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PII: S0895-9811(15)30019-5

DOI: 10.1016/j.jsames.2015.07.003

Reference: SAMES 1420

To appear in: *Journal of South American Earth Sciences*

Received Date: 27 March 2015

Revised Date: 2 July 2015

Accepted Date: 3 July 2015

SHELF MORPHOLOGY AS AN INDICATOR OF SEDIMENTARY REGIMES: A SYNTHESIS FROM A MIXED SILICICLASTIC-CARBONATE SHELF ON THE EASTERN BRAZILIAN MARGIN

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ABSTRACT

Modern shelf morphology is the result of the interplay between short and long term sedimentary processes. The relation between rates of sediment supply/carbonate growth and accommodation space creation will not only control coastal transgression

and regression, but will also define the shelf sedimentary regimes acting to shape the seabed. Herein, shelf morphology and sedimentology are investigated in order to discuss how these characteristics can be representative of distinct sedimentary regimes. The study area is the eastern Brazilian shelf where coastal transgression and regression coexist with the most important coral reef system of the South Atlantic. A compilation of existing published and unpublished data was carried out in order to produce morphological and faciological maps and compare the mapped features with high-resolution seismic and sonographic data. The results show three major regions or morphological compartments: Abrolhos Shelf, Doce River Shelf and the Paleovalleys Shelf. In terms of shelf sedimentary domain, rhodolith beds predominate over the outer shelf along the entire area, coralline reefs are present along the northern Abrolhos inner shelf and a significant terrigenous mud deposit is observed associated to the Doce River adjacent inner shelf beds. The rest of the shelf is composed by bioclastic or terrigenous mud sand and gravel. Terrigenous sedimentation is always restricted to the shoreface or inner shelf shallower areas and carbonate sands and gravels are predominant elsewhere. The Abrolhos shelf shows two distinct sectors; the northern area is a typical mixed sediment environment that has a supply regime along the coast/shoreface, mainly due to longshore transport and a carbonate regime along the inner and outer shelf. The southern shelf morphology and sedimentation are controlled by the antecedent topography and is typically a accommodation regime shelf with associated rhodolith beds. The Doce river shelf is a supply regime environment with the formation of a 5 to 8m thick regressive deposit with downlapping clinoforms. Southward from the Doce river shelf, a significant shift in sedimentary regime is observed as the morphology becomes very irregular with associated hardbottoms and unfilled paleovalleys. This sector of the shelf (Paleovalley shelf) is characterized by an accommodation regime. The interpretation shows that the entire study area can be defined as a mixed sedimentation shelf, showing supply and accommodation regimes. Shelf morphology worked as an indicator of these changes. Carbonate/terrigenous deposition during a highstand/regressive phase coeval along the eastern Brazilian shelf, either laterally and across shelf. This lateral/along coast variation in sediment supply and carbonate production leads to distinct lateral facies and geometry. These spatial changes in morphology and facies, with coexistence of carbonate and siliciclastic sedimentation, are very important for the correlation and interpretation of the geological record, especially stratigraphic surfaces and sequence units.

Keywords: shelf morphology, sedimentary regimes, eastern Brazilian Shelf, shelf sedimentation.

Introduction

Shelf morphology is the result of a complex interplay between short- and long-term processes, such as: hydrodynamic conditions; sediment transport; relative sea-level changes; sediment input; biological activities and geological framework, etc (Sternberg and Nowell, 1999; Pratson, et al., 2007; Schattner et al., 2010; Brothers et al., 2013). Modern shelf morphology framework is influenced strongly by Late Quaternary sea-level changes, when high frequency regression and transgression events were determinant in setting up distinct sedimentary regimes (Riggs et al., 1996; Locker et al., 2003;

Porebski and Steel, 2006; Nichol and Brooke, 2011). Based upon this concept, sequence stratigraphy have been applied extensively to investigate the development of shelf deposits and stratigraphic surfaces.

The regime concept proposed by Swift and Thorne (1991) is used widely to understand clastic shelf sedimentation and, consequently, their morphological product. The regime concept follows the idea that over a geological time-scale, the shelf surface is in dynamic equilibrium, i.e., the variables (rates in base level changes, rates of sediment input, hydrodynamic energy and resulting sediment transport) will combine to produce the seabed morphology and the sedimentary deposits. These variables define the accommodation/starving and supply regimes; they may change with time, leading to shifts in prevailing sedimentary processes and products.

Accommodation and supply shelves are described in terms of low/high sediment input and erosive processes. In a sense, these regimes will dictate the establishment of regressive or transgressive coasts (based on Catuneanu, 2002; Catuneanu et al., 2009; Zecchin and Catuneanu, 2013) and determine the morphology of the continental shelf. The regime concept is applied mostly to clastic shelves but, in many cases, mixed sedimentation and carbonate shelves are observed. *In-situ* carbonate production associated with terrigenous sediment input will imprint also a distinct morphology to the shelf. In many cases, a karstic paleotopography represents the maximum regressive surface of the last glacial maximum (Schlager, 2005).

The reciprocal sedimentation concept, proposed by Wilson (1967), describes the alternation in carbonate-siliciclastic sedimentation between the shelf, slope and basin. This concept indicates that carbonate facies dominate slope and basin sedimentation during transgression and highstand, while siliciclastic deposits are predominant during lowstand. Along the shelf, the predominance between carbonate or siliciclastic sedimentation is a matter of the prevailing type of sedimentary regime (Swift and Thorne, 1991) and, inevitably, if there are appropriate oceanographic conditions and sufficient space for carbonate growth. Several authors have remarked that the reciprocal sedimentation concept may not reflect exactly last post-glacial sedimentation processes (e.g. Francis et al., 2007; Hinestrosa et al., 2014)

Thus, modern shelf morphology could be used as a proxy for a preliminary understanding of prevailing sedimentary regimes on continental shelves, considering that it is in dynamical equilibrium for the period from the last glacial maximum up to the present day. It might be argued that the sedimentary distribution is not in equilibrium, on the basis of the occurrence of relict sediments (Swift et al., 1971); nevertheless, this is in accordance with the regime concept (accommodation regime).

Herein, two major topics are discussed, in relation to shelf morphology and sedimentology: a) the use of shelf morphology as an indicator of modern sedimentary regimes; and b) the implications of spatially-heterogeneous sedimentary regimes, for a geological/stratigraphic interpretation. The study area is part of the eastern Brazilian shelf, including Espirito Santo and South Bahia States. The analysis presented is based upon: a compilation of existing datasets; combined public databases; published papers; and unpublished geophysical and sedimentological datasets, collected over the past 10 years by the Geological Oceanography Laboratory – Federal University of Espirito Santo Brasil. Thus, the described results are based on unpublished and published data, in order to produce an overview of the shelf morphology and sedimentology. The discussion focuses on the interpretation of distinct shelf sedimentary regimes based on seabed morphology and comparison with other modern and ancient examples.

Study Area

The study area is located between the southern latitudes of 17^{o} 30`S and 21^{o}, along the eastern Brazilian margin. It will be referred here as the Espírito Santo-Abrolhos Shelf (ESA) (Fig. 1). The ESA continental shelf is characterized by a significant variation in shelf width. From Guarapari to the Doce River, the shelf is around 50 to 60km wide with a shelf break depth around 60 to 70m water depth. Towards the north, the so-called Abrolhos Shelf or Bank is characterized by a wider shelf (of up to 240km wide), breaking at water depth of 80 to 90m. Shelf widening is associated to the Abrolhos volcanic complex, formed during the Paleogene (Sobreira and França, 2006).

Restricting the present investigation to the Quaternary, the eastern Brazilian shelf has undergone several changes in relative sea level; these have shaped its morphology and controlled patterns of sediment distribution. Dominguez (2009) has concluded that these changes have influenced the morphological elements of the Brazilian coastal zone.

In terms of sediment distribution, the major database is that obtained during the 1970´s by the REMAC Program. Different sediment and facies distribution maps have been published for the area, focusing on different ways to describe seabed composition (França, 1979; Kowsman and Costa, 1979). The most comprehensive publication for part of the area is that of Melo et al., 1975. In general, sediment composition varies from terrigenous sand and mud along the coast, to bioclastic gravel towards the mid/outer shelf. Along the Abrolhos Shelf, reefs are observed. More recently, Amado Filho et al. (2012) have indicated that the majority of the Abrolhos shelf is composed of an extensive rhodolith bed. Moura et al. (2013) have produced also a map of seabed domains for the Abrolhos shelf; the shelf is composed mainly of rhodolith beds, reefs and unconsolidated sediments.

In terms of long-term shelf processes, the eastern Brazilian coast has undergone a major transgression, reaching a maximum height ranging from 2 to 5m above modern sea level, around 5000 years BP (Angulo et al., 2006; Martin et al., 2003). The last 5000 years has been characterized by a fall in relative sea level, characterizing a regressive coast. This phase is associated with the development of several deltaic and coastal plains along the Doce River delta plain and the Caravelas coastal Plain (Fig. 1).

Short-term processes are related to tides, together with storm and wind-induced waves along the coast. The tidal range along the coast is no greater than 1.6m. Northeasterly winds are the most frequent and south-southeasterly winds are associated with cold fronts and storms. Pianca et al. (2010) show that the dominant waves reaching the eastern Brazilian shelf are from the east, with an increase in wave energy during the passage of cold fronts coming from the south. The most frequently occurring wave height and period are 1m and 6-8s, respectively. The Brazil Current, a boundary current that is related to the South Atlantic Subtropical Gyre, may directly influence the occurrence of carbonate deposits along the Abrolhos Shelf. The current flows from north to south, intrudes over the Abrolhos Shelf bringing oligotrophic oceanic waters and sweeping sediments (Silveira et al., 2000; Knoppers et al., 1999; Ghisolfi et al., 2015).

Methods and Database

The results presented here are based on a compilation of published and unpublished datasets.

Altimetry and Bathymetry

The regional bathymetric map is used to interpret the seabed morphology; this was produced from the Brazilian Navy database. The database was obtained by scanning and digitizing the original sounding sheets produced by the Brazilian Navy Hydrographic Office (Diretoria de Hidrografia e Navegação, DHN). All coordinates were transformed to WGS84 Datum. The final map was produced by interpolating more than one hundred thousand points. Interpolation was undertaken using Surfer® 9 (Golden Softwares) with kriging geostatistics gridding method. The grid spacing was establish as 250x250 m, with a matrix of 1000 columns and lines.

Altimetric data was used in order to produce a digital terrain model of the coastal and land areas. Altimetric data were obtained from the TopoData databank (Instituto de Pesquisas Espaciais – Inpe, Brazilian Space Research Institute), which is based on the Shuttle Radar Topography Mission (SRTM) from Nasa.

Both of the above datasets were combined to integrate a GIS model from where all the morphometric information presented was derived.

Sedimentary Facies

The seabed sedimentary facies map was based on a compilation of distinct published and unpublished data. The final map was produced as an interpolation from maps available for the study area; these are based upon only a sediment sample database, or in a combination of sediment samples and seabed acoustic mapping.

The original and regional sediment database is archived at the National Oceanographic Data Bank (BNDO), which is managed by the DHN. Based upon this database, several maps have been proposed using distinct classification: Melo et al. (1975); Kowsman and Costa (1979) and Dias (2002). Other authors have combined the BNDO database with acoustic data (side scan sonar), in order to produce seabed habitat maps (Moura et al., 2013).

The sediment database, from the Geological Oceanographic Laboratory of the Federal University of Espirito Santo, was used also for the final compilation. Most of this database originates from unpublished Master and Doctoral Dissertations; most of these combine side-scan sonar data, with sediment samples. Table 1 lists all the dataset used here, their source, area location and mapping method. As such, the map proposed is based upon an interpretation derived from the original available maps. Sediment samples were not interpolated into the results presented. Digital version of all available maps were used and combined, within a Geographic Information System (GIS).

Acoustic/Seismic Data

In order to characterize the sedimentary regime and reveal the geometry of the deposits, together with the seabed morphology, side-scan and seismic data were used. Figure 1 shows the data coverage for the study area. All the sonograms or seismic profiles used were collected, processed and interpreted by the authors. Side-scan data were always acquired with an Edgetech 4100, dual-frequency system (100/500 kHz). Sub-bottom profiling was obtained using a Syquest Stratabox system operating in 10 or 3.5 kHz, whilst seismic data were acquired with a Boomer source operated in 250J on a Meridata system. Table 1 lists also the type of acoustic data collected and their location.

Results

Three major regions, or compartments, can be distinguished in terms of shelf morphology: the Abrolhos Shelf; the Doce River Shelf; and the Paleovalleys Shelf (Fig. 2). In terms of shelf sedimentary domain, rhodolith beds predominate on the outer shelf over the entire area; coralline reefs are present along the northern Abrolhos (inner) Shelf; whilst significant terrigenous mud deposit is observed to be associated with the Doce River (adjacent inner) Shelf beds (Fig. 3). The remainder of the shelf is composed of bioclastic or terrigenous mud, sand and gravel. Terrigenous sedimentation is restricted to the shoreface or shallower inner shelf areas, while carbonate sands and gravels are predominant elsewhere.

Abrolhos Shelf

The Abrolhos shelf represents an enlargement of the eastern Brazilian shelf, with an area of 46000 km^2, a maximum width of 200km and a shelf break at around 80 to 90m water depth. The morphology can be described in terms of two major regions: the northern shelf and southern shelf (Fig. 4). The northern shelf is characterized by a wide inner shelf (up to 30m water depth), marked by an extensive occurrence of modern and submerged reefs. Sedimentary facies show a transition, from terrigenous sediments along the coast to bioclastic sand/mud/gravel offshore. This transition is marked by the widespread occurrence of coral reefs, forming distinct morphologies, including reef banks and pinnacles. Submerged pinnacles and banks are also observed along the inner shelf, for example, in the Abrolhos Channel (Fig. 4a). Offshore from the Abrolhos Islands, submerged and coralline reefs are observed in water depths of up to around

50m. These reef morphologies are either pinnacles or banks, associated also with paleovalley margins. The mid and outer shelf are dominated by rhodolith beds. Figures 4b and 4c show sonographic images of submerged reefs, with distinct morphologies; these lie both in the mesophotic zone and the shallow water areas.

Seismic sections across the inner and outer shelf reavel the mixed sedimentary regime that characterizes the northern Abrolhos Shelf (Fig. 5). The influence of the terrigenous sedimentation is indicated by the deposition of coastal sediments downlapping a possible karstic topographic surface. To seaward of a depth of from 15m, carbonate sedimentation dominates and coastal reefs are observed. The seismic line along the outer shelf shows a typical carbonate sedimentation regime characterized by rhodolith beds. Figure 4d represents an example of an acoustic image of rhodolith beds.

The southern Abrolhos shelf is characterized morphologically by a depression (Figs. 4e,f), reaching water depths of 60m. The Besnard Channel, at the southern end of the depression, shows a maximum water depth of 100m.

Side-scan sonar surveys over the area have indicated the occurrence of submerged patch reefs (Fig.4c). The sedimentary facies are typically terrigenous sand/mud along the coast. Sediment distribution in the depression is composed of carbonate muds, whist rhodoliths dominates the outer shelf.

Doce River Shelf

The Doce River Shelf is about 50 km wide, which contrasts to the Abrolhos Shelf to the north. The shelf is characterized by a regular morphology, showing a deltaic lobe feature immediately offshore of the river mouth (Fig. 6). This deltaic lobe is composed mainly of terrigenous mud/sandy mud. The sub-bottom profiler sections (Figure 6) show the morphology and geometry of the mud deposit along the adjacent inner shelf. Towards offshore, the seabed morphology becomes flatter and a transition to terrigenous or mixed medium/coarse sands is observed. Rhodolith beds become predominant in water depths greater than 40m (Fig. 3).

The mud deposit is 5 to 8m in thickness, showing low-angle clinoforms downlapping a possible transgressive surface.

Paleovalleys Shelf

Southward of the Doce River influence, the shelf morphology becomes irregular and the inner shelf (considered here as being up to 30m water depth) narrows significantly (Fig 2). Figure 7 illustrates this significant change in shelf morphology, from a deltaic lobe to an erosive surface. This change in shelf morphology follows the coastal geomorphology. This is characterized, in term, by marine abrasion terraces and soft cliffs (the Barreiras Formation), with associated unfilled estuaries (e.g. the Piraque Açu Estuarine System) (Fig. 8). The Barreiras Formation tablelands predominate to the south, extending up to the Espirito Santo and Vitória Bay system. Here, bedrock headlands begin to control the coastal morphology. The Vitoria Bay system is the only embayment along the coast throughout the study area.

The adjacent shelf morphology reflects the low sediment input to this area, forming an irregular morphology, with relict features such as paleovalleys. A series of partially-filled and unfilled paleovalleys are observed throughout this compartment: the northern Paleovalley System; the Vitoria PaleoValley; and the Guarapari Paleovalley (Fig. 9). These paleovalleys are located generally perpendicular to the coast and can be observed in water depths ranging from 30m, up to the shelf break (Fig. 9). Their width can reach up to 600m. Sub-bottom profiler and boomer seismic data reveal that these paleovalleys are partially-filled, showing growing reefs along their margins, especially the Guarapari Paleovalley (Fig. 9). The Guarapari Paleovalley is predominantly filled by carbonate mud, whilst the northern paleovalleys are mainly filled by carbonate medium sands, with less than 15% of carbonate mud or rhodoliths.

In terms of shelf sedimentology, this compartment is composed mainly of mixed to bioclastic sands, with terrigenous sediments very much constrained to the coast. The mid/outer shelf is dominated by rhodolith sedimentation. Another interesting feature is the submerged terraces, forming hardbottoms. Submerged hardground can be associated to either laterite marine terraces formed during the last transgression and present also along the coast, or by a seabed bedrock outcrop covered by encrusted organisms. Southward from the city of Vitoria, the coast is characterized morphologically by the presence of headlands. The altimetry map shows the influence of the crystalline basement to the coastal morphology and to the shelf morphology (Fig. 2). Basement rocks outcrop above sea level, forming continental islands. Some of these outcrop below sea level, forming an important hardbottom for the encrustation of bryozoans, calcareous algae, etc.

Southward from Guarapari, the shelf shows another change in morphology. The inner shelf becomes wider and paleovalleys are not observed. In terms of seabed mapping, this area shows an extensive occurrence of rhodolith beds and carbonate sand/gravel intermingled with submerged biogenic reefs, composed mainly by calcareous algae. This seabed type creates a very irregular shape for the inner shelf in the area.

Discussion

Morphology and Sedimentary Regimes, Last Post-Glacial Transgression and Past 5000 years Regression

The three morphological compartments described for the eastern Brazilian shelf define distinct sedimentary regimes. Supply regimes were observed associated to depositional features along the inner shelf, forming a deltaic lobe adjacent to the Doce River and an elongated/coastal parallel deposit adjacent to the Caravelas Plain. The seabed morphology has revealed a regular surface dipping seaward. Seismic data corroborate the supply regime by revealing the geometry and downlapping deposits on a transgressive surface (Figs. 5 and 6).

The supply regime is associated to a regressive phase which took place along the eastern Brazilian coast, during the last 5000 years. Dominguez (2009) has classified the eastern Brazilian coast as the wave-dominated deltaic coast, which shows four delta plains (Paraiba do Sul, Doce, Jequitinhonha and São Francisco) in between starved of sediment coasts. On the altimetry map (Fig. 2), the deltaic plain is typically a prograding system with an associated delta front on the inner shelf. To the south and northward from the delta plain, the coast is characterized by soft cliffs (higher altitudes on the altimetry map), with narrow beach deposits. These soft cliffs are formed on the Barreiras Formation, which is a Miocene deposit forming coastal tablelands, extending from the southeast to the northern coast of Brazil. In the case of the Doce River shelf, the lobe morphology represents a regressive deltaic deposit indicating a local supply sedimentary regime.

Thus, a combination of delta development, river discharge and longshore transport are responsible for the deposition of terrigenous sediments along the coast, mainly from the Doce River to the north, towards the Caravelas plain (Dominguez et al., 1991, Andrade, 2003, Dominguez, 2009). This supply regime follows the concept that river input (Q) and grain size (M) overcome the variables related to accommodation space (relative sea-level rise, R and reworking capacity, D). Thus, the shelf regime is determined by the equation (Swift and Thorne, 1991) ¥= RD/QM, for the Doce River shelf case, ¥<1. In an attempt to classify deltas according to their changes within the sea-level cycle, Porebski and Steel (2006) considered that supply regime shelves present the conditions for delta development. These authors describe two scenarios, which they defined as the R mode and the Q mode. The R mode or accommodation-driven delta is related to deltas that are controlled by relative sea level changes, i.e., they shift their positions across the shelf, over short periods of time. The Q mode, or supply-driven delta, are able to prograde up to the shelf break and remain for longer periods, even within the context of high-frequency fluctuations in relative sea level.

The combined morphological and seismic analysis reveals that the Doce River is an inner shelf, accommodation-driven delta, i.e., its position across the shelf should be dictated by accommodation space, fluvial influx and potential tectonic reactivations (Rossetti et al., 2015; Dominguez and Wanless, 1991). The riverine mud distribution is confined up to the 25m isobaths, which also indicates that the river delta submerged deposit can be described as proximal accumulation dominated, following Walsh and Nittrouer (2009).

A shift in sedimentary regime is indicated also by the morphology when, southward from the Doce River shelf, the seafloor becomes very irregular, i.e. with partially-filled and unfilled paleovalleys and hardground terraces. These features are indicative of low sediment supply and/or erosive processes. This is a typical accommodation regime morphology. Southward from the Doce River, there is no major riverine sediment input, characterizing a sediment starving shelf, following the cliff coastal morphology (as described by Dominguez, 2009). Even though the paleochannels are partially filled, these are drowned features and an indication of an accommodation regime. Low sedimentation might have been one of the variables controlling the establishment of significant carbonate sedimentation along the accommodation regime areas.

Examples of accommodation regime shelves are widespread (Riggs et al., 1996; Paphitis et al., 2010). One characteristic of these regime shelves is the significant occurrence of hardbottom, unfilled paleovalleys and linear sedimentary features, such as sand ridges (Edwards et al., 2003). Usually, when these shelves are exposed also to seasonal storm conditions, they form shoal complexes (Denny et al., 2013), ridges/sandbanks (Bastos et al., 2003; Paphitis et al., 2010) and sorted bedforms/rippled scour depressions (Eittreim et al., 2002), by reworking the seabed. Storm bedforms have been observed along the Paleovalley shelf by Moscon and Bastos (2010).

It is important to note that these changes in morphology are well defined by the 30m depth contour line. The 30m isobath defines the width of the inner shelf. Throughout accommodation regime areas, this width is around 5km, but it can reach up to 15km in front of the Doce River mouth and more than 40km in the Abrolhos sector.

An interesting aspect of describing and understanding these spatial changes in morphology and facies is the application to the interpretation of the geological record. A lateral/along coast variation in sediment supply leads to distinct facies and geometry. Thus, as pointed out by Catuneanu et al. (2009) and Zecchin and Catuneanu (2013), these shifts along depositional strike have to be considered when interpreting stratigraphic surfaces, especially in cases where mixed sedimentation occurs. Paphitis et al. (2010) suggested this situation for the English Channel, where hydrodynamic pattern leads to a bedload parting zone; this in terms incorporates an erosive and hardground bed that changes laterally into sandwaves and sand sheets. The case study presented herein shows a clastic regressive deposit that laterally coeval with autochthonous carbonate sedimentation. One might consider that a transition from terrigenous sediments to calcareous algae dominated beds will normally follow the water depth; however, in this case, an along-shelf shift (not following a water depth gradient) is also observed (Fig. 10). There are a number of similar modern and ancient examples of cross-shelf mixing of siliciclastic and carbonate sediments. For example, Marshall et al. (1998) show a cross-shelf transition from fine siliciclastic sands, to bioclastic gravel and rhodoliths, across the Frasier Island, eastern Australian. Ancient examples of siliciclastics and rhodolith beds along the shelf are described also elsewhere (Coffey and Read, 2004; Brandano and Roca, 2013).

Likewise, the morphology along the Abrolhos shelf is diagnostic also of sedimentary regimes and evolution. However, it must be considered that the Abrolhos shelf is much wider than the Doce River and Paleovalleys shelves, which influenced sedimentation during the last post-glacial transgression and modern sediment input to the mid/outer shelf. The contrasting morphology between the north and the south Abrolhos shelf reflects distinct sedimentary processes. This is mainly because carbonate sedimentation predominates along the northern part. Extensive reef growth dominates the seabed morphology along the northern area, where the inner shelf is at its maximum width.

The very irregular and shallow morphology along the northern part could be described as a “clastic” accommodation regime. However, it is essentially, a carbonate regime shelf. In a sense, it could be argued that carbonate sedimentation will only take place where “clastic” accommodation regime predominates. This is true for the development of the rhodolith beds along the entire outer shelf, as described before. However, it is not necessarily the case for the coastal reefs in Abrolhos (Leão and Ginsburg, 1997; Leão et al., 2003; Dutra et al., 2006), which coeval with coastal sediments up to 15m water depth. Submerged reefs occurring deeper than 20m are not influenced entirely by terrigenous sedimentation. Leão and Ginsburg (1997) have pointed out that terrigenous sediments are limited along the coast/shoreface. The southern Abrolhos shelf is characterized by the relict depression feature and sparse drowned reefs. It can be described as a longshore supply inner shelf, together with an accommodation regime mid/outer shelf, because of very low sediment input.

Thus, the Abrolhos shelf presents a supply regime along the inner shelf and a carbonate regime offshore. In a sense, this transition could be compared with what is observed along the Belize platform, although the morphology is different. The Belize platform is characterized by a typical barrier reef, with an adjoined lagoon (Purdy and Gischler, 2003). In contrast, the Abrolhos Shelf is an open shelf, with two reef arcs formed by bank reefs with isolated pinnacles and incipient fringing reefs along the coast and islands (Leão et al., 2003). The southern Abrolhos shelf morphology and sedimentation are controlled by the antecedent topography. It is clearly a lower/deeper area that used to receive sediments from the north during lowstand periods (according to Vicalvi et al., 1978). However, it is important to note that the shelf geological framework can be a major controlling parameter for Quaternary sedimentation and modern morphology. Sobreira and França (2006) present a map of the geometry of the Abrolhos volcanic complex, formed by NeoCretaceous and Paleogene volcanic rocks. The annular distribution of this complex may control the modern morphology, with the depression in the centre.

The entire study area can be defined as a mixed sedimentation shelf. The shoreface and inner shelf are dominated by terrigenous sediments, with an exception being the northern Abrolhos inner shelf, which is characterized by coralline reefs. Mid and outer shelves are dominated by carbonate sand and gravels, with extensive rhodolith beds distributed throughout the entire area. The only exception is the Abrolhos depression where carbonate muds occur.

Thus, in a modern mixed sedimentation shelf, the morphology associated to an accommodation regime is not necessarily indicative of seabed erosion or lack of sedimentation. In these cases, it is possible that the irregular morphology follows the drowned relict features, but carbonate sedimentation takes place and dominates the sedimentary regime. In the case study presented here, the typical accommodation shelf morphology presents a carbonate facies, composed mainly of rhodoliths and grainstones (skeleton/shell fragments). Hence, what is observed is a coeval carbonate/terrigenous deposition during a highstand/regressive phase throughout the eastern Brazilian shelf.

Conclusions

An integrated analysis of the bathymetric and faciologic maps lead to the interpretation and recognition of three sedimentary regimes throughout the area: Supply, Accomodation and Carbonate Sedimentation. The entire study area can be defined as a mixed sedimentation shelf, showing coeval carbonate/terrigenous deposition during a highstand/regressive phase along the eastern Brazilian shelf. The understanding of sedimentary regimes in a mixed shelf must consider the carbonate sedimentation process and its morphological signature. In a modern mixed sedimentation shelf, the morphology associated to an accommodation regime is not necessarily indicative of seabed erosion or lack of sedimentation, but actually it can be related to carbonate sedimentation.

In the study area, the sedimentary regimes can be recognized in association with three morphological compartments. In general, the Doce River shelf is dominated by a supply regime characterized by regressive deposits forming an inner shelf delta. The Paleovalleys shelf is associated with an accommodation regime revealing hardbottom and unfilled paleovalleys. However, the outer shelf, throughout both compartments, is characterized by authoctonous carbonate sedimentation dominated by rhodolith beds. The Abrolhos shelf represents a combination of longshore supply along the shoreface, accommodation along its southern part and a carbonate regime along its central-northern part and on the outer shelf.

Acknowledgements

The research was financially supported by CNPq/Sisbiota - Rede Abrolhos-FAPES/CNPq (563266/2010-4), FAPES Universal Grant (54682860/2011), CNPq Universal Grant (479425/2011-6), CAPES Ciências do Mar. The first author received a Pos-Doctoral Fellowship by CNPq Science without Borders and developed part of this manuscript during a sabbatical at RSMAS-University of Miami. This manuscript is a contribution to INCT-MAR Ambitropic.

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Figure 3: Sedimentary facies distribution map (for used dataset, see table 1).

Figure 4: Detailed bathymetric map of the Abrolhos Shelf: a) side scan image showing submerged reefs along the Abrolhos Channel (point A); b) side scan image showing mesophotic reefs at 32m deep (point B); c) side scan image showing mesophotic reefs along the southern part of the shelf (point C); d) side scan image showing rhodolith beds (point D); e) N-S bathymetric profile showing change in water depth along the shelf; f) E-W bathymetric profile showing the Abrolhos depression.

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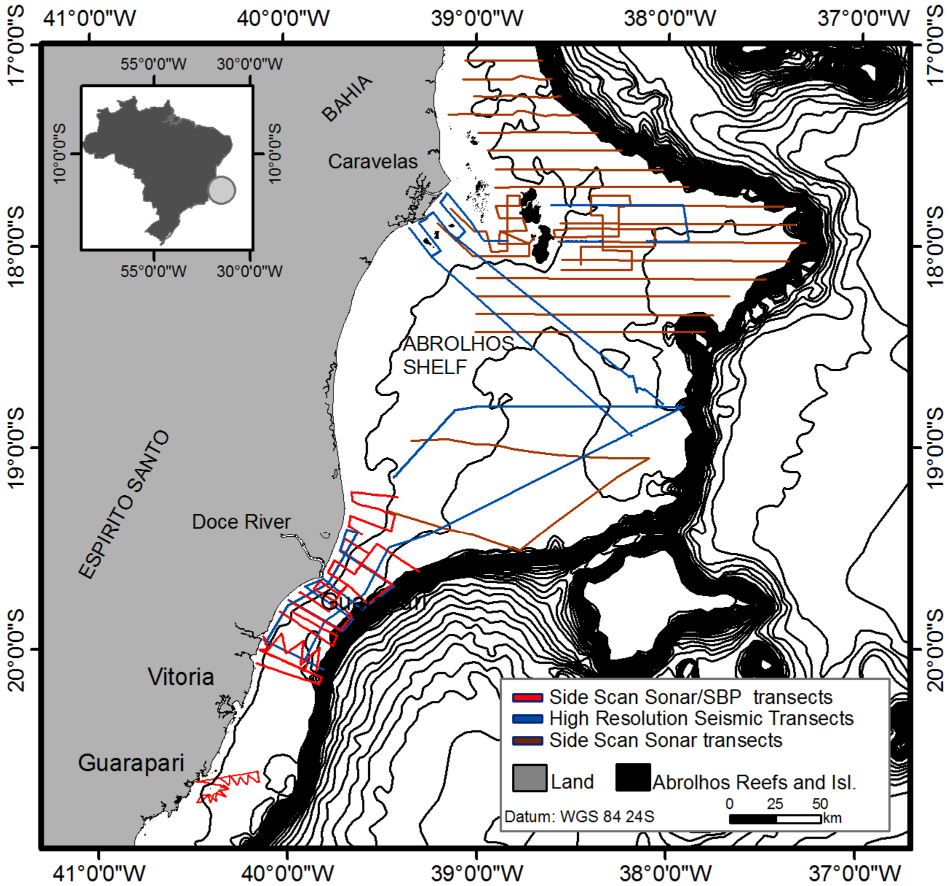
Figure 8: Aerial Photograph of the Piraque Açu estuarine mouth, showing an example of exposed coastal terraces (photograph) and submerged hardbottom (side scan image). These features are associated to tableland erosion and the formation of wave-cut terraces. P shows the location of the photographs (Figure 9).

Figure 9: Detailed map of the Paleovalleys shelf showing two bathymetric profiles across the shelf. A) Profile 1 shows the paleovalleys along the northern shelf, adjacent to the Piraque Açu Estuary; B) Profile 2 shows the interpreted hardbottom marine terraces along the shelf. NP- Northern Paleovalleys, VP- Vitoria Paleovalley, GP-Guarapari Paleovalley; C) 10 kHz Sub-bottom profiler transect and side scan sonar image across the Guarapari Paleovalley (Modified from Cetto, 2009).

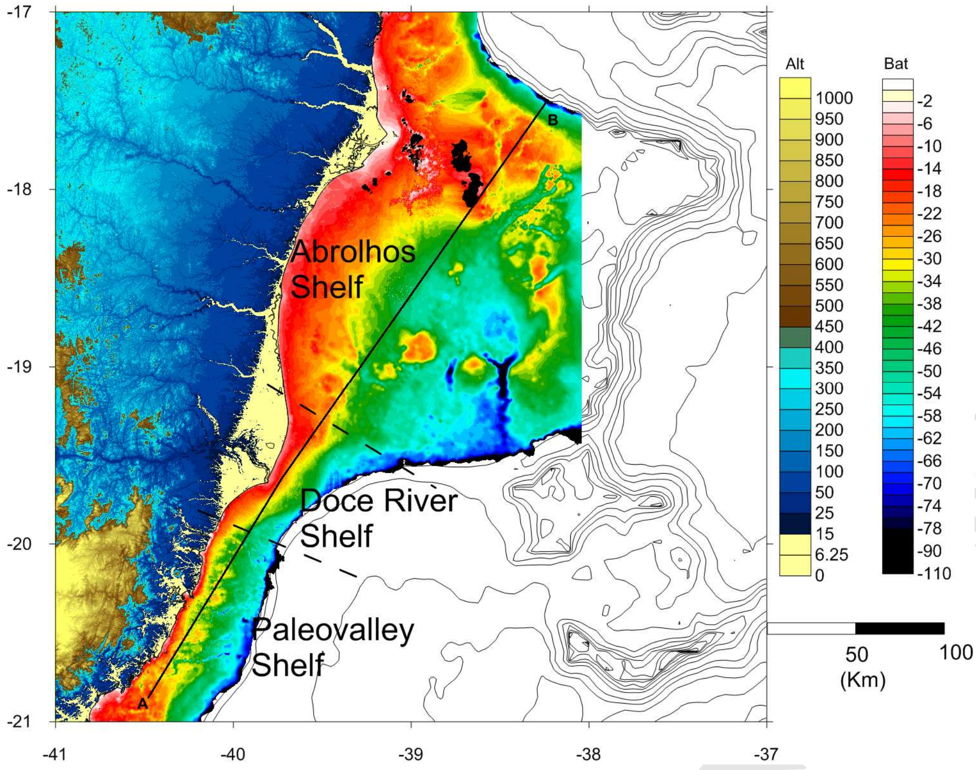
Figure 10: Strike bathymetric profile (for location, see Figure 1) with the associated seabed sedimentary domain. A lateral shift on sedimentary facies can be observed throughout the shelf, varying from bioclastic and terrigenous sediments to reef/rhodolith domains.

Table 1: List of the acoustic, sediment and public database available for this study. SED- sediment samples (processed by the authors); SS- side scan sonar data; SBP- sub-bottom profiler data; SIS- high resolution seismic data.

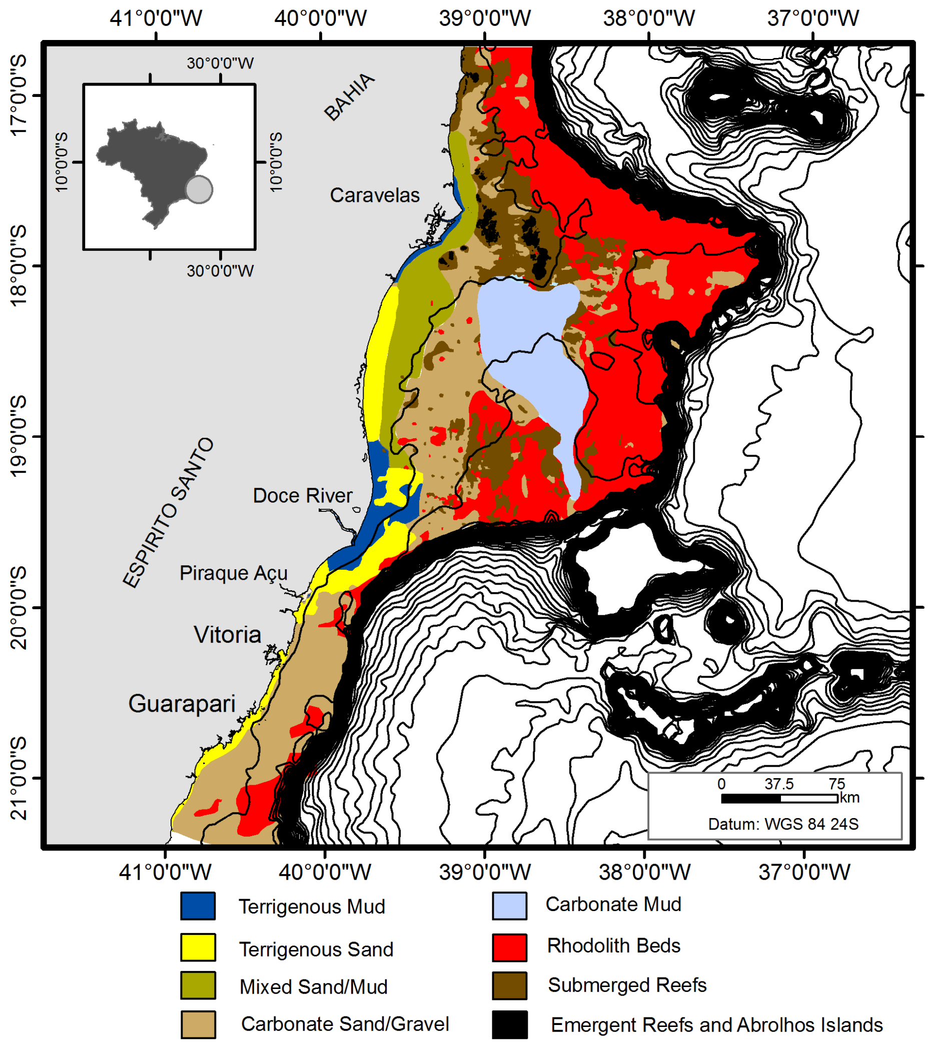
Reference	Database	Location	Source
Cetto (2009)	SED, SS, SBP	Guarapari shelf	Unpublished dissertation
Secchin (2011)	SS, ROV images	Abrolhos shelf	Published in Moura et al. (2013)
Delpupo (2011)	SED (25), SS	Guarapari shelf	Unpublished dissertation
D'Agostini (2012)	SED (36), SIS	Abrolhos Shelf	Unpublished dissertation
Bourguignon (2013)	SED (338), SS, SBP	Piraque Açu/Rio Doce shelf	Unpublished dissertation
Melo et al. (1975)	Sedimentary Facies Map	Abrolhos shelf	published
Marangoni (2009)	Bathymetric data	Eastern shelf	Unpublished dissertation
Dias (2002)	Sedimentary Facies Map	Eastern shelf	Unpublished report. Map based on BNDO databank
Moura et al. (2013)	SS, ROV images	Abrolhos Shelf	published



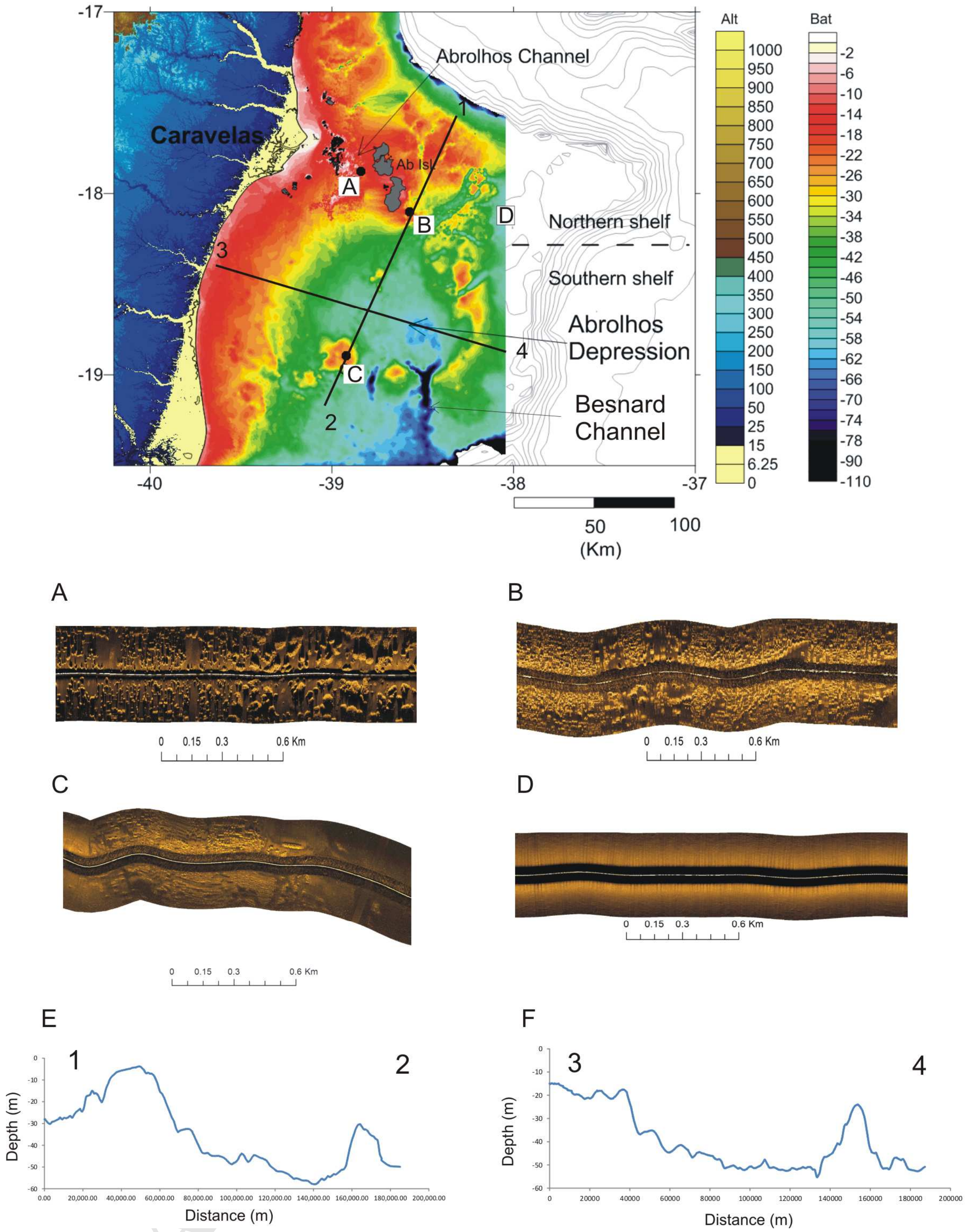
41°0'0"W
40°0'0"W
39°0'0"W
38°0'0"W
37°0'0"W
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
55°0'0"W
30°0'0"W
10°0'0"S
BAHIA
Caravelas
ABROLHOS SHELF
ESPIRITO SANTO
Doce River
Vitoria
Guarapari
Side Scan Sonar/SBP transects
High Resolution Seismic Transects
Side Scan Sonar transects
Land
Abrolhos Reefs and Isl.
Datum: WGS 84 24S
0 25 50 km



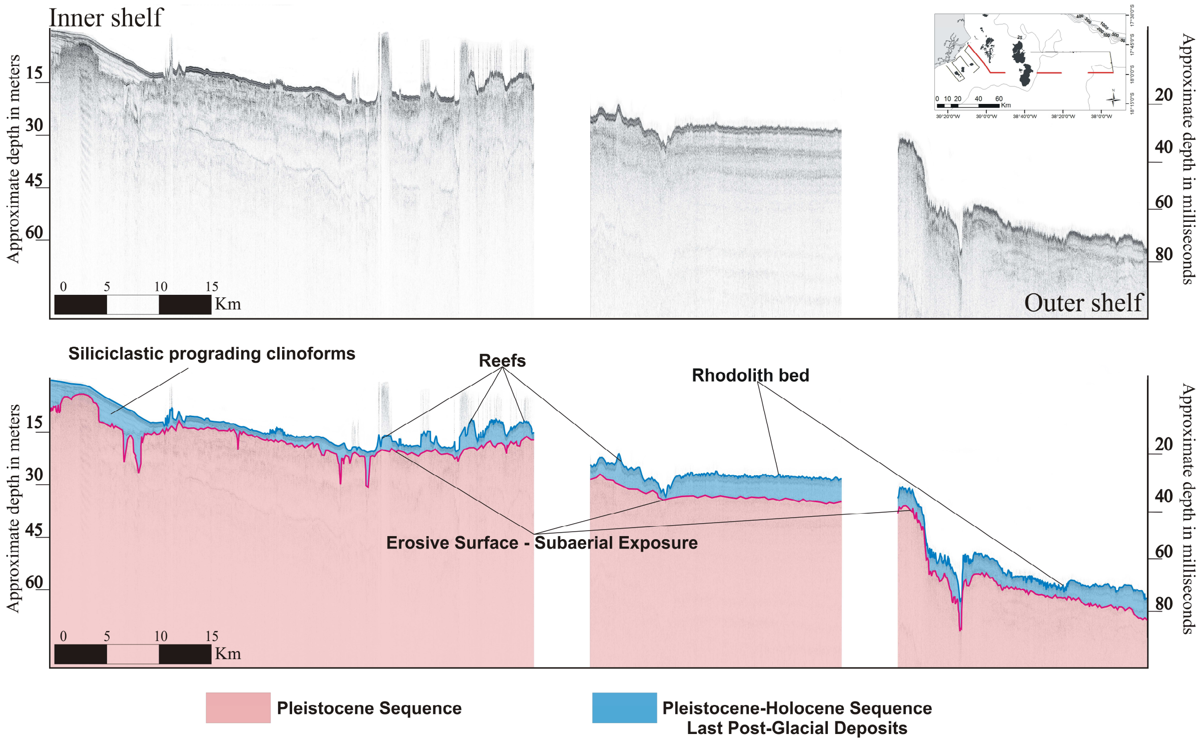
Abrolhos Shelf
Doce River Shelf
Paleovalley Shelf
A
B
Alt
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
25
15
6.25
0
Bat
-2
-6
-10
-14
-18
-22
-26
-30
-34
-38
-42
-46
-50
-54
-58
-62
-66
-70
-74
-78
-90
-110
50
100
(Km)
-17
-18
-19
-20
-21
-41
-40
-39
-38
-37

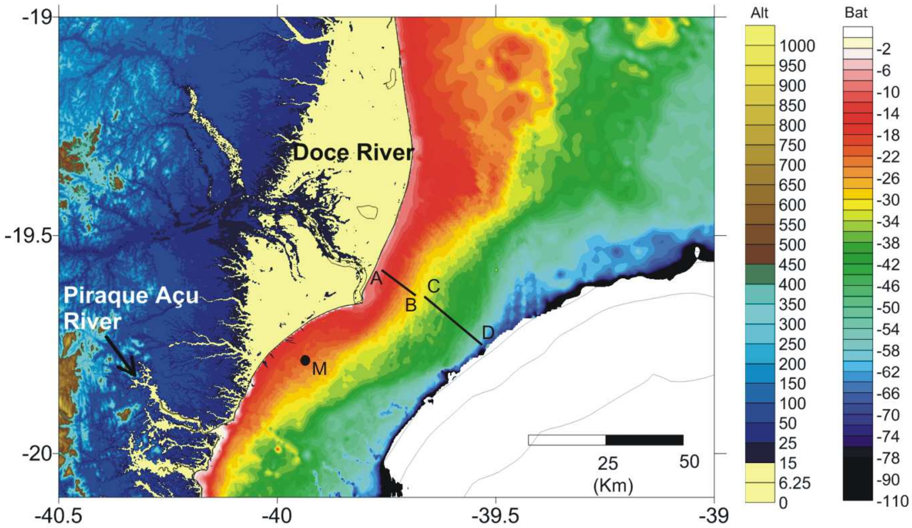


41°0'0"W
40°0'0"W
39°0'0"W
38°0'0"W
37°0'0"W
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
21°0'0"S
30°0'0"W
10°0'0"S
BAHIA
Caravelas
ESPIRITO SANTO
Doce River
Piraque Açu
Vitoria
Guarapari
0 37.5 75 km
Datum: WGS 84 24S
Terrigenous Mud
Terrigenous Sand
Mixed Sand/Mud
Carbonate Sand/Gravel
Carbonate Mud
Rhodolith Beds
Submerged Reefs
Emergent Reefs and Abrolhos Islands

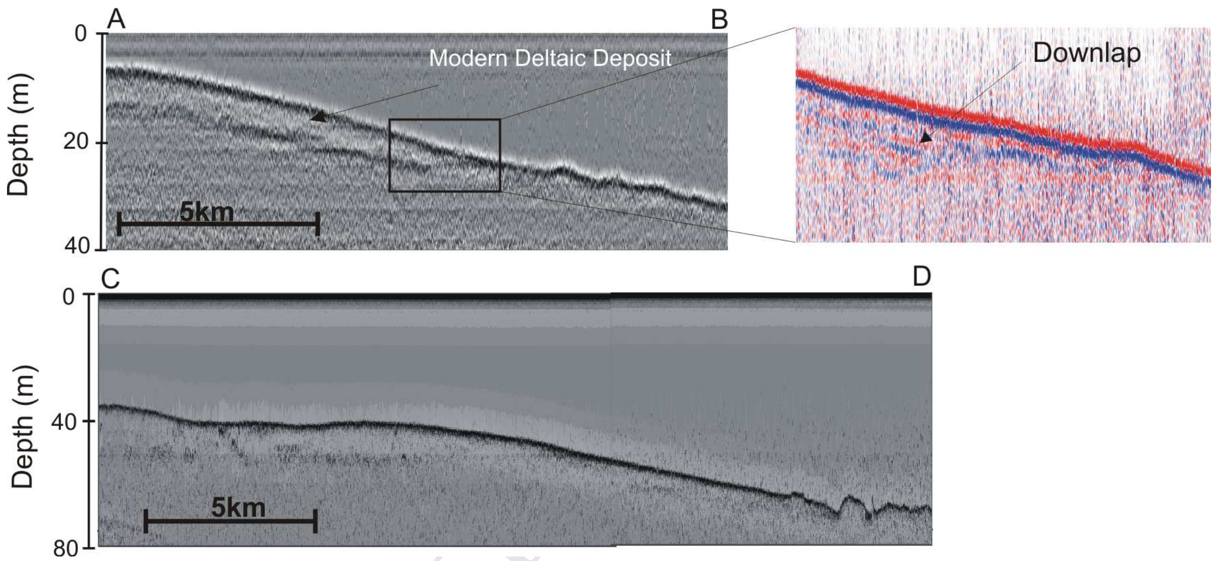


Abrolhos Channel
Caravelas
Ab Isl
A
B
C
D
1
2
3
4
Northern shelf
Southern shelf
Abrolhos Depression
Besnard Channel
-17
-18
-19
-40
-39
-38
-37
Alt
Bat
50
100
(Km)
A
B
C
D
0 0.15 0.3 0.6 Km
E
F
Depth (m)
Distance (m)

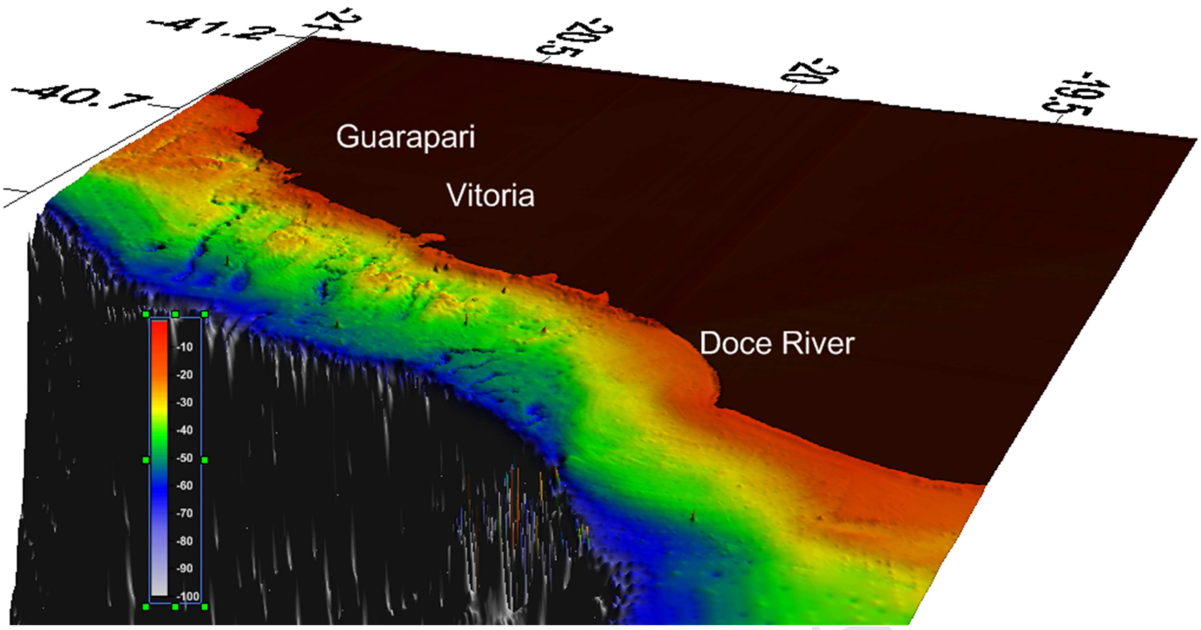

Inner shelf
Outer shelf
Approximate depth in meters
Approximate depth in milliseconds
15
30
45
60
20
40
60
80
0 5 10 15
Km
Siliciclastic prograding clinoforms
Reefs
Rhodolith bed
Erosive Surface - Subaerial Exposure
Pleistocene Sequence
Pleistocene-Holocene Sequence
Last Post-Glacial Deposits



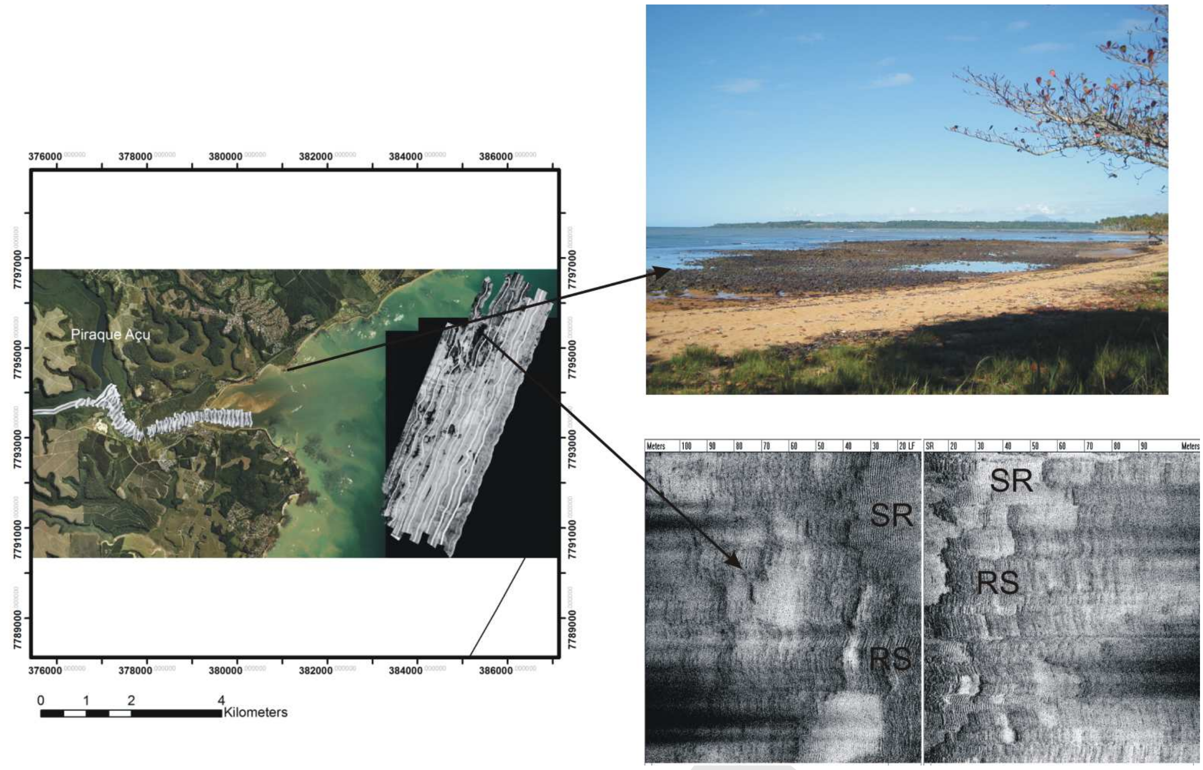
Doce River
Piraque Açu River
A
B
C
D
M
Alt
Bat
25
50
(Km)
-19
-19.5
-20
-40.5
-40
-39.5
-39



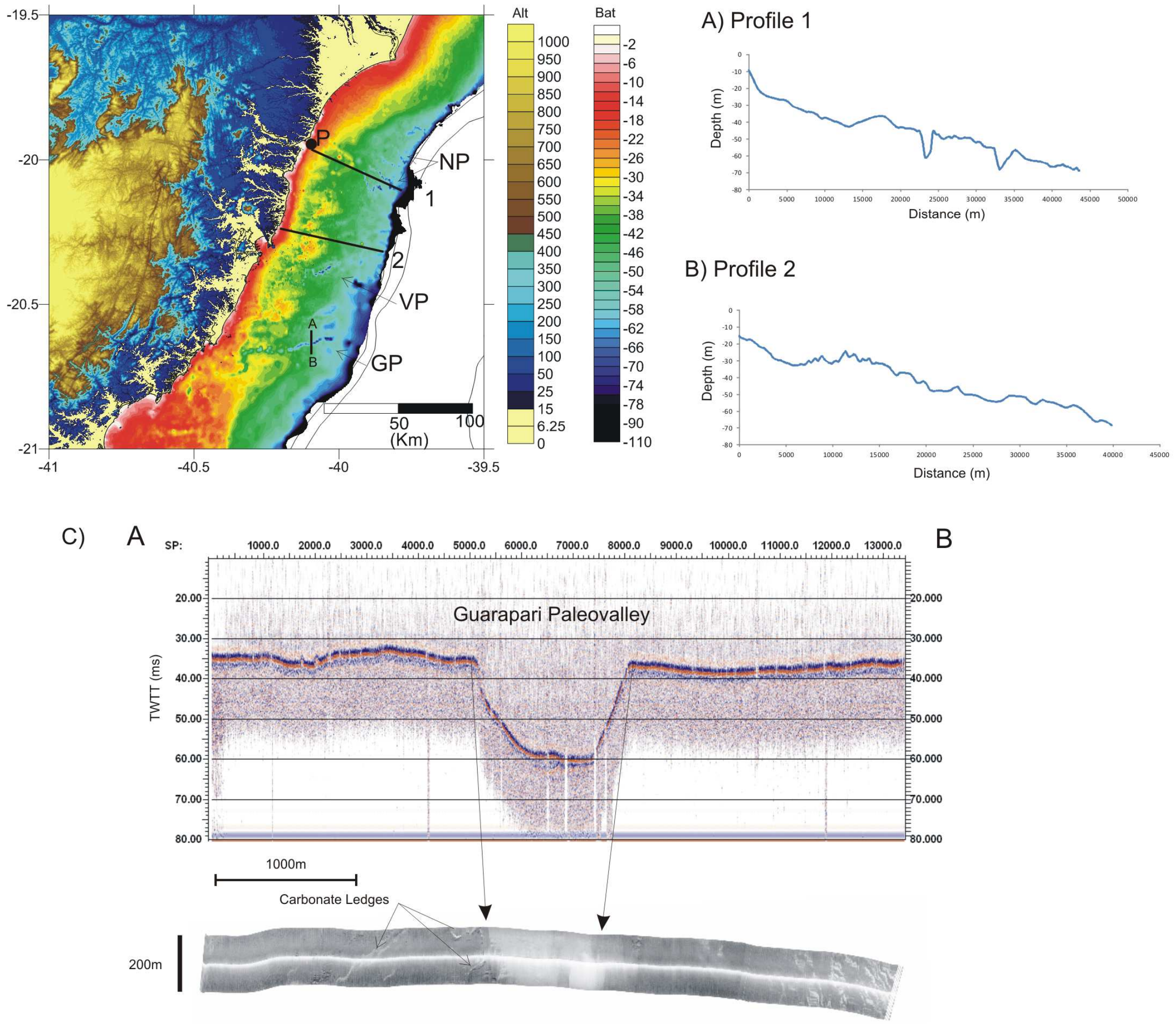
A
B
Modern Deltaic Deposit
Downlap
Depth (m)
5km
C
D



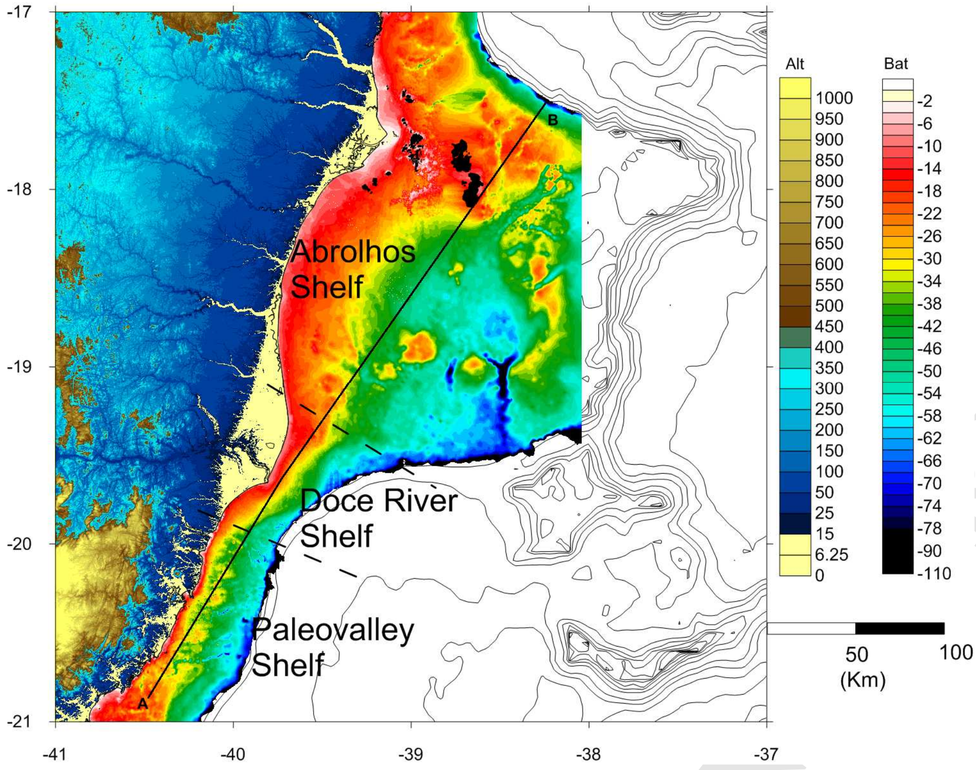
-41.2
-40.7
-21
-20.5
-20
-19.5
Guarapari
Vitoria
Doce River
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100

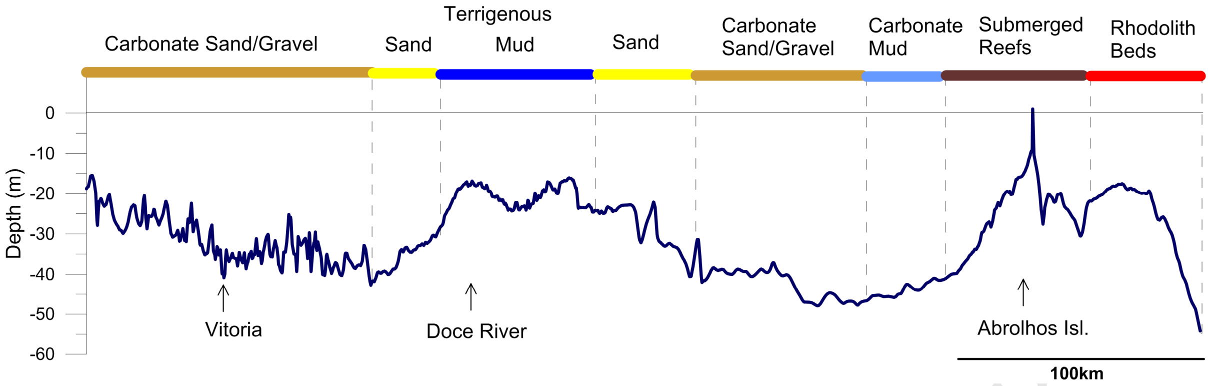


376000
378000
380000
382000
384000
386000
7797000
7795000
7793000
7791000
7789000
Piraque Açu
0
1
2
4
Kilometers
Meters
SR
RS
SR
RS



A) Profile 1
Depth (m)
Distance (m)
B) Profile 2
Depth (m)
Distance (m)
Alt
Bat
P
NP
1
2
VP
GP
50
100
(Km)
C)
A
B
SP:
TWTT (ms)
Guarapari Paleovalley
1000m
Carbonate Ledges
200m


Abrolhos Shelf
Doce River Shelf
Paleovalley Shelf
A
B
Alt
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
25
15
6.25
0
Bat
-2
-6
-10
-14
-18
-22
-26
-30
-34
-38
-42
-46
-50
-54
-58
-62
-66
-70
-74
-78
-90
-110
50
100
(Km)
-17
-18
-19
-20
-21
-41
-40
-39
-38
-37


Terrigenous
Carbonate Sand/Gravel
Sand
Mud
Sand
Carbonate
Sand/Gravel
Carbonate
Mud
Submerged
Reefs
Rhodolith
Beds
Depth (m)
0
-10
-20
-30
-40
-50
-60
Vitoria
Doce River
Abrolhos Isl.
100km

Research Highlights

Eastern Brazilian shelf morphology indicates distinct sedimentary regimes;

Mixed sedimentation shelf showing coeval carbonate/terrigenous deposition during a highstand/regressive phase along the eastern Brazilian shelf;

Sedimentary regimes in a mixed shelf must consider the carbonate sedimentation process and its morphological signature;

In a modern mixed sedimentation shelf, the morphology associated to an accommodation regime is not necessarily indicative of seabed erosion or lack of sedimentation.