahia, Brazil: geodynamic features. Precambrian Research 133, 1–27.

Bard, E., Hamelin, B., Delanghe-Sabatier, D., 2010. Deglacial meltwater pulse 1B and younger dryas sea levels revisited with boreholes at Tahiti. Science 327, 1235–1237.

Berger, W., 2008. Sea level in the late Quaternary: patterns of variation and implications. International Journal of Earth Sciences 97, 1143–1150.

Blum, M.D., Hattier-Womack, J., 2009. Climate change, sea-level change, and fluvial sediment supply to deepwater depositional systems. In: Kneller, B., Martinsen, O.J., McCaffrey, B. (Eds.), External Controls on Deep-Water Depositional Systems. SEPM Special Publication, 92. SEPM, Tulsa, Oklahoma, USA, pp. 15–40.

Campos, R.H.S., Dominguez, J.M.L., 2010. Mobility of sediments due to wave action on the continental shelf of the northern coast of state of Bahia. Brazilian Journal of Oceanography 58, 57–63.

Carannante, C., Esteban, M., Milliman, J.D., Simone, L., 1988. Carbonate lithofacies as paleolatitude indicators: problems and limitations. Sedimentary Geology 60, 333–346.

Cawthra, H.C., Neumann, F.H., Uken, A.M., Smith, A.M., Guastella, L.A., Yates, A., 2012. Sedimentation on the narrow (8 km wide), oceanic current-influenced continental shelf off Durban, Kwazulu-Natal, South Africa. Marine Geology 323–325, 107–122.

Cobbold, P.R., Gilchrist, G., Scotchman, I., Chiosso, D., Chaves, F.F., Souza, F.G., Lilletveit, R., 2010. Large submarine slides on a steep continental margin (Camamu Basin, NE Brazil). Journal of the Geological Society 167, 583–592.

D'Avila, R.S.F., Souza Cruz, C.E., Oliveira Filho, J.S., Jesus, C.M., Cesero, P., Dias Filho, D.C., Lima, C.C., Queiroz, C.L., Santos, S.F., Ferreira, E.A., 2004. Fácies e modelo deposicional do Canyon de Almada, Bacia de Almada, Bahia. Boletim de Geociencias da Petrobrás 12, 251–286.

Dominguez, J.M.L., 2007. Sediment transfer mechanisms from the coastal zone/shelf to the slope/basin during the last 400,000 yrs: a case study for the north-central shelf of Bahia state. Tenth International Congress of the Brazilian Geophysical Society, Rio de Janeiro, Brasil (CD-ROM — 4 pp.).

Dominguez, J.M.L., 2009. The coastal zone of Brazil. In: Dillenburg, S.R., Hesp, P. (Eds.), Geology and Geomorphology of Holocene Coastal Barriers of Brazil. Springer-Verlag, Berlin, Heidelberg, pp. 17–52.

Dominguez, J.M.L., Bittencourt, A.C.S.P., 2009. Geologia. Cap II. In: Hatge, V., Andrade, J.B. (Eds.), Baía de Todos os Santos – Aspectos Oceanográficos. EDUFBA, Salvador, Bahia, Brazil, pp. 25–66.

Dominguez, J.M.L., Andrade, A.C.S., Almeida, A.B., Bittencourt, A.C.S.P., 2009. The Holocene barrier strandplains of the state of Bahia. In: Dillenburg, S.R., Hesp, P. (Eds.), Geology and Geomorphology of Holocene Coastal Barriers of Brazil. Springer-Verlag, Berlin, Heidelberg, pp. 253–288.

Dominguez, J.M.L., Nunes, A.S., Rebouças, R.R., Silva, R.P., Freire, A.F.M., 2012. A Plataforma Continental do Estado da Bahia. In: Barbosa, J.M.L., Mascarenhas, J., Gomes, L.C.C., Dominguez, J.M.D. (Eds.), Geologia da Bahia, vol. 2. Companhia Baiana de Pesquisa Mineral, Bahia, Brazil, pp. 427–496.

Falkowski, P.G., Jokiel, P.L., Kinzie III, R.A., 1990. Irradiance and corals. In: Dubinsky, Z. (Ed.), Coral Reefs — Ecosystems of the World, vol. 25. Elsevier, Amsterdam, pp. 89–107.

Ferreira, T.S., Caixeta, J.M., Lima, D., 2009. Controle do embasamento no rifteamento das bacias de Camamu e Almada. Boletim de Geociências da Petrobrás 17, 69–88.

George, D.A., Hill, P.S., 2008. Wave climate, sediment supply and the depth of the sand–mud transition: a global survey. Marine Geology 254, 121–128.

Ginsburg, R.N., 1956. Environmental relationships of grain size and constituent particles in some South Florida carbonate sediments. American Association of Petroleum Geologists Bulletin 40, 2381–2427.

Harris, P.T., Baker, E.K. (Eds.), 2011. Seafloor Geomorphology as Benthic Habitat. Geohab Atlas of Seafloor Geomorphic Features and Benthic Habitats. Elsevier Insights (900 pp.).

Hydros-Orienta-Derba, 2011. Estudo de Impacto Ambiental Porto Sul. Technical report. Tomo 2, vol. 6. Derba, Governo do Estado da Bahia, Brazil (226 pp.).

James, N.P., 1997. The cool-water depositional realm. In: James, N.P., Clarke, J.A.D. (Eds.), Cool-Water Carbonates. SEPM Special Publication, 56. SEPM, Tulsa, Oklahoma, USA, pp. 1–20.

Karam, M.R.K., 2005. Integração de Ferramentas Multidisciplinares para o Estudo de Feições Tectônicas e Sismoestratigráficas na Bacia de Camamu-Almada, Bahia. (Ph.D. Thesis) Universidade Federal do Rio de Janeiro, Brasil — COPPE/UFRJ (189 pp.).

Lantzsch, H., Hanebuth, T.J.J., Bender, V.B., 2009. Holocene evolution of mud depocentres on a high-energy, low-accumulation shelf (NW Iberia). Quaternary Research 72, 325–336.

Lea, D.W., Martin, P.A., Pak, D.K., Spero, H.J., 2002. Reconstructing a 350 ky history of sea level using planktonic Mg/Ca and oxygen isotope records from a Cocos Ridge core. Quaternary Science Reviews 21, 283–293.

Leão, Z.M.A.N., Kikuchi, R.K.P., Testa, V., 2003. Corals and coral reefs of Brazil. In: Cortés, Jorge (Ed.), Latin American Coral Reefs. Elsevier, Amsterdam, pp. 9–52.

Lees, A., Buller, A.T., 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Marine Geology 13, 67–73.

Lessa, G.C., Cirano, M., 2006. On the circulation of a coastal channel within the Abrolhos coral-reef system — Southern Bahia (1740′ S), Brazil. Journal of Coastal Research SI39, 450–453.

Lima, J.B., 2008. Caracterização Oceanográfica da Plataforma Continental na Região sob Influência dos Emissários Submarinos da Cetrel e Millennium. Monograph.Universidade Federal da Bahia, Brazil (63 pp.).

Martin, L., Suguio, K., Flexor, J.-M., Dominguez, J.M.L., Bittencourt, A.C.S.P., 1996. Quaternary sea-level history and variation in the dynamics along the central Brazilian coast: consequences on coastal plain construction. Anais da Academia Brasileira de Ciências 68, 303–354.

Milliman, J.D., 1974. Marine Carbonates. Springer-Verlag, New York (375 pp.).

Milliman, J.D., Summerhayes, C.P. (Eds.), 1975. Upper Continental Margin Sedimentation of Brazil. Contributions to Sedimentary Geology, vol. 4. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany (175 pp.).

Mohriak, W.U., 2006. Interpretação geológica e geofísica da Bacia o Espírito Santo e da região de Abrolhos: petrografia, datação radiométrica e visualização sísmica das rochas vulcânicas. Boletim de Geociências da Petrobrás 14, 133–142.

Mohriak, W.U., Paula, O., Szatmari, P., Cordani, U.G., Blakekovic, A., Sobreira, J.F., Parsons, M., MacQueen, J., Undli, T.H., Berstad, S., Weber, M., Horstad, I., 2003. Volcanic provinces in the Eastern Brazilian margin: geophysical models and

alternative geodynamic interpretations. Proceedings 8th International Congress of the Brazilian Geophysical Society, Rio de Janeiro, Brazil (CD-ROM — 4 pp.).
Mohriak, W., Nemcok, M., Enciso, G., 2008. South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil. In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., De Wit, M.J. (Eds.), West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. Geological Society, London, Special Publications, 294, pp. 365–398.
Moura, R.L., Secchin, N.A., Amado-Filho, G.M., Francini-Filho, R.B., Freitas, M.O., Minte-Vera, C.V., Teixeira, J.B., Thompson, F.L., Dutra, G.F., Sumida, P.Y.G., Guth, A.Z., Lopes, R.M., Bastos, A.C., 2013. Spatial patterns of benthic megahabitats and conservation planning in the Abrolhos Bank. Continental Shelf Research. http://dx.doi.org/10.1016/j.csr.2013.04.036 (in press).
Neumann, A.C., Macintyre, I.G., 1985. Reef response of sea level rise: keep-up, catch-up or give-up. In: Gabrie, C., Toffart, J.L., Salvat, B. (Eds.), Proceedings of the Fifth International Coral Reef Congress, Tahiti, vol. 3. Antenne Museum, French Polynesia, pp. 105–110.
Nunes, A.S., 2009. A Utilização da geologia na identificação dos habitats mais adequados para o estabelecimento de áreas marinhas protegidas na Costa do Dendê, Bahia, Brasil. (Ph.D. Thesis) Universidade Federal da Bahia, Brazil (178 pp.).
Olavo, G., Costa, P.A.S., Martins, A.S., Ferreira, B.P., 2011. Shelf-edge reefs as priority areas for conservation of reef fish diversity in the tropical Atlantic. Aquatic Conservation: Marine and Freshwater Ecosystems 21, 199–209.
Phillips, J.D., 2007. The perfect landscape. Geomorphology 84, 159–169.
Pianca, C., Manzzini, P.L.F., Siegle, E., 2010. Brazilian offshore wave climate based on NWW3 reanalysis. Brazilian Journal of Oceanography 58, 53–70.
Purdy, E.G., 1963. Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary facies. Journal of Geology 71, 472–497.
Rebouças, R.C., Dominguez, J.M.L., Bittencourt, A.C.P.S., 2011. Provenance, transport and composition of Dendê coast beach sands. Brazilian Journal of Oceanography 59, 339–347.
Rodrigues, R.R., Rothstein, L.M., Wimbush, M., 2007. Seasonal variability of the South Equatorial Current bifurcation in the Atlantic Ocean: a numerical study. Journal of Physical Oceanography 37, 16–30.
Rossetti, D.F., Bezerra, F.H.R., Dominguez, J.M.L., 2013. Late Oligocene–Miocene transgressions along the equatorial and eastern margins of Brazil. Earth-Science Reviews 123, 87–112.
Santos Filho, R.B., 2009. Estratigrafia de Seqüências no Complexo Vulcano-Sedimentar de Abrolhos (Eoceno da Bacia do Espírito Santo, Brasil). (MSc. Thesis) Universidade Federal do Rio Grande do Sul, Brazil.
Shepard, F.P., 1963. Submarine Geology. Harper and Row, New York, USA (557 pp.).
Sobreira, J.F.F., França, R.L., 2006. Um modelo tectono-magmático para a região do complexo vulcânico de Abrolhos. Boletim de Geociências da Petrobrás 14, 143–147.
Suguio, K., Martin, L., Bittencourt, A.C.S.P., Dminguez, J.M.L., Flexor, J.-M., Azevedo, A.E.G., 1985. Flutuações do Nível do mar durante o Quaternário Superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira. Revista Brasileira de Geociências 15, 273–286.
Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Science Reviews 21, 295–305.
Walsh, J.P., Nittrouer, C.A., 2009. Understanding fine-grained river-sediment dispersal on continental margins. Marine Geology 263, 34–45.
Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377–392.
Wilson, M.E.J., 2012. Equatorial carbonates: an earth systems approach. Sedimentology 59, 1–31.
Wilson, M.E.J., Vecsei, A., 2005. The apparent paradox of abundant foramol facies in low latitudes: their environmental significance and effect on platform development. Earth-Science Reviews 69, 133–168.