A non-deltaic clinoform wedge fed by multiple sources off São Sebastião Island, southeastern Brazilian Shelf

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Abstract

São Sebastião Island (SSI) marks the latitudinal boundary between two sedimentological and geochemical provinces in the São Paulo Bight, an arc-shaped sector of the southeastern Brazilian shelf. The island is separated from the continent by the narrow, deep São Sebastião Channel (SSC). A relatively thick sediment wedge—the São Sebastião Wedge (SSW)—has been formed offshore SSI. This study explores the possible genetic and evolutionary mechanisms of the wedge, bearing in mind that clinoform wedges can form at considerable distances from major fluvial sources. For that, a marine geological database has been interpreted comprising high-resolution seismic data, a surficial sediment map and several sediment cores, from which radiocarbon dates were obtained and sedimentation rates deduced. A wave model was also applied to obtain the dominant wave directions. The SSW is a wedge-shaped deposit, and its internal structure presents three seismic units. The two lowest are wedge shaped and arranged in a backstepping pattern. The most recent unit is mostly aggradational and can be divided into three seismic subunits. Sedimentological data show that at least the most recent unit is composed of a mixture of sands and silts. Modeled wave

conditions indicate a major influence from southerly waves that are able to remobilize shelf sediments and to create a bypass sediment zone until the foreset of the deposit is reached at the water depths where the SSW is found. Taken together, these data suggest that the SSW formed through contributions from different sediment sources, and should be regarded as an intermediate case of a non-deltaic clinoform wedge. Sand transport in the area involves wind-driven currents passing through the SSC and sediment remobilization by energetic southerly waves. Fine-grained sediment is derived mostly from the joint contributions of many minor catchments located north of the island, and this sediment is later transported southwestward by the prevailing surface currents. The morphological obstacle presented by the island leads to current veering and subsequent sediment deposition. The internal architecture of the wedge indicates that its deposition was probably initiated during the last part of the postglacial transgression, but its present-day morphology is mostly a product of episodic highstand sedimentation that began under conditions of gently falling sea levels during the last 5 ka, after the Holocene glacio-eustatic maximum.

INTRODUCTION

The development of clinoform wedges appears to be governed by similar physical laws across a range of scales, from individual deltas associated to single river sources to entire continental margins (Patruno et al. 2015). At the deltaic scale, clinoform wedges may be linked to nearby high-volume sediment supplies, and they develop into either proximal-accumulation-dominated systems or subaqueous deltaic clinoforms (Walsh and Nittrouer 2009). These deposits associated with high-volume sediment supplies have traditionally received considerable attention, because they constitute major depocenters and trap substantial amounts of sediments and pollutants at or close to the catchment–coast interface. However, a growing body of evidence reveals the rather pervasive occurrence of shallow-water clinoform wedges of scales comparable to those of individual deltas, which are not related to direct fluvial inputs. Instead, these wedges may share a number of morphological (e.g., shore-parallel distributions), stratigraphic (e.g., sigmoid cross sections) and chronological (preferential development during the Holocene stillstand) similarities with their truly deltaic counterparts (Patruno et al. 2015). This study refers to such deposits that are detached from direct, significant fluvial inputs as non-deltaic clinoform wedges (nDCWs). These deposits largely fall into two end-member cases, muddy and coarse-grained nDCWs.

Muddy nDCWs are usually referred to as muddy wedges (e.g., Hanebuth et al. 2015). They can be regarded as a type of marine dispersal-dominated system, and they are characterized by river input discharging (and subordinated) to a moderate- to high-energy oceanographic environment (Walsh and Nittrouer 2009). The most complex system of muddy wedges has been recognized in the Yellow Sea and the East China Sea, where these wedges constitute a laterally continuous depocenter extending hundreds of kilometers along the coast (Liu et al. 2006, 2009). Although the growth of these elongated muddy wedges may be coupled to their parent deltaic systems (Cattaneo et al. 2003), in most cases the depocenters appear to be located at considerable distances from their sediment sources, implying very effective along-shelf sediment dispersal by advective processes (Liu et al. 2009).

Sandy nDCWs, which are designated as nearshore sand bodies, infralittoral prograding wedges or offshore depositional terraces, have been reported from narrow, steep shelves with negligible fluvial supply. Representative cases have been described from the southwestern Australian coast (Field and Roy 1984), the shelves of the southern Iberian Peninsula (Hernández-Molina et al. 2000; Lobo et al. 2005), off volcanic islands in the Tyrrhenian Sea in the western Mediterranean (Chiocci and Orlando 1996; Casalbore et al. 2017), in the Azores archipelago (Quartau et al. 2012, 2015) and around oceanic islands (Quartau et al. 2014). The inferred depositional model is based on coastal erosion of cliffs and/or beaches by energetic wave regimes and subsequent offshore sediment transport by downwelling storm currents (Field and Roy 1984; Chiocci and Orlando 1996; Hernández-Molina et al. 2000; Meireles et al. 2013).

The entire spectrum of nDCWs develops similar morphologies and internal architectures that are primarily controlled by the energetic hydrodynamic regimes that they experience and secondarily by local geomorphological conditions. Muddy nDCWs imply the action of alongshore dispersal systems driven by powerful coastal currents that derive sediments from a distant sediment source, as reflected in their characteristic elongated distribution patterns (Cattaneo et al. 2003; Lantzsch et al. 2014; Gao et al. 2015; Lee et al. 2015). In contrast, sediment production is relatively close to the sediment depocenters in the case of sandy nDCWs, due to the considerable influence of energetic wave regimes that tend to develop a primarily seaward progradation trend, although it is modulated in areas of enhanced littoral drift (Hernández-Molina et al. 2000; Massari and Chiocci 2006; Ortega-Sánchez et al. 2014).

The São Paulo Bight constitutes an arc-shaped, extensive shelf environment where recent sedimentary processes appear to be controlled by an intense, spatially variable hydrodynamic setting (Figueiredo and Tessler 2004; de Mahiques et al. 2009). A recent geophysical survey (Núcleo de Apoio à Pesquisa "Geodinâmica das Bacias Sedimentares e Implicações para o Potencial Exploratório", NAP-Geosedex Cruise, 2013) conducted off São Sebastião Island

(SSI) revealed the occurrence of a relatively thick, shallow-water sediment wedge with internal clinoforms dipping seaward. Since the uplift of a coastal mountain chain (Serra do Mar) during the late Cretaceous, the rivers that once flowed seaward have now started to run in the opposite direction, and therefore the mountain chain blocked the sedimentary input to the shelf.

Thus, it is hypothesized that the existence of this relatively shallow-water clinoform wedge must be influenced by complex interactions between the sediment dispersal system and the coastal geomorphological configuration. This study intends to (1) provide a genetic model for the São Sebastião clinoform wedge, within the framework of present knowledge about nDCWs development, and (2) decipher the accumulation of this stratigraphic feature in the context of Holocene sea-level rise and the subsequent stillstand (i.e., an evolutionary model) by correlating local evidence with radiocarbon-dated, regional sea-level data and with a global postglacial sea-level curve.

STUDY AREA

Geological setting

SSI is located in the São Paulo Bight, an arc-shaped embayment that extends approx. 1,100 km from Cabo de Santa Marta (28°30′S–49°00′W) in the south to Cabo Frio (23°00′S–42°00′W) in the north (Fig. 1a, b; Zembruscki 1979). This embayment represents the shallow-water expression of the Santos Basin, which attained a passive margin configuration during the late Cretaceous as a result of the uplift of the Serra do Mar mountain chain, a major regional physiographic feature that extends parallel to the coast for approx. 1,200 km and is up to 2,200 m high (Almeida 1976).

SSI is an alkaline volcanic complex that is separated from the continent by the 22-km-long, deep (up to 45 m) and narrow (1.6 to 6.4 km wide) São Sebastião Channel (SSC). Its origin is associated with the Cretaceous–Paleogene reactivation of the southeastern Brazilian margin, as well as subaerial and marine erosion caused by sea-level oscillations throughout the Quaternary (Alcántara-Carrió et al. 2017).

Oceanographic setting

The region is micro-tidal, with a maximum tidal range of 1.2 m (Sousa et al. 2013), and it is influenced by meteorological tides related to cold fronts (Campos et al. 2010). The dominant waves reach the area from the south and east. With the exception of the easterly wave-dominated spring months, the dominant waves come from the southerly quadrant. These dominant waves have heights ranging from 1 to 2 m during summer and fall, and they increase to 2 to 3 m in winter (Pianca et al. 2010). These are also the most energetic waves, associated with the passage of cold fronts (Pianca et al. 2010).

In terms of currents, the coastal waters flow along the inner shelf of the São Paulo Bight where they are vertically homogeneous and bounded seaward by a deep thermal front defined by the landward intrusion of the South Atlantic Central Water (Cerda and Castro 2014). Within this inner domain, the currents are controlled mainly by the interplay between the coastal buoyancy flux stress and the wind shear stress, and secondarily by tidal currents (Silva et al. 2005). Bidirectional coastal jets are induced by changing wind regimes, and they can flow toward the northeast or the southwest, parallel to the coast (Cerda and Castro 2014). In the area around SSI, surficial wind-driven currents are directed toward the southwest during winter, spring and summer (Silva et al. 2004). In contrast, surficial currents are directed toward the northeast in autumn, when wind activity is minimal (Silva et al. 2004, 2005; Cerda and Castro 2014). Within the SSC, wind-driven currents also exhibit a bidirectional pattern, although the northeast-directed current dominates under the influence of southerly cold front events (Paixão 2008).

Coastal sediment sources

Between Cabo Frio and SSI, the coastal plains are very narrow, due to the nearby Serra do Mar mountain chain. The average annual precipitation within the study area ranges from 1,000 to 3,000 mm (Fig. 2). The highest values occur northwest of the study area, in the Ubatuba region (Fig. 1c). Water discharge shows a seasonal pattern, with values ranging between 33 and 186 $m^3 s^{-1}$ (Kjerfve et al. 1997).

Several mud-prone (50–80%) embayments showing poorly developed coastal plains constitute the remnants of late Quaternary paleo-channels, such as the Guanabara and Ilha Grande bays (Fig. 1b; Kjerve et al. 1997; Belo et al. 2002). Smaller embayments that preferentially accumulate coarse sediments occur between Ilha Grande Bay and the SSC. In the vicinity of SSI, the Juqueriquerê River (Fig. 2) extends from the Serra do Mar mountain chain to the coastal plain. It occupies an 850 km^2 drainage basin and features low fluvial discharges (2.79 $m^3 s^{-1}$).

The coastline is more regular southwest of SSI, although several embayments occur. The northward-flowing, low-density La Plata River plume (Fig. 1a, sediment discharge approx. 23.3×10^3 $m^3 s^{-1}$) only influences deposition up to 25°S (Piola et al. 2000; de Mahiques et al. 2008).

Shelf geomorphology and sediments

The maximum shelf width in the São Paulo Bight is 230 km off Santos, and it is narrower at the bight's northern (50 km off Cabo Frio) and southern boundaries (70 km off Cabo de Santa Marta). Average seafloor gradients are lower than 0.1° on average, and the shelf can be subdivided into three distinct domains (inner, middle and outer) based on seafloor gradients (Zembruscki 1979). The inner shelf exhibits irregular topography, due to the presence of islands.

The surficial sediment distribution exhibits a contrasting pattern north and south of SSI (de Mahiques et al. 1999, 2004). To the north, the sediment distribution has a patchy, heterogeneous pattern (with grain sizes ranging from muds to very coarse sands), due to the irregular seafloor and coastal morphology. An elongated muddy belt is observed on the inner shelf, whereas most of the remaining shelf is covered by coarse-grained sediments. South of the island, the inner to middle shelf is covered by fine and very fine sands, whereas mud contents increase toward the outer shelf (de Mahiques et al. 1999, 2004).

Recent evolution and sea-level changes

The incision of paleo-valleys around SSI (Conti and Furtado 2006, 2009) is related to the sea-level fall that preceded the last glacial maximum lowstand (Conti 2009). Regional sea level rose after the end of the last glacial maximum (i.e., 17.5–6.5 ka), with average rates of 12 m per 1,000 years (Corrêa 1996).

The maximum sea-level position (5 m above present sea level) occurred at 5.6 ka and was followed by a smooth sea-level fall (Martin et al. 2003; Angulo et al. 2006). The recent sedimentation processes around SSI are strongly controlled by the hydrodynamic regime; in general, sedimentation rates are very low and erosional processes prevail (de Mahiques et al. 2011). Northward export of sandy sediments occurs in the SSC under the influence of northwestward-directed currents (Alcántara-Carrió et al. 2017).

MATERIALS AND METHODS

The morphology and internal structure of the sedimentary wedge were assessed based on acoustic and sedimentological data acquired during three oceanographic cruises near SSI (Fig. 1c): NAP-Geosedex (February 2013), Cunha 1 (January 2015), and Cunha 2 (December 2015). Additionally, a surficial sediment distribution map and the output from wave modeling experiments were integrated into the study.

Seismic data

The seismic source used during the NAP-Geosedex cruise was a chirp of 3.5 kHz emission frequency. A total of 167 km of seismic lines were acquired that were oriented mostly SE–NW and SW–NE, with a few trending N–S. During the Cunha 1 cruise, a 2–8 kHz chirp and a 0.5–2 kHz boomer served to acquire 423 km of seismic lines oriented SE–NW and SW–NE. During the Cunha 2 cruise, 205 km of seismic lines were acquired using the same seismic sources as those of the Cunha 1 cruise, plus a 0.3–2 kHz sparker.

The seismic data were processed by means of Radexpro™ software following a standard single-channel seismic processing procedure, including bandpass filtering (Ormsby filter), swell filtering, a time-varied gain, tide correction and static corrections. Large-scale geomorphological and distribution patterns as well as the internal structure were interpreted using the Kingdom™ software package (IHS). The interpreted horizons were interpolated to a grid based on the Flex Gridding algorithm, which served to generate isopach and paleo-surface maps. This interpolation was performed only at the south–southeast limit of the wedge, due to the higher density of the data. The maps assisted in the interpretation made with ArcGIS™ software (ESRI).

The seismic architecture was correlated with the postglacial sea-level curve of Lambeck et al. (2014) and with a suite of regional sea-level data. All of the regional data have been recalibrated using the SH13 or Marine13 calibration curves (Reimer et al. 2016). Marine samples were corrected for a global reservoir effect of 400 years.

Sedimentological data

The sedimentological data consist of a surface distribution map and six sediment cores. A map of surficial grain-size distribution was produced using sediment data collected with grab sampling devices during numerous previous oceanographic cruises spanning the last 30 years. The dataset was interpolated by means of ArcGIS™ software (ESRI), the interpolation method being the Natural Neighbor with a grid size of 450 m. A 4-m-long piston core (NAP61 in Fig. 1c) was collected during the NAP-Geosedex cruise. The other five cores were collected using a gravity corer and are 0.5 m long, on average. All the cores were sampled every 2 cm to perform grain-size analysis.

Radiocarbon dating was performed on the carbonate fraction of core NAP61 at selected depths, by means of the accelerator mass spectrometry (AMS) at Beta Laboratories (Table 1). Calibrated ages were calculated using a local reservoir effect (ΔR) of 7±200 years (cf. Lund et al. 2015) and the Marine13 database available online at http://calib.org (Reimer et al. 2016). Grain-size analyses were performed on decarbonated samples from the same core using a Malvern Mastersizer laser analyzer at the Oceanographic Institute of the University of São Paulo.

Wave modeling

Based on the regional offshore wave information extracted from the global wave generation model WaveWatch III (NCEP/NOAA, Tolman et al. 2002), a numerical model was applied in order to propagate the waves onshore until they reached the area of interest. The numerical model applied was the Delft3D WAVE module (specifically, the open source version from Deltares). This module simulates the propagation and transformation of wind-generated waves as they move over varying bottom morphologies (Holthuijsen et al. 1993), simulating effects such as wave refraction, diffraction, shoaling and setup in coastal areas.

The wave propagation model used in this application covers the whole continental shelf of the São Paulo state and includes adjacent areas, keeping the area of interest away from the model borders. The grid resolution varies within the domain, with increased resolution nearshore. Boundary wave data, defined at the shelf break, represent three scenarios based on the dominant and extreme conditions for the region. Thereby, the southern and eastern wave conditions that represent approx. 40% of the waves occurring in the region have been simulated. Additionally, an extreme scenario (1% occurrence, represented by waves from the south with a significant wave height of 4 m and a 12 s period) for the region has been simulated.

RESULTS

Seismic stratigraphy

A wedge-shaped deposit—designated here as the São Sebastião Wedge (SSW)—extends laterally for approx. 32 km off SSI as a relatively narrow band parallel to the coast (Figs. 3, 4, 5, 6 and 7). The seismic stratigraphic analysis is focused on this major regional depocenter. The SSW is composed of three seismic units (U1 to U3) that rest on top of a basal surface.

<u>Basal surface (Bs)</u>

This surface underlies the sediment wedge and shows a southeastward dip; it extends up to the 72 m isobath (Fig. 7a). The steepest surface gradients (approx. 1°) occur southeast of SSI. Throughout the remainder of the region, the surface exhibits gentler gradients, up to 0.4°.

The Bs exhibits a small-scale rough morphology, and several paleo-valleys are eroded into it (e.g., Figs. 4 and 6); the lateral continuations of these paleo-valleys were not captured in this study. The paleo-valleys are hundreds of meters wide and up to 20 m deep, and they extend as far as 33 km offshore. Additionally, several mounded positive relief features (up to 236 m wide and 5 m high) appear to limit the seaward extension of the wedge (Fig. 3), as the distal bottomsets of the wedge abut against these topographic highs.

Seismic unit 1 (U1)

This seismic unit is partially masked by the occurrence of acoustic turbidity within the sediment wedge. Its seismic configuration exhibits very low-angle, oblique, parallel to sub-parallel stratified reflectors (Fig. 4).

The thickness distribution of U1 reflects a seaward-thinning wedge shape, with thickness values up to 10 m in proximal locations and decreasing steadily to 2–6 m farther seaward (Fig. 7d). The top boundary of U1 is a subtle erosional truncation in the landward portion of the unit (Fig. 6d). This upper boundary is steepest next to SSI and becomes gentler to the northeast (Fig. 7b).

Seismic unit 2 (U2)

This unit is only identified in a proximal location close to the southern tip of SSI, where the internal reflectors show a sub-parallel stratified configuration with moderate to high amplitudes (Fig. 5). These reflectors are erosionally truncated at the seaward termination of the unit, which occurs at approx. 1.8 km from the coast of SSI. The maximum thickness of this unit is approx. 12 m, and its base is located approx. 48 m below the current sea level.

Seismic unit 3 (U3)

Seismic unit 3 comprises three subunits and has a maximum thickness of approx. 17 m, occurring at the foreset of the deposit and becoming progressively thinner both seaward and landward (Fig. 7e). The stacking pattern of the internal subunits is strongly aggradational.

Subunit 3a is also partially masked by the occurrence of gas accumulations. It is characterized by a distinct, low-angle, parallel-oblique progradational pattern, with downlap terminations against the lower boundary (Fig. 4). The internal reflections show low amplitudes and high lateral continuity.

The maximum thickness (approx. 9 m) seems to occur in the middle of the unit and decreases both seaward and landward, where the subunit terminates against the basal surface in the vicinity of Búzios Island. The upper surface is steepest in the middle part of the deposit, where the gradient may be as high as 1.6°, becoming gentler northeastward and southwestward.

Subunit 3b can be observed in all seismic profiles, since it occurs at shallower depths than the gas features. The internal reflectors show a predominantly sub-parallel and stratified configuration with low amplitude and high lateral continuity. Landward, internal reflections are scarcely observed, and the seismic configuration becomes transparent (Fig. 4).

This subunit is relatively thin and sheet-shaped, with higher thickness values (up to 3 m) in the foresets, and it becomes thinner (approx. 1 m) landward and seaward. The inclination of its upper boundary southeast of SSI is up to 1.6° and becomes gentler to the northeast (up to 0.6°).

Subunit 3c is the most recent deposit and shows a sub-parallel configuration (Fig. 4). The internal reflectors feature planar-parallel stratifications with seismic amplitudes that are slightly higher than those observed in other units within the sedimentary wedge, particularly in the distal portion of the deposit. It is a very thin unit (2–3 m thick) with a characteristic external sheet shape that extends from 33 to 70 m in terms of water depth.

<u>Upper boundary of sediment wedge</u>

East of SSI, the upper surface shows a proximal flat profile up to water depths of 33 m; a convex rollover is identified at depths up to 39 m (Fig. 7c). The seaward limit of the deposit occurs at an average depth of 70 m. The topography of the upper boundary is steep (up to 1.6°) off SSI, becoming gentler to the northeast of the study area.

Sedimentary data

<u>Surficial sediment distribution</u>

The grain-size distribution of the surficial sediments of the SSW ranges from medium to coarse silt, with the medium silty area forming an eastern shadow zone surrounded by a coarse-silt belt (Fig. 8). Coarser grain sizes (very fine to coarse sand) are found to the south of SSI, to the north entrance of the SSC and to the northeast, close to Anchieta Island.

<u>Sediment core facies</u>

Core NAP61 was collected along seismic line Geosedex_18 (Fig. 9a), and it penetrates the two topmost subunits (U3a and U3b). Alternating silty sands and sandy silts are found from the core base up to a depth of 175 cm (approx. 1,600 cal yr BP). From 175 cm upward, however, silty sands and sandy silts exhibit a laminated pattern, with the silty fraction varying from 20 to more than 60% (Fig. 9a). A depth–age model based on linear interpolation (R=0.99) provided a sedimentation rate of 220 cm per 1,000 years (Fig. 9b and Table 1).

Wave modeling

Onshore-directed wave propagation shows that the area of interest is relatively exposed to wave action, although it is partially protected by SSI. Waves that reach the area from the southerly or easterly quadrants refract as they propagate over the steep bathymetric slope adjacent to SSI at water depths ranging from 70 to 35 m. Southerly and easterly waves reach the area of interest with similar significant wave heights, between 1.0 and 1.5 m; however, the southerly waves, which usually have higher periods, result in higher bottom orbital velocities (Fig. 10). Easterly waves result in orbital velocities of approx. 0.15 m s^{-1} over the SSW, whereas southerly waves generate orbital velocities of 0.25 m s^{-1}. The most energetic case considered in the wave scenarios covers waves that have a 1% probability of occurrence, representing strong storm conditions for the area. In this case, waves reach the SSW area with significant heights of approx. 3 m, and generate bottom orbital velocities of up to 0.5 m s^{-1} (Fig. 10).

DISCUSSION

The analysis of these data allowed (1) to establish a genetic model of the SSW, taking into account the existing knowledge on shallow-water sediment wedge deposition away from major fluvial inputs, based on the deposit's morphology, internal stratigraphy and composition, the coastal physiographic configuration and the regional hydrodynamics; (2) to establish an evolutionary model of the sediment wedge, considering the limited chronologic information that is available and the present knowledge of regional sea-level changes.

Genetic model

The development of nDCWs is basically dictated by the magnitude and intensity of sediment transport and their source. Thus, sandy nDCWs occur in close proximity to the parent shoreline deposits that are thought to feed them. They can extend laterally for tens of km, but remain 2–3 km away from the nearby coastlines (Field and Roy 1984; Hernández-Molina et al. 2000; Quartau et al. 2012, 2015; Casalbore et al. 2017). In contrast, muddy nDCWs are remote depocenters that extend hundreds of kilometers along coasts and have across-shelf extensions of tens of km (Liu et al. 2006, 2009).

The down-section sediment composition, morphological configuration, distribution patterns and internal structure of the SSW show characteristics that represent a mixture between sandy and muddy nDCWs. Thus, the upper part of the SSW appears to be composed of a mixture of sands and silts. In addition, the overall clinoform sigmoid geometry, which reflects a proximal flat surface and a distinct offlap break, is similar to the morphological rollover characteristic of sandy nDCWs, their development being controlled mainly by storm-wave base levels (Mitchell et al. 2012). However, sigmoid patterns have also been observed in mature, remote muddy wedges (Cattaneo et al. 2003; Gao and Collins 2014). The restricted distribution pattern of the SSW, which has an average thickness of 24 m and extends for at least 41 km parallel to the coast, seems to be more similar to the patterns exhibited by the most significant examples of sandy nDCWs (Fernández-Salas et al. 2009; Casalbore et al. 2017).
However, the surficial distribution of sediments indicates that silty sediments mainly cover the area where the SSW outcrops at the seafloor. In addition, the dominant internal configuration of the SSW (low-angle progradational oblique to sub-parallel) is more characteristic of muddy wedges, due to the prevalence of long-distance, shore-parallel advective sediment transport (Cattaneo et al. 2003; Liu et al. 2009). In contrast, sandy nDCWs tend to develop higher-angle progradational clinoforms, driven by sediment avalanching caused by offshore bottom current activity (Field and Roy 1984; Chiocci and Orlando 1996; Hernández-Molina et al. 2000; Lobo et al. 2005).
The genetic model for the SSW is based on the existence of two different sediment sources. Hence, the model would involve the transport of sandy and muddy sediment, driven by the dominant wind-driven current pattern over the inner shelf of the study area (Fig. 11). Regarding sand sources, it is assumed that coastal erosion is not able to produce a significant amount of sediment in the study area, as the coasts of the rocky island and the nearby inland area are essentially devoid of major sediment accumulations. However, northeastward-directed sand transport has been detected in the SSC, connected to the activity of wind-driven currents during cold fronts (Alcántara-Carrió et al. 2017). Indeed, the northeastern exit of the channel is mainly covered by sandy sediments, attesting to the effectiveness of sand transport along the channel. These coarse sediments that become dispersed over the inner areas of the island can be episodically remobilized by highly energetic waves, which have been revealed to occur in the study area through wave modeling. Although the region is partially protected from wave action, the dominant waves are able to produce sediment transport with wave orbital velocities ranging from 0.15 m s^{-1} (less energetic easterly waves) to 0.25 m s^{-1} (southerly waves). Extreme wave conditions result in orbital velocities of up to 0.5 m s^{-1}

(Fig. 10). Thereby, dominant wave conditions seem to be able to remobilize coarse-grained sediments toward the south–southeast.

The amount of silt found in the SSW indicates the existence of an additional, more distant sediment source. The contributions of the major regional sediment supplier (i.e., the La Plata River) are unlikely to influence sediment deposition in the study area (de Mahiques et al. 2010), taking into account its distant location and the protective effect of the island itself (Alcántara-Carrió et al. 2017). In addition, the small discharges of the nearby Juqueriquerê River seem to be insufficient to cause a major progradation off SSI, but instead they become concentrated in the protected coastal embayment landward of SSI and the adjacent minor islands.

North of the island, several minor streams supply small amounts of water and sediment. However, collectively, these rivers may constitute a linear source, especially under the influence of intense rainfall regimes from November to March when the transport of terrigenous sediment to the inner shelf may be enhanced (Castro Filho et al. 1987; de Mahiques et al. 1999). This pattern may be comparable to the joint supplies of small rivers documented in the Yangtse dispersal system, which can contribute to the outbuilding of an alongshore clinoform deposit (Liu et al. 2007a), although at a much smaller scale. The prevalence of southwest-directed coastal jets from summer to winter (Cerda and Castro 2014) would lead to the entrainment of fine-grained supplies from the small streams located north of the island. These southwest-directed coastal jets would also lead to the seaward displacement of the coastal water (de Mahiques et al. 2004).

Morphological obstacles are reported to influence significant deposition along active lateral dispersal systems, as evidenced in the Gargano Promontory in the Adriatic Sea (Cattaneo et al. 2003). Within the study area, focused deposition seems to have been enhanced by the obstacle effect of SSI, which would lead to current veering and subsequently sediment deposition attached to the island. The rapid disappearance of the SSW southwest of the island could be related to the seasonal erosional activity of wind-driven currents (i.e., northeastward-directed during autumn) in areas where the sheltering capacity of the island disappears. The depression observed between Buzios Island and SSI is interpreted as another morphological expression of the deflection of the sediment load carried by the wind-driven currents, causing them to be deposited both seaward and landward.

Evolutionary model: transgressive to highstand

Most known examples of nDCWs are regarded as compound features whose initial formation occurred during the postglacial transgression and whose main development has occurred during successive Holocene highstand phases (Field and Roy 1984; Yang and Liu 2007; Liu et al. 2007a; Ercilla et al. 2009; Xu et al. 2012; Martínez-Carreño et al. 2017). In particular, the development of sigmoid configurations in muddy wedges is interpreted to be indicative of a mature stage of development (Gao and Collins 2014). A tentative timing of events recorded in the seismic architecture of the SSW is proposed, based on the following evidence: (1) chronological information provided by core NAP61; (2) a set of regional sea-level data (Vicalvi et al. 1978; de Mahiques et al. 2011); (3) comparison of depths of occurrences of seismic units 1 and 2 with a global postglacial sea-level curve (Lambeck et al. 2014).

The seismic signature of the basal surface, which is irregular with a small-scale topography and is affected by paleo-channels, indicates that the surface is erosional. In fact, the observed paleo-valley is considered to be a remnant of the Búzios paleo-valley, whose major incision phase was apparently connected with the sea-level fall leading to the last glacial maximum lowstand (Zembruscki 1979; Conti and Furtado 2009). The basal surface is thus interpreted as a polygenetic surface formed during low sea levels by subaerial processes and subsequently reworked during the postglacial sea-level rise. This interpretation would place the entire SSW in the postglacial interval, when it formed under conditions of rising to stable sea levels.

The marked seaward thickness decrease of U1, as well as the occurrence of relatively high-amplitude internal reflections, is interpreted as the result of deposition in a relatively high-energy depositional environment and shallower water, compared to the subsequent units. The fact that unit 2 is located landward tends to support the hypothesis that the genesis of unit 1 occurred during a transgressive context. The initial onset of nDCWs is usually ascribed to the terminal phase of the postglacial transgression, usually after the Younger Dryas event, and more typically during the 10–7 ka interval (Field and Roy 1984; Liu et al. 2007a; Ercilla et al. 2009; Quartau et al. 2012; Martínez-Carreño et al. 2017). Based on the range of observed depths (47–65 m) of the top boundary of seismic unit 1, the formation of this deposit is related to the period of shelf flooding occurring approx. between 11 and 9.5 ka, which was terminated by a period of reduction in the rate of sea-level rise (Lambeck et al. 2014; Fig. 12). Unit 2 is observed only in a very proximal location (approx. 1.8 km from the SSI coast), at a water depth of 35 m. Taking into account the limited depth information obtained from this unit, and its correlation with the global sea-level curve (Lambeck et al. 2014) and regional sea-level data (de Mahiques et al. 2011), the formation of this unit is suggested to have occurred during a renewed period of rapid shelf flooding between 9.5 and 8.2 ka, after an inflection point of the sea-level curve at about 9.5 ka (Fig. 12).

The seaward erosional truncation of the internal reflections of seismic unit 2 is interpreted to have occurred in a submarine environment, due to the continuous sea-level rise trend occurring during and after the estimated genesis of this seismic unit. Indeed, it is proposed that the erosion could have been favored during conditions of sea-level rise approaching the eustatic maximum between 8.2 and 6 ka at relatively low rates; these sea-level conditions would have favored the landward displacement of coastal currents driven by density gradients, and the interaction of these coastal currents with the southeastern tip of SSI. Similar coastal erosional events have been reported in Chesapeake Bay (Lentz and Largier 2006) and the Yangtze River Estuary (Deng et al. 2017).

Unit 3 displays a dominantly sub-parallel internal configuration, with low-amplitude, highly continuous reflectors. These seismic facies are indicative of deposition under relatively low-energy conditions established during the Holocene stillstand, as recognized in numerous Holocene depositional systems (Walsh and Nittrouer 2009; Gao and Collins 2014). Assuming constant sedimentation rates during the deposition of U3, its formation would have taken place during the last 5 ka. Since the sea-level highstand occurred at approx. 5,600 yr BP (Angulo et al. 2006), U3 would have been deposited during the middle Holocene highstand period, in agreement with depositional trends recognized in other clinoform wedges (Liu et al. 2007a; Ercilla et al. 2009; Xu et al. 2012; Martínez-Carreño et al. 2017).

The identification of internal subunits during this most recent depositional event would indicate the occurrence of different depositional phases alternating with periods of reduced deposition, possibly governed by climate-driven events interfering with anthropogenic impacts (de Mahiques et al. 2016). Radiocarbon ages also indicate that the sedimentation rates are significantly higher than at adjacent locations (220 cm per 1,000 years at the study site versus 2 to 68 cm per 1,000 years at neighboring sites; de Mahiques et al. 2011). In particular, a change of depositional patterns may have occurred at approx. 1,600 cal yr BP. These depositional trends are in agreement with evidence from the Adriatic Sea (Cattaneo et al. 2003) and the East China Sea (Liu et al. 2007b), where periods of variable sedimentation rates seem to have been favored during the last 1,000 years (Cattaneo et al. 2003; Yang and Liu 2007; Liu et al. 2007b), usually triggered by climatic events such as the Little Ice Age (Cattaneo et al. 2003).

CONCLUSIONS

A non-deltaic clinoform wedge (nDCW) designated the São Sebastião Wedge (SSW) attached to the coastal São Sebastião Island (SSI) is thought to represent an intermediate scenario between known cases of muddy and sandy nDCWs, as both fine-grained and coarse-grained sediment transport seem to be involved in its formation. The combination of a wind-driven hydrodynamic regime leading to active lateral sediment dispersal and a major coastal protuberance may focus deposition and generate a spatially confined depocenter, even under conditions of low fluvial discharges. The importance of SSI is highlighted not only as a regional boundary between different grain sizes and oceanographic regimes, but also as a physical barrier that is capable of enabling deposition of a kilometer-scale sedimentary body. Coarse-grained sediment sources involve the northeastward transport of sands through the São Sebastião Channel, which then undergo subsequent reworking and remobilization due to the activity of energetic southerly waves. These energetic wave base levels may have caused the development of a well-defined rollover geometry. The transported fine-grained sediment is interpreted to be derived mainly from the contributions of several small drainage basins located north of the island and acting as a linear source; these fine-grained sediments would be subsequently transported southwestward by the surface currents that prevail throughout most of the year under the influence of northeasterly winds. The coastal protuberance constituted by the island itself would cause the surface currents to veer, and favors deposition attached to the morphological obstacle.

The evolution of the SSW has been guided by the postglacial sea-level rise, and shows both transgressive and highstand developments. The transgressive setting probably involved the formation of two backstepped coastal wedges, with limited aggradation and local signs of erosion. The highstand stage was probably influenced by a gradually declining sea level during the last 5 ka, and exhibits several growth phases attributed to climatically driven depositional events.

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Fig. 1 Geographical locations: **a** São Paulo Bight; **b** study area; **c** collection of data used in this study. *White lines* Seismic data from the Cunha 1 and 2 cruises (2–8 kHz chirp, 0.5–2 kHz boomer, 0.3–2 kHz sparker sources). *Black lines* Data from the NAP-Geosedex cruise (3.5 kHz chirp source). *Green dots* Surface sediment samples, *red dots* sediment cores

Fig. 2 Maps showing the average annual precipitation (AAP) and the different drainage basins along the littoral zone between São Sebastião Island and Cape Frio (data sources: Agência Nacional de Águas – Brazil 2017; Comitê de Bacias Hidrográficas do Litoral Norte 2014)

Fig. 3 Stratigraphic architecture of the sediment wedge southeast of São Sebastião Island: *top* uninterpreted chirp seismic profile; *bottom* interpreted chirp seismic profile. Acoustic masking (cyan surface) partially blocking the seismic signal from approx. 80 ms. The presence of mounded relief features on the basal surface (*red*) limits the seaward extension of the wedge

Fig. 4 Stratigraphic architecture of the sediment wedge southeast of São Sebastião Island: *top* uninterpreted boomer seismic profile; *bottom* interpreted profile highlighting a transgressive unit (U1) over a lowstand surface (Bs) and the subsequent unit (U3) deposited in a highstand environment. Color legend as in Fig. 3

Fig. 5 Stratigraphic architecture of the sediment wedge off the southern tip of São Sebastião Island: **a** uninterpreted boomer seismic profile; **b** interpreted profile highlighting the stacking patterns of internal seismic units. The seaward erosion of unit 2 is also evident. Color legend as in Fig. 3

Fig. 6 Stratigraphic architecture in the landward sector of the sediment wedge: **a** uninterpreted boomer seismic profile north of the island; **b** interpreted profile showing the landward limit of the sediment wedge and an older paleo-valley; **c** uninterpreted boomer seismic profile east of the island; **d** interpreted profile showing the landward limit of the sediment wedge and the erosion of unit 1 off the surficial depression between SSI and Búzios Island. Color legend as in Fig. 3

Fig. 7 Mapping of the seismic stratigraphy of the sediment wedge (values in meters): **a**–**c** paleo-surface maps of the basal surface, the top boundary of unit 1, and the top boundary of unit 3, respectively; **d**–**f** thickness distribution maps of unit 1, unit 3 and unit1+unit 3, respectively

Fig. 8 Surface sediment distribution map. Finer grain sizes (medium to coarse silts) are observed within the area occupied by the sediment wedge; coarser grain sizes are observed southeast of SSI, at the north entrance of SSC, and close to Anchieta Island

Fig. 9 NAP61 core sediment analysis results: **a** grain size and age distribution (*blue and yellow* silt and sand content, respectively); **b** sedimentation rate and linear fit calculated from dated core sediment

Fig. 10 Modeled significant wave heights and bottom orbital velocities (color scale) for wave scenarios representing dominant (**a**, **b**) and extreme (**c**) wave conditions. The orbital velocities are plotted on top of the bathymetry (isolines). *White arrows* Dominant wave directions

Fig. 11 Genetic model proposed for the SSW: *yellow arrows* transport of sediment from the continent and through the SSC; *light blue arrows* northeastward- and southwestward-directed nearshore wind-driven current flow; *dark blue arrows* westward-directed extreme waves and southwestward-directed dominant wave flow

Fig. 12 Evolutionary model proposed for the SSW, based on the datings of the upper part of the sediment wedge, and the correlation of the observed stratigraphy with a global sea-level curve (Lambeck et al. 2014) and regional sea-level data (*black symbols* and associated error bars: Vicalvi et al. 1978; de Mahiques et al. 2011; Reimer et al. 2016; regional mid- to late-Holocene sea-level curve: Angulo et al. 2006). Each specific segment of the sea-level curve has been highlighted in colors associated with the basal surface and the seismic units composing the SSW. For more information, see main text

Table 1 Sediment analysis result of NAP61 sediment core

BETA number	Core/depth (cm)	d13C (‰)	Conventional age BP	Median probability (2σ calibration) (yr BP)	Percent modern carbon	Fraction modern	Δ14C (‰)
368256	NAP61-1/004-006	–1.5	1,220±30	785 (452–1,190)	85.9±0.3	0.8591±0.0032	–140.9±3.2
368257	NAP61-1/054-056	–1.1	1,460±30	1,010 (628–1,395)	83.4±0.3	0.8338±0.0031	–166.2±3.1
368258	NAP61-1/104-106	0.0	1,590±30	1,130 (715–1,540)	82.0±0.3	0.8204±0.0031	–179.6±3.1
368259	NAP61-1/154-156	–0.3	1,960±30	1,530 (1,090–1,980)	78.3±0.3	0.7835±0.0029	–216.5±2.9
368260	NAP61-1/200-202	+0.2	2,160±30	1,750 (1,300–2,215)	76.4±0.3	0.7642±0.0029	–235.8±2.9
368252	NAP61-1/202-204	–1.4	2,230±30	1,830 (1,370–2,305)	75.8±0.3	0.7576±0.0028	–242.4±2.8
368253	NAP61-1/252-254	–2.0	2,330±30	1,950 (1,460–2,450)	74.8±0.3	0.7482±0.0028	–251.8±2.8
368254	NAP61-1/302-304	+1.3	2,430±30	2,070 (1,585–2,610)	73.9±0.3	0.7390±0.0028	–261.0±2.8
368255	NAP61-1/352-354	–1.2	2,640±30	2,330 (1,830–2,785)	72.0±0.3	0.7199±0.0027	–280.1±2.7