THE MODERN MIXED CARBONATE–SILICICLASTIC ABROLHOS SHELF: IMPLICATIONS FOR A MIXED DEPOSITIONAL MODEL

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ABSTRACT: High-resolution seismic facies analysis and stratigraphy of a mixed carbonate–siliciclastic shelf yields insights into sedimentation controlled by interactions among carbonate production, siliciclastic sediment supply, and changes in relative sea level. High-resolution seismic, core, and surface samples collected along the northern area of the Abrolhos shelf (Brazil), including the inner, middle, and outer shelf, constrain the genesis of the shelf. Two sets of seismic sequences were identified: a Pleistocene sequence and Pleistocene–Holocene sequence. A subaerial unconformity from subaerial exposure during the last glacial maximum separates the two sequences. The upper seismic sequence, the focus of this study, comprises retrograding–aggrading (transgressive) and aggrading–prograding (regressive) seismic geometries. Carbonate sedimentation predominated within the last postglacial transgressive phase. The subsequent regressive phase was dominated by nearshore siliciclastic sedimentation at shallow depths (up to ~ 12 m). Below 12 m depth, a transition occurs to mixed siliciclastic–carbonate facies, and ultimately, carbonate sedimentation farther offshore. Seismic data indicate that Holocene nearshore coral reef growth was influenced by the positive antecedent relief of a Pleistocene reef platform and terrigenous sedimentation. Although siliciclastic–carbonate mixed sedimentation has been reported in other successions during periods of regression, siliciclastic sedimentation in northern Abrolhos shelf is limited to nearshore settings rather than bypassing the shelf.

INTRODUCTION

Siliciclastic and carbonate sedimentation coexist along several continental shelves, in both the geological record and in modern examples (Gillespie and Nelson 1996; Kent et al. 2001; Harrison et al. 2003; Kwon et al. 2006; Hine et al. 2009). At lower latitudes, these systems are known as tropical mixed siliciclastic-carbonate systems and are characterized by lateral and vertical association of carbonate and siliciclastic facies (Mount 1984; Doyle 1987; Handford and Loucks 1993). Wilson (1967) introduced the term cyclic-reciprocal sedimentation to explain the alternation in carbonate-siliciclastic sedimentation among the shelf, slope, and basin. This concept implies that carbonate facies dominate slope and basin sedimentation during transgression and highstand, whereas siliciclastic deposits are predominant during lowstand. However, some authors have shown a coeval deposition of carbonate and siliciclastic sediments along the slope during highstand (Francis et al. 2007). This observation suggests that reciprocal sedimentation can vary according to prevailing oceanographic and geological conditions, as carbonate and siliciclastic systems respond to relative changes in sea level differently. The resulting stratigraphic patterns of tropical mixed sedimentary shelves have been described worldwide by several authors trying to understand how sequence stratigraphic concepts can be applied to mixed systems (Heap et al. 2001; Zinke et al. 2001; McNeill et al. 2004; Hine et al. 2009).

The Abrolhos shelf (South Atlantic, Brazil) is one of the largest modern examples of a tropical mixed carbonate–siliciclastic depositional system, combining coral reef growth with terrigenous sediment input along the inner-shelf and extensive rhodolith beds along the middle and outer shelf (Leão and Ginsburg 1997; Amado-Filho et al. 2012). To better understand this system, modern coastal to inner-shelf sedimentation processes and reef growth patterns on the Abrolhos Shelf have been studied by several authors (Leão and Ginsburg 1997; Leão et al. 2003; Leão and Kikuchi 2005; Dutra et al. 2006). However, studies concerning the evolution of Pleistocene and Holocene mixed carbonate–siliciclastic sediments from a sequence stratigraphy perspective are lacking.

The purpose of this study is to investigate the seismic facies architecture of a tropical mixed carbonate–siliciclastic shelf. Results from this study will propose a conceptual sedimentation model for the last postglacial transgression and subsequent regression phase in the late Pleistocene to Holocene. We will evaluate two hypotheses for the timing of the transgressive and regressive sequences and consequently the maximum flooding surface.

Regional Setting

The Abrolhos shelf is located along the eastern Brazilian coast and is characterized by an enlargement of the Brazilian shelf, reaching approximately 200 km in width. This enlargement is associated with the Paleogene Abrolhos Volcanic Complex (Sobreira and França 2006). Shelf morphology is irregular, representing the sedimentary response to the last postglacial transgression (Fig. 1). The shelf can be described in terms of two areas, the southern and the central to northern shelf. The southern shelf is characterized by the Abrolhos Depression, which represents a paleo-lagoon (Vicalvi et al. 1978). Vicalvi et al. (1978) illustrated benthic
foraminiferal analysis from a gravity core that revealed that between 11,000 to 8,000 yr BP, the area was a mixohaline lagoon, becoming open marine during the last 8,000 yr. The central-northern shelf includes both the widest and narrowest areas of the shelf. The geomorphology and sedimentary facies at the central-northern shelf is dominated by siliciclastics along the coastal zone, mixed sediments between the coastal reef zones, and mesophotic reefs (up to 40 m depth) and rhodolith beds along the middle and outer shelf (Melo et al., 1975; Leão and Ginsburg, 1997; Leão and Kikuchi, 2005; Leão et al., 2006; Amado-Filho et al., 2012; Moura et al., 2013). According to Leão and Ginsburg (1997), the mixed facies is associated with a relative sea-level fall that occurred during the last 5,600 yrs along the Brazilian coast.

In terms of reef morphology, Leão and Ginsburg (1997) describe two arcuate reef zones: a coastal arc and an outer arc. The coastal arc is formed by reef banks of various shapes and dimensions, whereas the outer arc, which borders the east side of the Abrolhos Islands, is formed by isolated pinnacles ("chapeiros") in water depths greater than 20 m.

Based on analysis of radiocarbon-dated corals of the Coroa Vermelha Reef located at the coastal arc, Leão et al. (2003) suggested that coral-reef development during the last postglacial transgression includes four phases. The first phase marks the beginning of coastal coral-reef growth around 8,000 yr BP, when the eastern Brazilian continental shelf was totally drowned (Vicalvi et al., 1978). The base of the pre-Holocene sequence in the coral core analyzed by Leão and Ginsburg (1997) is at 10.7 m below the seabed. During this first phase, coral reefs grew on top of the pre-Holocene surface at a rate around 1.5 mm/year (Andrade et al., 2003). Leão et al. (2003) indicate that reef growth in eastern Brazil could not have started earlier during the drowning phase, characterized by the "give-up" reefs along the shelf edge. The second phase initiated around 5,600 yr BP, just after the maximum postglacial highstand for the Brazilian eastern coast (3 to 4 m above modern sea level). This phase is characterized by a rapid vertical growth of coral reefs (rates of ~ 5.5 mm/year), representing the "catch-up" mode of reef growth, the climax phase of reef development in Brazil (Leão et al., 2003). The reef structures reached the present sea level, and upward reef aggradation stopped. Since that time, during the last two phases of reef development (the last 4,000 yr), reefs accreted laterally, marking a passage from a phase of reef aggradation to reef progradation (Andrade et al., 2003; Leão et al., 2003).

MATERIALS AND METHODS

Seismic Data

High-resolution seismic data along the inner to outer Abrolhos shelf were acquired with a boomer seismic profiler operated in 1 kHz mode with 250 J. Approximately 220 km of seismic data included five shallow-water transects perpendicular to the coast and two cross-shelf transects in the middle to outer shelf (Fig. 1A). Navigation and positioning utilized a differential global positioning system (DGPS). Seismic data were acquired with Meridata MD-DSS software and exported as SEG-Y data, then processed and interpreted using Seissee and SonarWiz Map5 software. Conversion of seismic time to sediment thickness used an average velocity of 1650 m/s.

To identify the bounding surfaces (facies boundaries), seismic facies, and seismic sequences, the concepts of seismic stratigraphy (Mitchum et al., 1977) were applied to define the stratigraphic terminations and internal configuration. Sequence stratigraphic terms proposed by Catuneanu (2002, 2006), and Catuneanu et al. (2009) were adopted to identify genetic units and stratigraphic surfaces.

Surface Sediments and Core Data

Thirty-six surface sediments were collected using a van Veen sampler, and one core (T1) was collected by divers using a push-core system (Fig. 1B). The core came from 12 m water depth, and 1.04 m of sediment was recovered. Surface samples were analyzed for grain size and calcium carbonate content. Grain-size distribution of the sand, silt, and clay fractions (0.002 to 2 mm) was determined using Mastersizer 2000 particle-size analyzer. The gravel fraction (> 2 mm) was weighed to determine its percentage. Calcium carbonate content (weight percent) was determined by CaCO₃ loss by dissolution with a 10% HCl (Suguio, 1973).

A mollusk shell was selected to determine radiocarbon age from core T1 (96 cm depth). AMS at the Beta Analytic Radiocarbon Laboratory (Florida, USA) are reported as radiocarbon years before the present. Calibration by Beta Analytic used the reference standard 95% of the 14C activity of the National Institute of Standards and Technology Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5,568 yr).

RESULTS

Seismic Stratigraphy

Seismic interpretation identified six main seismic sequences (SqA, SqB, Sq1, Sq2, Sq3, and Sq4) bounded by erosional (SA, SB, S1, and S2) and nonerosional (S3 and S4) surfaces (Fig. 2). Seismic sequences were grouped into two seismic sequence sets (Set I and Set II), which were distinguished by a surface, identified as S1. Set I includes the lower stratigraphic seismic sequence and is represented by SqA and SqB. Set II corresponds to the upper stratigraphic seismic sequence and is represented by Sq1, Sq2, Sq3, and Sq4. Sq1 and S2 were not represented (Fig. 2) because they were identified only along the middle-shelf and outer-shelf seismic lines. Figure 3 summarizes the characteristics of the distinct seismic units.

Set I is characterized by a pattern of aggradational seismic sequences, from acoustic basement to reflector S1. The lower seismic sequence of this set, SqA, is characterized by a reflection-free seismic configuration, and is bounded below and above by unconformity surfaces (SA and SB). SA is highly irregular but continuous, forming a high-amplitude reflection that represents the acoustic basement. SqA is truncated above by SB, a highly irregular, discontinuous, and high-amplitude reflector. The upper seismic sequence of this set, SqB, overlies SqA and shows a chaotic reflection pattern. S1 is a highly irregular, continuous, and high-amplitude reflector, separating Sets I and II, interpreted as a major unconformity. Figures 4 to 9 show the interpreted seismic sections collected along the study area.

Set II sequences overlie S1, and are marked by retrograding, progradig, and aggrading seismic sequences. The basal sequence, S1, is evident only on the middle and outer shelf. This sequence has a chaotic internal configuration, but shows retrograding reflectors that onlap S1. This sequence is bounded at the top by surface S2, a highly irregular, but continuous, high-amplitude reflector that is present only along the middle to outer shelf (Fig. 9).

Along the middle shelf, the seismic sequence Sq2 overlies surface S1 and is overlain by S3, a slightly irregular, continuous, moderate- to high-amplitude reflector. Sq2 is characterized by two seismic facies: an aggradational reflection-free configuration and, parallel and subparallel reflectors that fill erosional lows and onlap S1. The overlying sequence, Sq3, shows an internal configuration of seaward-dipping clinoforms that thin and downlap onto S3 and are present only updip. Sq3 is bounded above by S4, a regular, continuous and moderate- to high-amplitude reflector. The upper seismic sequence of Set II is Sq4, which is bounded at its base by S1, S2, and S4, as Sq2 and Sq3 are discontinuous. Sq4 includes two seismic facies with distinct internal geometry and reflection character: 1) seaward-prograding reflectors until 12 m depth and 2) parallel reflectors, in areas of deeper water (Figs. 4 to 8).
Surface Sediment Distribution

Surficial sediment distribution in the study area is composed predominantly of mud (>50%) and mixed carbonate–siliciclastic content (20–65% CaCO₃) (Fig. 10). Along nearshore (<12 m depth), siliciclastic mud is more abundant (mud >50% mud and CaCO₃ >40%), with the exception of one sampling station showing only 10% mud. Offshore, a transition from siliciclastic mud to a mixed carbonate–siliciclastic mud facies (40–60% of CaCO₃) is observed. This mixed mud transition occurs mainly in the central-northern area. In the southern area (especially around the reefs), sediment facies are coarser (0–25% mud) and include a high carbonate content (>70%).

Radiocarbon Dating

The radiocarbon age (at 96 cm in core T1) calibrated in calendar years corresponds to between 2,700 and 2,360 yrs BP. This core is from the central seismic line (Fig. 6, inset), and the sample corresponds to approximately the middle of seismic sequence Sq4.

DISCUSSION

Seismostratigraphic Interpretation

Seismic data from the Abrolhos shelf reveal a complex sedimentary evolution. Seismic stratigraphic analysis of a series of sequences, bounded by regionally correlative surfaces, provides a means to unravel the late Pleistocene to recent sedimentary evolution of the shelf, leading to a better understanding of postglacial sedimentation.

The basal surface (S1) is described by Bastos et al. (2013). These authors describe the formation and occurrence of large cup-shaped depressions, named “buracas,” similar to sinks or blueholes that occur in consolidated carbonate substrate along the middle to outer Abrolhos shelf (Fig. 11A; see Fig. 1B for location). Bastos et al. (2013) interpreted this surface as a subaerial exposure surface that formed during a previous sea-level lowstand, either Marine Isotope Stage (MIS) 6 (ending around 130,000 yr BP) or MIS 2 (last glacial maximum, around 20,000 yr BP). These authors present carbon-14 ages of 39,000 yr BP from a limestone sample at the base of a buraca and 8,630 ± 90 yr BP from a buraca wall (35 m deep). The latter age was interpreted to represent Holocene biogenic carbonate growth above the erosional surface. Although the authors suggested that this surface may correspond to MIS 6, it is more likely the last glacial maximum erosional surface (MIS 2) (which is more consistent with the MIS 2 age of 39,000 yr). Leão and Ginsburg (1997) described a pre-Holocene sequence located approximately 11 m below present sea level, along the inner shelf (Fig. 12). The unconformity observed by Leão and Ginsburg (1997) was compared with the inner seismic lines, and the pre-Holocene surface appears to correlate to the S1 unconformity. Thus, the seismic data presented herein suggests that S1 is a karstic paleotopographic surface formed during shelf subaerial exposure in the last glacial maximum (Fig. 12A, B).

The S1 surface was mapped from the inner-shelf seismic lines and also shows continuity with the offshore seismic lines (Fig. 11B, C). Throughout the area, it includes a similar high-amplitude character. So, considering that this surface is well documented in the inner shelf by borehole data (Leão and Ginsburg (1997), we can confidently define its continuity farther offshore (Fig. 11, 12).

It was not possible to determine the exact age of the seismic sequences, but it can be inferred that S1 marks the top of the depositional sequences (Set I) formed up to and including the last Pleistocene glacial maximum period (MIS 2) and the base of the depositional sequences formed during the postglacial transgression (MIS 1), whereas the late Pleistocene–Holocene periods are represented in Set II. Set I and Set II are interpreted as a Pleistocene sequence and a Pleistocene–Holocene sequence, respectively (Figs. 13, 14).

Seismostratigraphic Sequences

No data are available to constrain the age of SqA and SqB (beyond the evident pre-Holocene age), but three high-amplitude reflectors (SA, SB, S1, S3, and S4. Set I is represented by SqA and SqB, whereas Set II, by Sq2, Sq3, and Sq4.

Fig. 2.—Nearshore high-resolution seismic section representing the five main seismic sequences (SqA, SqB, Sq2, Sq3, and Sq4) bounded by seismic surfaces SA, SB, S1, S3, and S4. Set I is represented by SqA and SqB, whereas Set II, by Sq2, Sq3, and Sq4.
<table>
<thead>
<tr>
<th>Seismic unit</th>
<th>Upper-boundary characteristics</th>
<th>Seismic facies</th>
<th>Sedimentary facies</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq4</td>
<td>Upper boundary: Seafloor Lower boundary: S1, S3 and S4</td>
<td>Seaward-prograding reflectors until maximum depths to 12 m.</td>
<td>Siliciclastic sediments (&lt; 40% CaCO3)</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Sq3</td>
<td>Regular, continuous and moderate- to high-amplitude reflector</td>
<td>Chaotic configuration facies associated with parallels reflectors after prograding facies.</td>
<td>Carbonates and mixed sediments (&gt; 40% CaCO3)</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Sq2</td>
<td>Slightly irregular, continuous and moderate- to high-amplitude reflector</td>
<td>Reflectors in toplap and prograding clinoforms downlapping S3. This clinoforms shows lower angle seaward.</td>
<td>Siliciclastic sediments</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Sq1</td>
<td>Highly irregular, continuous and high-amplitude reflector</td>
<td>Free configuration. Fill and aggradational internal configuration. Greater thickness in the southern seismic line.</td>
<td>Carbonates</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>SQB</td>
<td>Highly irregular, continuous and high-amplitude reflector</td>
<td>Parallel and subparallel reflectors onlapping S1. Fill internal configuration.</td>
<td>Carbonates</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>SqA</td>
<td>Highly irregular, discontinuous and high-amplitude reflector</td>
<td>Chaotic reflection pattern. Facies shows evidence of channel cuts being better express in the south.</td>
<td>Carbonates</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>[SA]</td>
<td>Highly irregular, continuous and high-amplitude reflector (acoustic basement)</td>
<td>Free internal configuration. Southward thickening.</td>
<td>Carbonates</td>
<td><img src="image7.png" alt="Image" /></td>
</tr>
</tbody>
</table>
and S1) are interpreted as indicators of earlier erosive processes within the Pleistocene. Considering the global sea-level curves compiled by Rabineau et al. (2006) (Fig. 13A), major regressive events may have been responsible for producing these erosional surfaces. Surfaces SA and SB could correspond to partial shelf exposure during regressive events that initiated in MIS 5c and MIS 5a, respectively (Fig. 13B).

The late Pleistocene–Holocene sequence was deposited above subaerial unconformity S1, and is composed of seismic sequences interpreted to represent transgressive (Sq1 and Sq2) and regressive (Sq3 and Sq4) conditions (Fig. 14). The accumulation of Sq1 (which occurred only in the middle to outer shelf) was associated with limited accommodation space that allowed carbonate accumulation on the outer part of the shelf. Sq1 shows a retrogradational stacking pattern similar to backstepping with strata that onlap 110 km from the coast. No evidence for the backstepping occurred landward of this position. Backstepping (as in Schlager 2005) is a geometrical characteristic of carbonate platforms that is common in rimmed platforms, and it is analogous to the standard siliciclastic retrogradational model. Vicalvi et al. (1978) document sea-level stabilization at approximately 11,000 yr BP on the Abrolhos shelf, at the 60 m isobath. This depth coincides with Sq1 depths (about 35 to 70 m depth). Seismic sequence Sq1 is capped by a high-amplitude and irregular reflector (S2) (Fig. 9).

Within the inner shelf, S3 represents an important boundary (downlap surface) which separates the aggradational sequences (Sq2) below from the overlying clinoformal sequences (Sq3 and Sq4). This surface is interpreted to represent a maximum-flooding surface (MFS) (Catuneanu 2006; Catuneanu et al. 2009).

Two seismic facies occur in Sq2: a reflection-free configuration and, parallel and sub-parallel reflectors sequence that onlap S1. The first is associated with carbonate buildups, interpreted to indicate high rates of carbonate production up to the maximum-flooding surface (Fig. 4, inset). The second seismic facies is interpreted to indicate inter-limestone fill by erosion and remobilization of biodetritus during the last postglacial transgression. During rapid transgressions, in general, the rates of rise of base level commonly are higher than the rates of carbonate production, and the carbonate platforms drown (Schlager 2005; Catuneanu 2006). On the Abrolhos shelf, results show evidence of substantial carbonate growth and bioclastic sediment production during the transgression. Zinke et al. (2001), Hine and Neumann (1977), and Larcombe and Carter (1998) also

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**Fig. 4.**—Seismic line representing the seismic sequences and surfaces identified. Sq4 seismic facies was delimited through seismic data analysis and CaCO3 content map. Inset: detailed image showing the erosional surface on top of Set I and large thickness of Sq2.
observed “keep up” growth of carbonates associated with bioclastic sediments during the last post-glacial transgression.

The offshore seismic lines show a thick (approximately 8–12 m thick) deposit of Holocene carbonates (Fig. 9), developed during transgressive to highstand periods on “give-up” reefs (Leão et al. 2003). Dias and Villaça (2011) suggested that carbonate sedimentation during the Holocene marine transgression along the eastern–southeastern Brazilian shelf is 6 to 8 m thick.

The distribution of terrigenous sedimentation in the study area is consistent with the seismic sequences with progradational geometries (Sq3) in the northern seismic lines (Figs. 6–8). The regressive deposits with offshore-directed clinoforms are typical of prograding siliciclastic systems (Catuneanu 2002, 2006). Sq3 is capped by a surface (S4) and has clinoformal reflectors that show a low seaward dip angle. This configuration suggests a decrease in sediment supply or an increase in accommodation space (Fig. 7, red inset and Fig. 8, insets).

Sq4 is interpreted to represent a combination of siliciclastic sedimentation and coral-reef growth along the coast. Offshore areas are dominated by rhodolith beds (Amado-Filho et al. 2012). Muddy carbonate sediment in the northern area, between southern reefs and Parcel das Paredes reef (Fig. 1), suggests some contribution from reef erosion during the last 3,000 to 4,000 yr. Siliciclastic sediment is restricted to the inner parts of the coastal zone (Fig. 10), comparable to that mapped by Leão and Ginsburg (1997) and Leão et al. (2006). Leão and Kikuchi (2005) report the growth of coral fauna adapted to low light levels and higher sediment influx during falling sea level, starting about 5,600 yr BP. Leão and Ginsburg (1997) and Leão et al. (2003) suggest that the Abrolhos coral reefs became more resistant to stress caused by water turbidity in coastal areas at about this same time. Carbonate sediment and reefs in lower areas (compared to reefs now emerged) are overlain by siliciclastic muddy or mixed facies (examples in Figs. 4, 5, 8).

Mixed sedimentation during periods of regression has been reported elsewhere. For example, areas of southwest Florida, South Florida, Northeast Australia, and the Gulf of Papua illustrate mixed carbonate–siliciclastic systems deposited during regression (Brooks et al. 2003; Dunbar and Dickens 2003; McNeill et al. 2004; Dickens et al. 2006). However, siliciclastic sedimentation in these environments has proven more effective, or is more prevalent, which is opposite to what is observed for the northern Abrolhos shelf.

**Relative Sea-Level Curves and Seismic Sequences**

Two relative sea-level fluctuation curves for the eastern Brazilian margin have been proposed (Martin et al. 2003; Angulo et al. 2006) (Fig. 14A, B). These sea-level curves suggest that the Brazilian margin experienced rising sea level from at least 8,000 yr BP up until a maximum highstand at about 5,600 yr BP, followed by a relative fall in sea level. However, the curve of Martin et al. (2003) suggests several smaller events within the overall fall of sea level (see Fig. 14) that may be important for the understanding of the processes observed herein.

Two hypotheses are presented here for the formation and timing of the seismic sequences and surfaces of Set II. Hypothesis 1 (H1) considers that the maximum-flooding surface (MFS) separating the transgressive sequences (Sq2) from regressive sequences (Sq3 and Sq4), was at approximately 7,000 yr BP (Fig. 14A). Hypothesis 2 (H2) is that the MFS occurred slightly later, at approximately 5,600 yr BP (Fig. 14B).

According to H1, the progradation of siliciclastic sedimentation from 7,000 to 5,600 yr BP may have influenced the lower reef accumulation
rate (1.5 mm/year) (Leão and Ginsburg 1997) of the Coroa Vermelha reef. The location of the coastal arc reef is exactly at the end of the Sq3 progradation. The region without emerged coral reefs corresponds to the area between the two northern seismic lines, which clearly shows these seismic facies (Fig. 7, blue inset and Fig. 8, blue inset).

For H2, the configuration of Sq3 and S4 would represent a period of high-frequency sea-level oscillations that occurred after 5,600 yr BP as suggested by Martin et al. (2003), Martin et al. (1996), and Martin et al. (1985). Alternatively, in H1, S4 occurs during a highstand at 5,600 yr BP, representing a change from highstand seismic sequences (Sq3) to regressive seismic sequences (Sq4). In fact, rapid vertical growth of the Coroa Vermelha reef (accumulation rates on the order of 5.5 mm/year) was observed after 5,600 yr BP, when there is a decrease of terrigenous sedimentation as suggested by sequence Sq3. This interpretation (H1) seems to agree better with the reef history formed at Coroa Vermelha reef (Leão and Ginsburg 1997; Leão et al. 2003).

Radiocarbon dating of core T2 also seems to better corroborate H1. Considering that 96 cm were deposited since approximately 2,700 yr BP, this yields an accumulation rate on the order of 0.35 mm/year. Therefore, considering that Sq4 thickness in the core location (Fig. 6. inset) is approximately 2 m, we would have an age of 5,700 yr BP at the base of Sq4. This age suggests that the S4 surface represents the top of the sea-level highstand. S3 would then represent a relative maximum-flooding surface (MFS). However, larger dating sample size is needed, mostly dating to confirm these stratigraphic assignments.

Conceptual Model for the Holocene of the Abrolhos Shelf

A conceptual model of sedimentation pattern of the northern area of the Abrolhos shelf during the Holocene (Fig. 15) highlights the influence of paleotopography. The interpretation integrates information on seismic character and analysis of the geomorphology from the area with previous studies.

The basal, major unconformity is the karstic surface, which developed pronounced paleotopography on the Pleistocene carbonates of Set I (Fig. 15B). With postglacial sea-level rise, the exposed shelf was
FIG. 7.—Seismic line representing the seismic sequences and surfaces identified. Sq4 seismic facies was delimited through seismic data analysis and CaCO$_3$ content map. Red inset: detailed image showing the clinoforms of Sq3 and Sq4, bounded above by nonerosional surface. Blue inset: detailed image of a paleotopographic high that may be coincident with the Pleistocene base of the emerged reef Sebastião Gomes.

FIG. 8.—Seismic line representing the seismic sequences and surfaces identified. Sq4 seismic facies was delimited through seismic data analysis and CaCO$_3$ content map. The high topography of the Set I southeast may be coincident with the Pleistocene base of Parcel das Paredes Holocene reef. Inset: detailed image showing the clinoforms.
progressively flooded (Vicalvi et al. 1978). During the postglacial transgression, the stabilization in sea-level rise that occurred between 14,000 and 10,000 yr BP allowed the development of the prograding carbonate deposits of sequence Sq1 (Fig. 15C). After 10,000 yr BP, the global sea-level curve shows a rapid sea-level rise. From 8,000 to 7,000 yr BP, the Abrolhos shelf was completely drowned. Thus, rhodolith banks and coral reefs developed on the offshore shelf without terrigenous sediment input. On the inner shelf, the incised channels were filled by carbonate and siliciclastic sediments (Fig. 15D). Coastal coral reefs began their growth at this time. During maximum highstand the coral reefs in Abrolhos reached the climax phase of reef development. Also during the maximum highstand, nearshore terrigenous sediment input and seaward progradation began. Offshore, rhodoliths and coral reefs continued their development (it is important to note that coral-reef growth was probably restricted to 20 to 30 m depth). Seabed mapping has shown the occurrence of modern mesophotic reefs, below 30 m, with less than 10% of coral coverage (Moura et al. 2013). During the subsequent regressive phase, the same sedimentation pattern occurred, with siliciclastic sedimentation along nearshore, out to near the coastal reef arc, a seaward transition to mixed facies and predominantly carbonate sedimentation offshore (Fig. 15E).

The sedimentation processes for the northern Abrolhos shelf differ from the southern area. Sediment distribution and geomorphology suggest that during the lowstand, siliciclastic sediments moved southward, towards the south-central depression (Abrolhos Depression). This depression drained the terrigenous sediments to the slope (Melo et al. 1975; Vicalvi et al. 1978) (Fig. 1), varying the vertical depositional pattern in this region compared to the northern area. Vicalvi et al. (1978) has carried out a paleoenvironmental analysis based on foraminifera, sedimentary facies, and age dating of a core in the Abrolhos depression (Fig. 1). They observed a transition of terrigenous to carbonate sedimentation (deepening) at about 65 to 70 m below current sea level.

Fig. 9.—Seismic line representing Sq1, bounded by S2 identified only in the middle and outer shelf.

Fig. 10.—A) Mud content of surficial sediment samples. B) Calcium carbonate content on surficial sediments. Red contour < 40% of CaCO3, yellow contour > 40%.
representing the last postglacial marine transgression. This change was radiocarbon dated to be around 10,300 to 8,200 yr BP. Such paleotopographic influence was also observed in south Florida (McNeill et al. 2004), where the transition from carbonate to siliciclastic sedimentation in the Miocene was influenced by a paleotopographic depression in the limestone surface of the middle Miocene Arcadia Formation that provides a pathway for the southward transport of siliciclastics.

Lowstand terrigenous deposits were not observed clearly in the seismic data from the northern Abrolhos shelf, but probably are present in the southern area because of the paleotopography. This topography suggests that the Abrolhos shelf had different sedimentation patterns, and during the last postglacial transgression, the lowstand terrigenous sediments of the southern area were transported to the middle shelf and the inner shelf, restricting carbonate production. Dunbar et al. (2000), in their study of the northeast Australian margin, suggest that the siliciclastic accumulation is greatly enhanced during transgression and it can be associated with the low gradient of the outer shelf. This low-gradient shelf stores fluvial sediment behind karstified reefs during lowstands and, subsequently, releases this material to slopes and basins during late transgression, affecting reef growth and carbonate production.

The depositional pattern suggested in this paper is different from other mixed carbonate–siliciclastic systems. For example, the Great Barrier Reef region had siliciclastic sedimentation dominating during lowstand and transgression (Harris et al. 1990; Larcombe and Carter 1998; Dunbar et al. 2000; Dunbar and Dickens 2003). On the western Florida coast, the siliciclastic sedimentation also dominated during lowstand and transgressive periods from the Oligocene until the present, while the carbonate facies resided in the more offshore areas during highstand (Hine et al. 2003; Hine et al. 2009).

The topography of the Abrolhos shelf shows that this platform had its own distinct sedimentary evolution during the last postglacial transgression. Thus, it is not possible to propose a single depositional model. The northern area is clearly the region which has shallower depths with incised channels and better development of Holocene coral reefs. Seismic lines show the influence of karstic paleotopography on coral-reef development and carbonate accumulation. Finally, the stratigraphic pattern resulting from the sedimentation is carbonate dominated offshore during the last postglacial transgression and subsequent regressive phase (eroded Pleistocene carbonate rocks overlain by carbonate deposition, possibly by coral–algae reef complexes and bioclastic debris). Seismostratigraphic analysis also indicates carbonate transgressive deposits in the nearshore...
and siliciclastic/mixed sedimentation only during highstand/regressive phase, and often associated with coral patch reefs.

CONCLUSIONS

The Abrolhos shelf is one of the largest modern examples of a tropical mixed carbonate–siliciclastic depositional system. The modern sedimentary regime includes coral-reef growth with input of terrigenous sediments along the inner shelf and mesophotic reefs and rhodolith beds along the middle to outer shelf. Thus, modern mixed sedimentation occurs along the inner shelf. Paleotopography is an important control on sediment distribution and reef growth. The geomorphology of the middle to outer shelf illustrates that the central-northern part is characterized by high-relief reefs and rhodolith deposits, whereas the southern part is marked by a depression with muddy sediments.

A model describing the sedimentary evolution of the northern Abrolhos shelf during the last postglacial transgression (about the last 15,000 yr) indicates that sedimentation was controlled by an interaction among carbonate production, siliciclastic sediment supply, and relative changes in sea level. Carbonate sedimentation predominated during the postglacial transgression in the late Pleistocene–Holocene period. At the end of this transgression and subsequent regression phase (last 5,600 yr along the eastern Brazilian coast), siliciclastic sedimentation took place nearshore, with a transition of mixed facies on the mid-shelf, and carbonate sedimentation dominated offshore. This pattern is valid for the northern part of the shelf but it is probably different from the southern area, where the antecedent topography allowed the accumulation of terrigenous sediments during the lowstand. This study indicates that, along the northern Abrolhos shelf, carbonate sedimentation was the main sedimentary process during transgression and highstand; a mixed shelf was observed over the past 5,600 yr, when terrigenous sediment and coral patch reefs coexisted along the inner shelf, and carbonate sedimentation dominated the middle-shelf to outer-shelf areas. This study illustrates the diversity of factors that can influence mixed sediment systems and how intrabasinal variations can occur.

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FIG. 13.—Seismic line with the Set I interpretation (Pleistocene Sequence). A) Compilation of global sea-level curves to the last 140,000 yr BP proposed by Rabineau et al. (2006). B) Correlation of the interpreted seismic sequences and surfaces on the sea-level curve proposed by Rabineau et al. (2006). Sq1 and Sq2 represent Set II.

FIG. 14.—Seismic line with the Set II interpretation (late Pleistocene–Holocene Sequence). A and B present the two hypothesis discussed in the text, considering the relative sea-level curves for the eastern Brazilian coast proposed by Martin (2003, in orange) and Angulo et al. (2006, in blue). The hypotheses are based on the position of the seismic sequences (Sq2, Sq3, and Sq4) and surfaces (S3 and S4) along the curves. (MFS: maximum-flooding surface).
FIG. 15.—Depositional model to the northern portion of the Abrolhos shelf: A) two seismic lines representing the inner-shelf and outer-shelf sequences (note: these lines are not continuous). B) Karstic relief formed during the last maximum glacial on Pleistocene carbonate rocks. C) Stabilization in sea level during the last postglacial transgression, which occurred between 14,000 and 10,000 yr BP and allowed the development of offshore retrograding-transgressive carbonate deposits. D) Maximum highstand at about 5,600 yr BP reaching up 5 m above current mean sea level. E) Relative-sea-level regression after this highstand until the present.


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