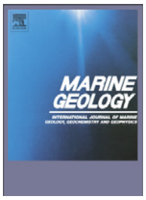
Marine Geology 323–325 (2012) 56–68

Contents lists available at SciVerse ScienceDirect

Marine Geology

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



Facies associations and controls on the evolution from a coastal bay to a lagoon system, Santa Catarina Coast, Brazil

Milene Fornari [a,*], Paulo César Fonseca Giannini [b], Daniel Rodrigues Nascimento Junior [a]

[a] *Universidade de São Paulo, Instituto de Geociências, Programa de Pós-Graduação em Geologia Sedimentar e Ambiental, Rua do Lago 562, São Paulo, SP 05508-080, Brazil*
[b] *Universidade de São Paulo, Instituto de Geociências, Departamento de Geologia Sedimentar e Ambiental, Rua do Lago 562, São Paulo, SP 05508-080, Brazil*

ARTICLE INFO

Article history:
Received 1 December 2011
Received in revised form 17 July 2012
Accepted 18 July 2012
Available online 2 August 2012

Communicated by J.T. Wells

Keywords:
coastal bay
lagoon
marine transgressive sandsheet
stratigraphic analysis
sedimentary dynamics

ABSTRACT

The diverse Holocene morphological features along the south coast of the state of Santa Catarina include lagoons and residual lakes, a barrier, a delta (constructed by the Tubarão River), and pre-existing incised valleys that have flooded and filled. This scenario contains the sedimentary record of the transition from a bay to a lagoon system, which occurred during the rise and subsequent semi-stabilisation of the relative sea-level during the Holocene. The geomorphological evolution of this area was investigated using a combination of morphology, stratigraphic analysis of rotary push cores, vibracores and trenches with radiocarbon dating, taxonomic determination and taphonomic characterisation of Holocene fossil molluscs. Palaeogeographic maps were constructed to illustrate how the bay evolved over the last 8000 years. The relative sea-level rise and local sedimentary processes were the prime forcing factors determining the depositional history and palaeogeographic changes. The Holocene sedimentary succession began between 8000 and 5700 cal BP with the deposits of transgressive sandsheets. These deposits correspond to the initial marine flooding surface that was formed while the relative sea-level rose at a higher rate than the input of sediments, prior to the formation of the coastal barrier. The change from a bay to a lagoon system occurred around 5700 and 2500 cal BP during the mid-Holocene highstand with the formation of the barrier and with the achievement of a balance between sea-level rise and sedimentary supply. Until 2500 cal BP, the presence of this barrier, the following gentle decline in sea level and the initial emergence of back-barrier features restricted the hydro-dynamic circulation inside the bay and favoured an increase in the Tubarão River delta progradation rate. The final stage, during the last 2500 years, was marked by the increasing back-barrier width, with the establishment of salt marshes, the arrival of the delta in the back-barrier, and the advance of aeolian dunes along the outer lagoon margins. This study shed light on the mechanisms of coastal bay evolution in a setting existed prior to the beginning of barrier–lagoon sedimentation.

1. Introduction

Bays and lagoons are transitional depositional systems with restricted fetch, developed under the influence of local wind-driven waves, sea waves, intensely refracted swells, and tidal variations (Dalrymple et al., 1992; Cooper, 1994; Kjerfve, 1994; Nordstrom et al., 1996; Jackson et al., 2002; Goodfellow and Stephenson, 2005; Carrasco et al., 2008; Troiani et al., 2011). Bays and lagoons are complex and dynamic systems that are sensitive not only to sea level fluctuations but also to sediment supply and morphological changes in the dimensions of the basin (width, length, and depth), which result in local scale variations in the fetch (speed, duration, and direction) and in the wave regime (height, period, and length). More open bays favour multiple fetch directions and directly influence sea waves and swells (Goodfellow and Stephenson, 2005). The bays long-period waves are refracted in the interior of the bay, where their crests are subparallel to the margins and have the capacity to rework bottom sediments. In contrast, in lagoons the most important depositional processes are related to the combined effects of storm surges and local wind-driven waves under limited fetch conditions. These local waves are characterised by less refraction, with the bottom ensuring that the wave base level is shallower (decimetres deep), and by a high margin erosion capacity resulting from the waves' short period (Nordstrom et al., 1996; Jackson et al., 2002). While the back-barrier is spatially restricted to the periphery of the lagoonal system in water depths generally <1 m, surrounded by salt marsh and hence it is prone to reworking due to internal wind-generated wave action and weak wind-generated currents. Simultaneously, the input of sediments in the back-barrier may be dominated by other processes, such as the migration of aeolian dunes and the influence of flood tide currents through inlet channels. In this way, inlets control the inland sediment migration and broaden of the coastal barrier through the formation of flood-tide deltas (Leatherman, 1979).

In most sedimentary models of coastal lagoon evolution, a strong emphasis has been placed on the formation and development of the

---

[*] Corresponding author. Tel.: +55 11 3091 4128; fax: +55 11 3091 4129.
E-mail addresses: milenefornari@yahoo.com.br (M. Fornari), pcgianni@usp.br (P.C.F. Giannini), danielpegmatito@yahoo.com.br (D.R. Nascimento).

0025-3227/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.margeo.2012.07.010

transgressive barrier (Galloway and Hobday, 1983; Leatherman, 1983; Evans et al., 1985; Oertel, 1985; Boyd et al., 1992; Dalrymple et al., 1992; Cooper, 1994; Morton, 1994; Roy et al., 1994; Timmons et al., 2010). In these models, which have also been applied to studies on the evolution of the lagoon systems on the southern Brazilian coast (Dillenburg, 1996; Lessa et al., 1998, 2000; Dillenburg et al., 2004; Souza, 2005; Travessas et al., 2005; Angulo et al., 2009; Dillenburg et al., 2009; Hesp et al., 2009), the transgressive facies are spatially restricted to the barrier itself and mark the onshore migration of coastal sediments over the lagoon deposits. In summary, most models suggest that modern lagoons formed during the Holocene transgression when the sediments stored in the shoreface migrated inland with sea-level rise, forming a transgressive barrier that isolated the lagoon from the dynamics of the open sea, although there is scarce information about when, where and by which process the barrier was formed. In this case, the initial hypothesis assumes that the occurrence of lagoon deposits requires the development of a transgressive barrier, even if the transgressive sedimentary barrier facies were not preserved (Timmons et al., 2010).

The present study, conducted on the southern coast of Santa Catarina, indicates that the modern lagoon system formed in response to the evolution of a palaeo-bay, as inferred by the identification of basal facies of a marine transgressive sandsheet that was deposited during the initial stage of formation of this bay. Thus, the lagoon system is not necessarily only the product of transgressive barrier migration during the rise in sea-level, as described by previous conceptual models of transgressive barrier–lagoon systems. Similar transgressive deposits formed during the transgressive maximum have been described in more recent models, such as those of the palaeogeographic evolution of barriers dominated by waves on the southeastern Australian coast (Sloss et al., 2006, 2010; Switzer et al., 2010). Moreover, the lagoon system between the cities of Jaguaruna and Laguna is located between rocky headlands and is partially filled by the Tubarão River delta system (Fig. 1). These conditions have produced a set of morphological features that are significantly different from those of other lagoon systems on the southern Brazilian coast.

There are differences in sedimentary processes and forms between bays, lagoons and back-barriers; in the areas where Holocene bays evolved to lagoons, it is hoped that this evolution may be inferred from the sedimentary facies succession record. Thus, this paper aims to study the facies associations, the facies distribution, chronology, and Holocene sedimentary succession of the transition from a bay to a lagoon and to detail the mechanism by which this transition may have occurred in the region between Jaguaruna and Laguna (Fig. 1). Subsequently, the effects of local factors affecting the infill of the palaeo-bay and the spatial and temporal changes of the sedimentary environments are discussed.

1.1. Regional setting

The lagoon system between Jaguaruna and Laguna cities on the southern coast of Santa Catarina is presently made up of three shallow (<2 m deep) bodies of water (Fig. 1): the Garopaba do Sul lagoon in the southwest, with a superficial area of 14 km^2; the Camacho

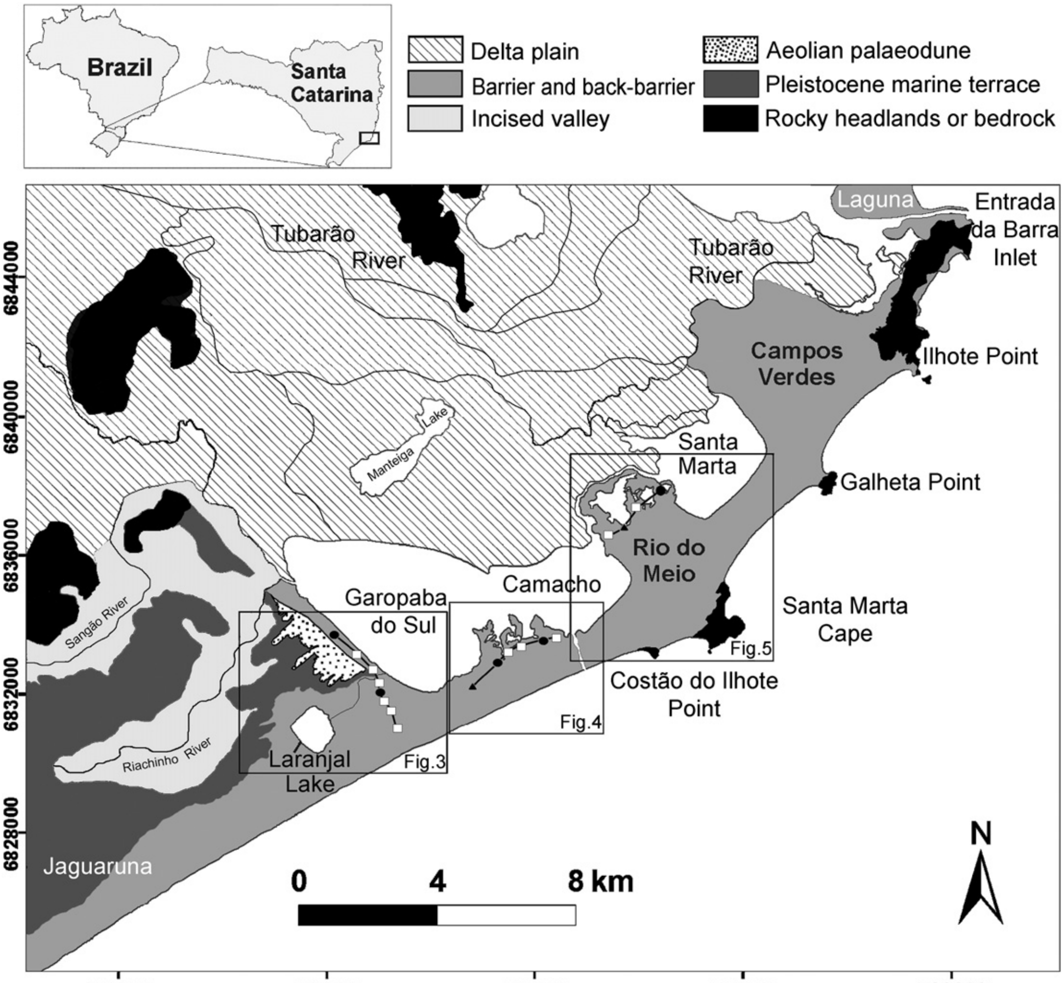


Fig. 1. Study area map along the Jaguaruna and Laguna coast showing the locations of data and subsequent figures.

lagoon in the central portion of the system, with an area of 10 km^2 and that is associated with the active Camacho inlet and its flood-tide delta; and the Santa Marta lagoon in the northeast, with an area of approximately 6 km^2. The three lagoonal basins are interconnected and NE–SW oriented with the same alignment of the local prevailing winds. Garopaba do Sul and Camacho lagoons are separated from the open sea by a narrow sand barrier (2 km wide) and are connected to the marine system through the Camacho inlet. Southeast of the Garopaba do Sul lagoon lies the Laranjal Lake, which is less than 1.5 m deep. The Santa Marta lagoon is connected to the Garopaba do Sul and Camacho lagoons through an inter-lagoon channel (Rio do Meio), and it is located at the rear of the rocky promontories Costão do Ilhote Point, Santa Marta Cape and Galheta Point. The modern lagoon system is bounded on the west by the delta plain of the Tubarão River, whose tributaries advance along the major part of the inner lagoon margin (Nascimento, 2011); on the southeast it is bounded by a system of Pleistocene incised valleys filled by lagoonal Holocene deposits (Amaral et al., 2011); and on the northeast it is limited by the Campos Verdes strandplain (Tanaka et al., 2009) and the Entrada da Barra inlet (Fig. 1). Presently, the circulation and sedimentation pattern of these lagoons is controlled by local wind-driven waves with fetch restricted by the presence of back-barrier prominent features with emergent salt marshes. Other factors controlling the water circulation in the lagoons are river inflow and storm surges, including the influence of swell waves reaching the Camacho inlet throat channel.

The microtidal regime is predominant on the Santa Catarina coast, with a tidal range of approximately 0.6 m and with diurnal irregularities (Klein et al., 1998; Giannini, 2002). However, the tide elevation and the wave height inside the lagoon bodies may vary as an effect of storm surges, which are larger during extratropical cyclones and/or the passage of strong cold fronts, especially when coincident with spring tide periods (Klein et al., 2010). According to Siegle and Asp (2007), the swell waves from southern and eastern quadrants, although less frequent, have high energy and a long period and control the alongshore transport of sediments to the northeast. The waves from the northeast (low energy and short period) are more frequent, but they are less important in the alongshore sedimentary transport. The most frequent wave period is 8 s for easterly waves, 12 s for southerly waves and their significant heights are 1.15 and 2 m, respectively (Araújo et al., 2003). In general, the longshore littoral drift is from S–SW to the N–NE, as indicated by geomorphologic features, sediment grainsize and mineralogical variations (Giannini, 2002; Martinho et al., 2006).

1.2. Holocene relative sea-level for the Santa Catarina coast

Angulo et al. (2006) critically reviewed all sea-level information along the Brazilian coast. Angulo et al. (1999) and Angulo et al. (2006) obtained Holocene relative sea-level variation data for the Santa Catarina coast in the Laguna region, using ^{14}C dating of vermetid, a highly accurate relative sea-level indicator (Fig. 2). This dataset shows that the maximum relative sea-level of the post-glacial marine transgression (PMT) was about 2.1 ± 1 m higher than the present at 5916–5587 cal BP, without a distinct peak (Angulo et al., 2006). After this maximum the relative sea-level has been smoothly falling to the present level without significant oscillations over the last 5500 cal BP (Angulo et al., 1999, 2006). This behaviour agrees with the tendency of other relative sea-level around the Southern Hemisphere (e.g. Isla, 1989; Angulo et al., 2006).

2. Methods

2.1. Field samples

To characterise the distribution of sedimentary facies, the sampling was performed at 45 points. In view of the large number of samples, the three cross-sections that best represent the Holocene sedimentary successions of the palaeo-bay were selected for presentation (Fig. 1). For the facies correlation were taken two rotary push cores measuring as much as15 m in length, six vibracores measuring as much as 3 m in length and 10 trenches (100 × 100 × 100 cm) excavated directly in the morphological features of the back-barrier (aeolian dunes, flood-tide delta, lagoon margin, beach ridges, and tombolo). In the laboratory, the rotary push cores and vibracores were opened, photographed, and described with an emphasis on the changes in the sedimentary facies. Subsamples were taken from the identified sedimentary facies to be analysed for grainsize, macrofossils, and chronological (dating ^{14}C) analysis. The topographic profile was surveyed along each cross-section using a Total Station. These data were used to correct for local elevation effects.

2.2. Facies analysis

The description of sedimentary facies in rotary push cores, vibracores and trenches included a set of descriptive attributes such as texture (grainsize variations), colour, fossil content (presence of shells and/or plant remains), sedimentary structures (syndepositional and penecontemporaneous), contact type (sharp or gradual), and layer geometry (lenticular, tabular, or wedge shaped). Genetically related sets of facies, deposited in a similar sedimentary macroform, were defined as facies associations. A grainsize analysis (pipetting and sieving at 0.5 phi intervals) was conducted on the terrigenous fractions of samples collected in each sedimentary facies; the fractions pre-treated with H_2O_2 and HCl to remove organic matter and carbonates, respectively. The statistic parameters of the grainsize distribution (mean diameter, standard deviation and skewness) were calculated using the Pearson's moments method

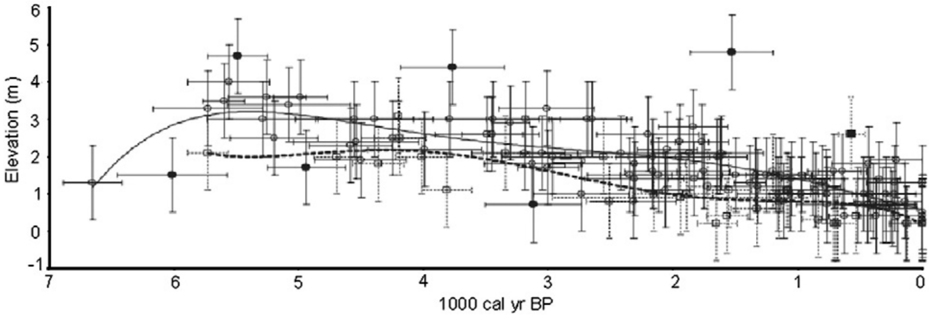


Fig. 2. Relative sea-level indicators from present to Mid Holocene. A 5th-order polynomial was fit to show an average palaeo-sea level trend. Data from the southern State of Santa Catarina are identified by empty squares and dashed lines, whereas the remaining data (empty circles and solid lines) represent data from other sectors of the eastern Brazilian coast. Outliers are shown with full circles and squares. Data are from Angulo et al. (2006).

for each sample. The value of each statistic was nominally classified according to Folk and Ward (1957).

2.3. Macrofossils sampling and analyses

Macrofossils (faunal elements > 2 mm) were studied in two stages to help interpret the facies. In the first stage, corresponding to a descriptive preliminary evaluation, a shell deposit was characterised according to the relative position of the shells (chaotic, oblique, or parallel to stratification). The presence of articulated and disarticulated bivalve shells and the degree of packing (loose vs. packed) were noted. In the second stage, a 50–100 g sample (average of 200 shells) from each sample of the same facies (fine to medium sand with shells) was wet-sieved using a 2 mm mesh screen to retain the bioclastic fraction for macrofossil identification. The whole, articulated, or disarticulated shells were manually separated from the fragmented shells. The taxonomic classification of macrofossils was performed as described in previous works on the Brazilian Southern Region (Rios, 1994; Boehs et al., 2004), especially with regard to the studies of Pitoni (1993) and Mendes (1993) concerning the Holocene fauna found in the lagoon and shallow marine systems of the Santa Catarina southern coast. The relative abundance of species in each facies associations was determined and classified as rare (0 to 10%), common (10 to 50%), or abundant (>50%) (Table 1). The taphonomic attribute of "fragmentation" refers to bioclasts with less than 90% of their original size preserved. This parameter can aid in interpreting the hydrodynamic conditions of deposition. The absence of fragmentation is suggestive of a calm hydrodynamic context without the direct action of waves and currents, whereas the presence of fragmented shells with altered external features suggests sedimentary transport by these agents (Kidwell, 1991).

2.4. Dating

Radiocarbon dating of 24 mollusc shells was used to determine the chronology of the sedimentary evolution of the palaeo-bay system (Table 2). All dated shells derive from the bivalve mollusc species *Anomalocardia brasiliana*. The collection of samples for dating was guided by facies, stratigraphic position, and the degree of preservation of the shell (whole, articulated, closed shells in the live position were preferred). The nine samples dated by the conventional ^{14}C method (abbreviated CEN) were analysed in the ^{14}C Laboratory of the Centre of Nuclear Energy in the Agriculture (Piracicaba, State of São Paulo, Brazil). In the 14 samples of rotary push cores and vibrocores, the ^{14}C dating using AMS was preferred, given the small sample mass, and was executed by Beta Analytic Inc. (Miami, Florida, United States). All radiocarbon dating was calibrated using the CALIB REV 6.0 programme (Stuiver and Reimer, 1993). The dating estimates are shown in Table 2, with probability distributions being considered in confidence intervals of 95.4% (2σ) and are expressed as calibrated calendar ages (cal BP). The calibration includes the correction of a regional reservoir effect ($<R$) of 8 ± 17 years, as determined by Angulo et al. (2005) for south and southeast Brazil.

2.5. Geomorphological evolution

The geomorphological evolution, in the region between Jaguaruna and Laguna during the Holocene is based on detailed geomorphological maps and on the spatial and temporal changes of facies described in three cross-sections. The depositional systems were defined based on facies associations, which were identified using sedimentological data, combined with macrofossils indicators, such as shells (Table 1) and preserved plant material or root casts. The time intervals were established according to the set of radiocarbon dates (Table 2).

3. Results

3.1. Late Quaternary framework

Previous mapping based on aerial photographs and satellite images (Klein et al., 1998; Giannini, 2002; Martinho et al., 2006; Giannini et al.,

Table 1
Relative abundance of macrofossils elements preserved in Holocene facies associations of Jaguaruna–Laguna palaeo-bay.

Species	Dominant habitat	Garopaba do Sul Transgressive sandsheet	Garopaba do Sul Lagoon	Camacho Transgressive sandsheet	Camacho Inlet channel	Camacho Flood tidal delta	Rio do Meio Transgressive sandsheet	Rio do Meio Lagoon
Anomalocardia brasiliana	Intertidal sand in sheltered beaches, lagoons and estuaries	R^F	A^{*WA}	R^F	A^{*WA}	A^{*WD}	R^F	A^{*WD}
Balanus sp.	Attached to rocks or shells in the upper half of the open ocean	–	–	R^W	–	–	–	–
Bulla striata	Sand-flats in inlet channels and shallow marine nearshore	–	–	R^W	C^W	R^W	C^F	R^F
Cerithium eburneum	Sandy substrates in the littoral zone of beaches	R^F	–	–	–	–	–	–
Codakia orbicularis	Shallow marine nearshore	C^{WD}	R^W	C^{WD}	R^F	–	–	–
Crassostrea sp.	Sand to sandy-mud substrates, intertidal in sheltered bays, estuarine, lagoon and, mangrove swamp	–	C^{WD}	–	–	–	–	C^{WD}
Diplodonta punctata	Shallow marine nearshore	R^{WD}	–	R^{WD}	R^{WD}	–	–	–
Divaricella quadrisulcata	Sandy shores in the shallow marine nearshore	R^{WD}	–	R^{WD}	R^{WD}	–	C^F	–
Encope emarginata	Stable sand substrates in the beaches and bays in the littoral zone between 5 and 20 m deep	C^F	–	C^F	C^F	–	–	–
Heleobia australis nana	Sand or sandy mud in lagoon and estuaries	–	R^W	–	–	–	–	R^W
Lytechinus variegatus	Subtidally in nearshore sandy coasts and sandy bays between 5 and 15 m water depth	–	–	C^F	–	–	–	–
Olivancillaria urceu	Sandy shores in the open ocean and shallow marine nearshore between 3 and 30 m water depth	–	–	C^W	C^W	–	–	–
Olivella sp.	Shallow marine nearshore	R^W	–	R^W	–	–	–	R^W
Tagelus plebeius	Intertidal sand in lagoons and estuaries	–	C^{WA}	–	–	–	–	C^{WD}
Tellina sp.	Sand to sandy-mud substrates in the marine nearshore and open bays	A^{*WD}	R^{WD}	A^{*WD}	C^{WD}	–	A^{*WD}	R^F
Tivela sp.	Shallow marine nearshore	R^F	–	–	–	–	R^F	–

R = Rare (0 a 10%); C = Common (10 a 50%); A = Abundant (>50%); *Dominant species; ^{F}Mainly fragments; ^{W}Mainly whole; ^{D}Mainly disarticulated; ^{A}Mainly articulated;

Table 2
Radiocarbon dating results and supporting information. Asterisk denotes an articulated bivalve.

Laboratory number	Figure	General location	Sample name	Sample depth (cm)	Conventional ^{14}C age (BP $\pm$ 1σ)	Age cal BP 2σ
CEN-1028	3	Garopaba do Sul	1	124–128	2690 ± 70	2950–2190
Beta-261855*		Garopaba do Sul	2	110–111	4140 ± 40	4355–4065
Beta-261852*		Garopaba do Sul	3	108–110	4330 ± 80	4765–4215
Beta-261853*		Garopaba do Sul	4A	100–105	4390 ± 80	4800–4330
Beta-261857*		Garopaba do Sul	4B	124–126	4740 ± 40	5170–4835
CEN-1030		Garopaba do Sul	5	126–132	4730 ± 50	5190–4825
CEN-1027		Garopaba do Sul	6A	(−) 026–035	4850 ± 40	5280–4995
Beta-261851*		Garopaba do Sul	6B	(−) 064–066	5090 ± 40	5560–5320
Beta-261849*		Garopaba do Sul	6C	(−) 136–138	6122 ± 32	6750–6320
CEN-02	4	Camacho	7	(−) 090–094	2680 ± 70	2645–2165
Beta-247991*		Camacho	8	(−) 096–098	2800 ± 70	2700–2340
CEN-1093		Camacho	9	(−) 090–094	2890 ± 70	2790–2400
CEN-1092		Camacho	10	(−) 090–094	3090 ± 80	3085–2700
Beta-247992*		Camacho	11	(−) 157–157.7	4140 ± 40	4360–4065
Beta-247993*		Camacho	12A	(−) 285–286	5350 ± 40	5840–5600
Beta-247994*		Camacho	12B	(−) 594–596	7510 ± 40	8070–7855
Beta-247995*		Camacho	12C	(−) 685–686	7640 ± 50	8185–7990
CEN-1031	5	Rio do Meio	13	(−) 016–020	2550 ± 70	2250–1850
CEN-1033		Rio do Meio	14	(−) 030–035	2400 ± 70	2355–2000
Beta-247991*		Rio do Meio	15A	(−) 040–042	2790 ± 40	2670–2400
CEN-1032		Rio do Meio	15B	(−) 067–071	2730 ± 70	2680–2300
Beta-247987*		Rio do Meio	16A	(−) 140–141	3130 ± 40	3035–2775
Beta-247990*		Rio do Meio	16B	(−) 193–194.5	4370 ± 40	4650–4380
Beta-247992*		Rio do Meio	16C	(−) 283–285	6450 ± 50	5570–5300

2007; Tanaka et al., 2009; Fornari, 2010; Amaral et al., 2011; Nascimento, 2011) suggest important morphological variations throughout the lagoon system. These changes permit the differentiation of four morphological sectors: Garopaba do Sul, Camacho, Rio do Meio and Campos Verdes.

In the southernmost sector of the study area, Garopaba do Sul (Fig. 3), the presence of a Pleistocene marine terrace (barrier system remnant from the last interglacial period) is highlighted and is partly covered by inactive parabolic dunes cut by the southwest margin of the Garopaba do Sul lagoon. These palaeo-dunes correspond to aeolian generation 2 as described by Giannini et al. (2007) and represent old dissected dune fields with a discernible depositional morphology that were formed prior to the maximum Holocene flood (which occurred in the region before 5700 cal BP). In this way, the Garopaba do Sul sector represents the heritance of previously incised coastal deposits that were eroded and drowned by the Holocene transgression and were partially filled since then. The central portion of the Garopaba do Sul sector is flat, has a maximum elevation of 2 m, is covered by vegetation and includes the Laranjal Lake (maximum dimensions measuring 1.5 m deep by 1 km wide) (Fig. 3).

The Camacho sector (Fig. 4) encompasses a narrow sand barrier (2 km), represented by dunefields and a deflation plain, which stretches SW–NE for 4 km and separates the Garopaba do Sul and Camacho lagoons from the open sea. This sector differs in morphology because it contains an active inlet channel (Camacho inlet) with associated flood-tide deltas, which serve as conduits for water and sediment exchange between the back-barrier, the lagoons, and the ocean (Fig. 4). Historical surveys indicate that the Camacho inlet alternates between opening and closing phases that last from years to decades (Klein et al., 1998; Giannini, 2002). The flood-tide deltas encompass 400 m wide emerged bars that are colonised by salt marsh, connect to the lagoon margin, and extend as much as 1.5 km northwest into the lagoons. This type of feature acts as a periodically flooded shallow water ramp and increases back-barrier width through the progradation of the lagoon margin landward (Leatherman, 1979; Mallinson et al., 2010).

The Rio do Meio, the central sector of the study area (Fig. 5), has as main particularity the position at rear of rocky headlands (Costão do Ilhote Point and the Santa Marta Cape). The local morphological data suggest that the Rio do Meio sector represents a tombolo. This interpretation is based on the observation that the back-barrier extends as much as 3 km to the northwest in a shallow area that is protected from ocean waves by rocky headlands and that links to the adjacent continent. The protection from the direct action of oceanic waves and associated longshore currents would have induced local sedimentation in the form of a tombolo (Zenkovich, 1967; Marriner et al., 2008). The sediments were available due to the erosion of the Pleistocene surface and sands transported by progradation of the Tubarão delta front, which in the Rio do Meio, reached a maximum advance over the lagoon. The inner (northwest) border of the tombolo controls the position of the Meio River, which is a natural channel connecting the Camacho and Santa Marta lagoons.

The morphology of Campos Verdes, the northernmost portion of the study area, is characterised by sets of beach ridge alignments that are transversally oriented to the modern shoreline and partially covered by palaeo-dunes. This strandplain is limited to the southwest by a tombolo or spit, which represents an area without beach ridges, oriented NW–SE (maximum 1 km width) and leeward of the Galheta Point rocky headlands. The beach ridges were anchored at this tombolo and initially prograded toward the northwest but later grew to the north and the northeast (Tanaka et al., 2009) in a pattern that suggests the action of a changing system of sea waves and that it may have been influenced by inlet processes.

A marsh platform preserves the outer lagoon margin from erosion by local wind-driven waves and tides, facilitating sedimentation and the consequent progradation of the back-barrier landward. To the east, the salt marsh passes to aeolian deflation plains with trailing ridges oriented from northeast to southwest, which are partially stabilised by the development of vegetation cover (Martinho et al., 2006). Active dune fields, without vegetation, are found in the most external portion of the back-barrier and near the shore. The advance of aeolian dunes on the back-barrier has been inhibited by growth of vegetation along of the dunefields outer border (precipitation and trailing ridges) and even by the presence of the lagoon and salt marshes.

3.2. Description and chronology of the facies associations

The detailed geomorphological reconstruction is based on all of the available data combined into the facies description to identify the processes responsible for the observed palaeo-bay sedimentary succession. This approach resulted in the identification of seven facies

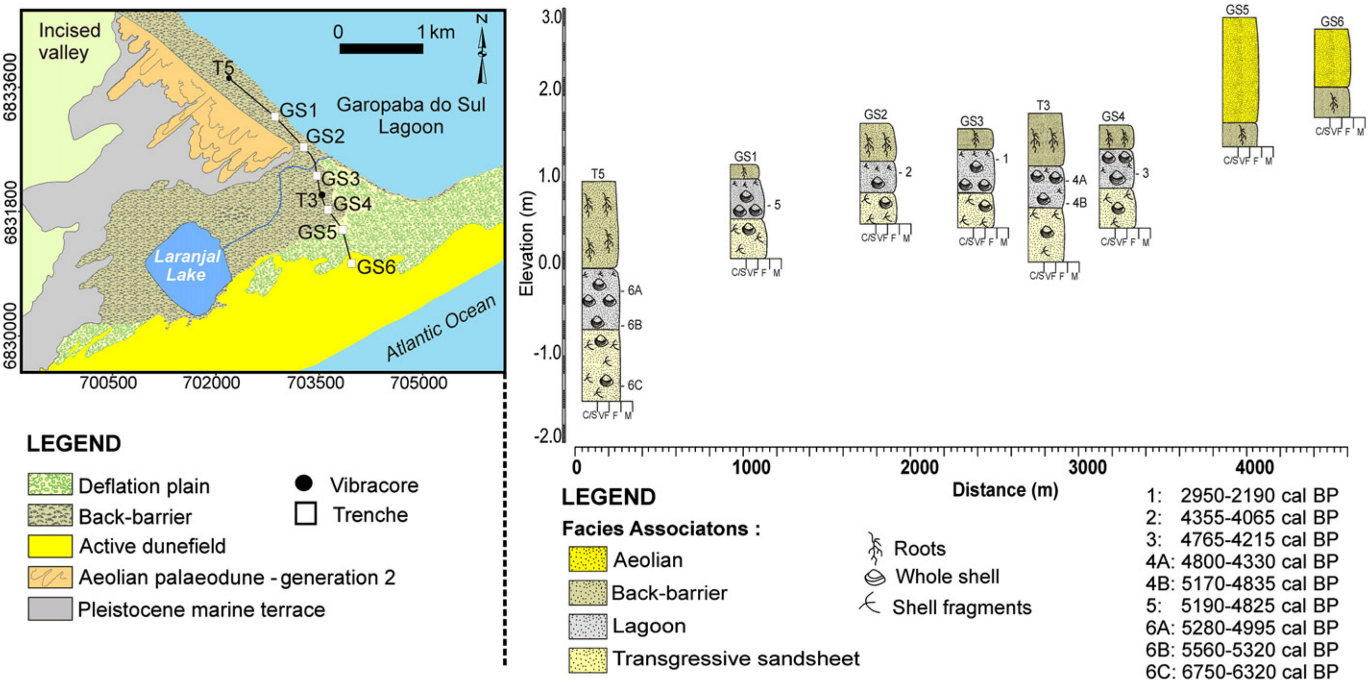


Fig. 3. Garopaba do Sul geomorphological features and cross-section. Terrigenous grainsize simbology: C/S, clay or silt; VF, very fine sand; F, fine sand; M, medium sand.

associations within the palaeo-bay with sediments and main macrofossils that are illustrated in Fig. 6 and Fig. 7, respectively. These facies associations are described from base to top, using one longitudinal cross-section (Fig. 3) and two transverse cross-sections (Figs. 4 and 5), relative to the lagoon axis.

3.2.1. Depositional succession in Garopaba do Sul drowning bay

The succession and correlation of facies in Garopaba do Sul (Fig. 3) allows for the identification of four facies associations from the base to the top: marine transgressive sandsheet, lagoon, back-barrier and aeolian dunes (Fig. 6). The transgressive sandsheet facies association consists of yellowish well-sorted fine-to-medium sand, which is strongly bioturbated and contains a variety of mollusc fossils represented by whole and fragmented shells (Table 1, Fig. 7). In this association, the shells from the bivalve *Tellina* sp. are abundant, *Codakia orbicularis* is common, and there are also rare specimens of the gastropod *Olivella* sp., *Cerithium eburneum* and bivalves *A. brasiliana*, *Diplodonta punctata*, *D. quadrisulcta* e *Tivela* sp. (Table 1, Fig. 7). Fragments from the echinoderm *Encope emarginata* are also common. All of the identified species are marine and live in sand substrates from the shallow marine nearshore to the littoral zone of beaches (Rios, 1994), both of which are subject to progressive reworking by the action of sea waves and currents (Table 1). The thickness of the

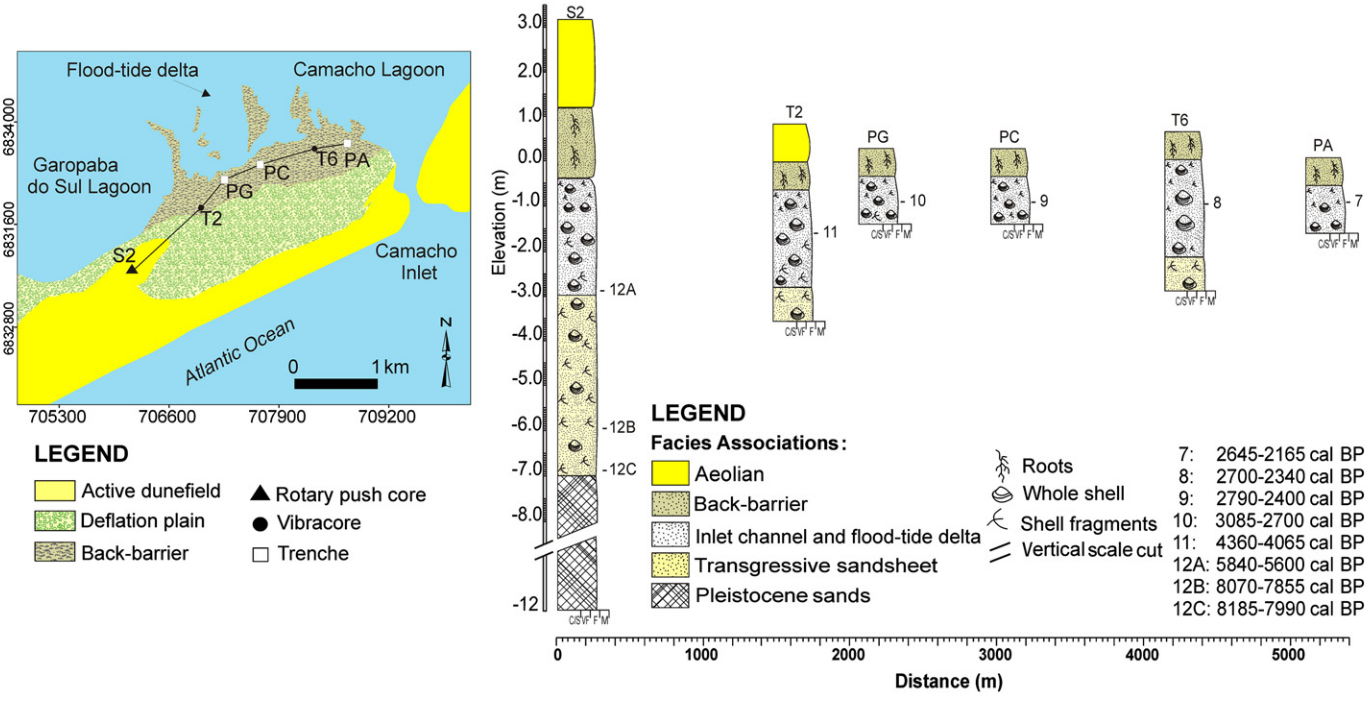


Fig. 4. Camacho geomorphological features and cross-section. Terrigenous grainsize simbology: C/S, clay or silt; VF, very fine sand; F, fine sand; M, medium sand.

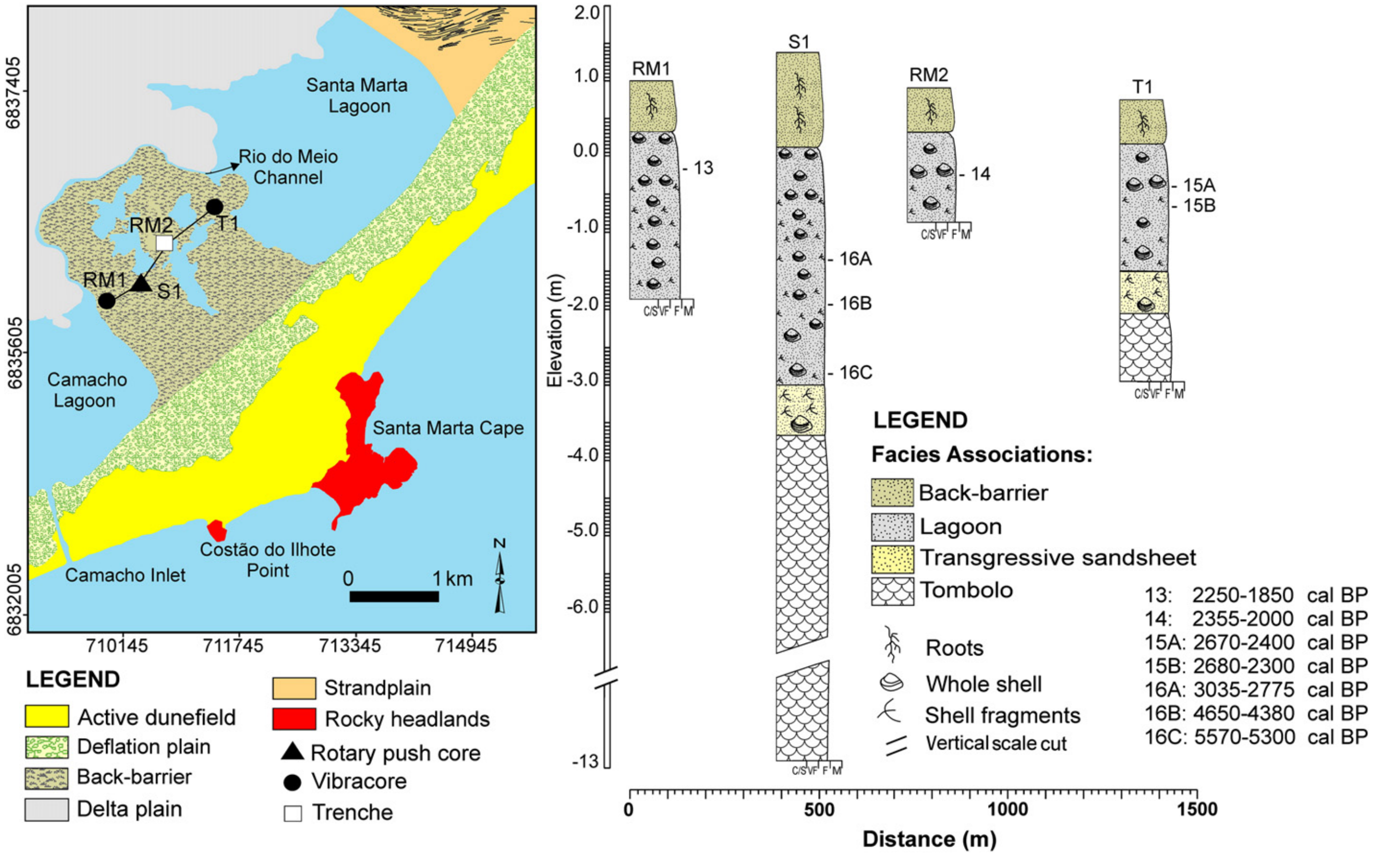


Fig. 5. Rio do Meio geomorphological features and cross-section. Terrigenous grainsize simbology: C/S, clay or silt; VF, very fine sand; F, fine sand; M, medium sand.

transgressive sandsheet deposits is variable (1.0 m at most), and the macrofossils are dominantly disarticulated (95%) and chaotically oriented, occurring in varied sizes (between 0.2 and 5 cm), and are loose or dispersed in the matrix. A reduction in the concentration of whole, disarticulated, and fragmented shells is observed toward the top of the facies association. The ^{14}C ages of *A. brasiliana* (Fig. 3) collected at the base of this facies association indicates that the corresponding sediments were deposited in the Garopaba do Sul sector since at least 6750–6320 cal BP. The ^{14}C ages from the top of the facies association indicate that marine sedimentary dynamics prevailed in this sector until approximately 5700 cal BP.

The deposits of the lagoon facies association consist of well-sorted fine-to-very fine sand and extend laterally along the present lagoon margin with a thickness of less than 1 m (Fig. 3). The macrofossils include shells of *A. brasiliana*, *Crassostrea* sp. and *Tagelus plebeius*, all predominantly whole, closed, and articulated, with some specimens in the live position. In the lagoon facies association, shells of the bivalve mollusc *A. brasiliana* became dominant (Table 1, Fig. 6C–Fig. 7D). The *A. brasiliana* shells preserved in the live position on the top of the lagoon facies association were dated to 2950–2190 ^{14}C cal BP. This dating enables us to interpret that the lagoon sedimentation occurred between 5500 and ~2500 cal BP (Fig. 3). The presence of articulated and closed shells, with specimens in the live position suggests that deposits from the base of this association correspond to the bottom of the lagoon, which is below the wave base level. In the overlying sedimentary column, where the whole disarticulated shells and fragmented shells became present, the deposition must have occurred in a shallower lagoon with shells reworked by internally generated wind-waves and currents.

The back-barrier facies association occurs with a sharp contact over the lagoon facies association, encompassing fine sand deposits, black colour, and plant remains, such as roots, leaves, and stalk fragments (total organic matter content from 10 to 15%) (Figs. 3 and 6B). This facies also displays an intensification of pedogenetic features. It does not contain whole or fragmented shells. The back-barrier was probably formed by sedimentation in the middle and upper parts of the intertidal zone with sediment transport induced by lagoon waves under conditions of crescent emergence and by growth of vegetation. The sedimentary trapping favoured by these conditions would result in the segmentation of the lagoon with the formation of an isolated lake (Laranjal). On the top of the Garopaba do Sul cross-section (Fig. 3) and in the most external part of the back-barrier, the aeolian facies association is represented by a well-sorted very fine sand that is light grey to yellowish (Fig. 6A). This deposit overlies a sharp contact in the back-barrier facies association. Remote sensing morphological aspects, field observation, and sedimentological analyses revealed its correspondence with low-lying aeolian features (parabolics, trailing ridges and gegenwalle), fixed by vegetation, which is characteristic of aeolian deflation areas.

3.2.2. Depositional succession in the Camacho palaeo-inlet channel

In the Camacho back-barrier, the sedimentary succession (Fig. 4) is formed by five facies associations. The basal facies, observed in the rotary push core (S2), were attributed to upper Pleistocene marine terraces or palaeo-dunes superimposed to them (Fig. 6G). This interpretation was based on a comparison with sedimentological data from Giannini et al. (2007). These deposits correspond to yellow-to-brown, well-to-moderately sorted fine sand, dominated by round quartz grains with signs of impregnation by ferruginous clay material and covered at a sharp contact by the transgressive sandsheet facies association. In the Camacho sector, the transgressive sandsheet facies association reaches a thickness of 4 m and is formed by well-sorted fine sands containing fragmented and whole shells. The macrofossils are similar to those described in the deposits of the Garopaba do Sul; however, in the Camacho region there is an increased abundance of marine species, which is

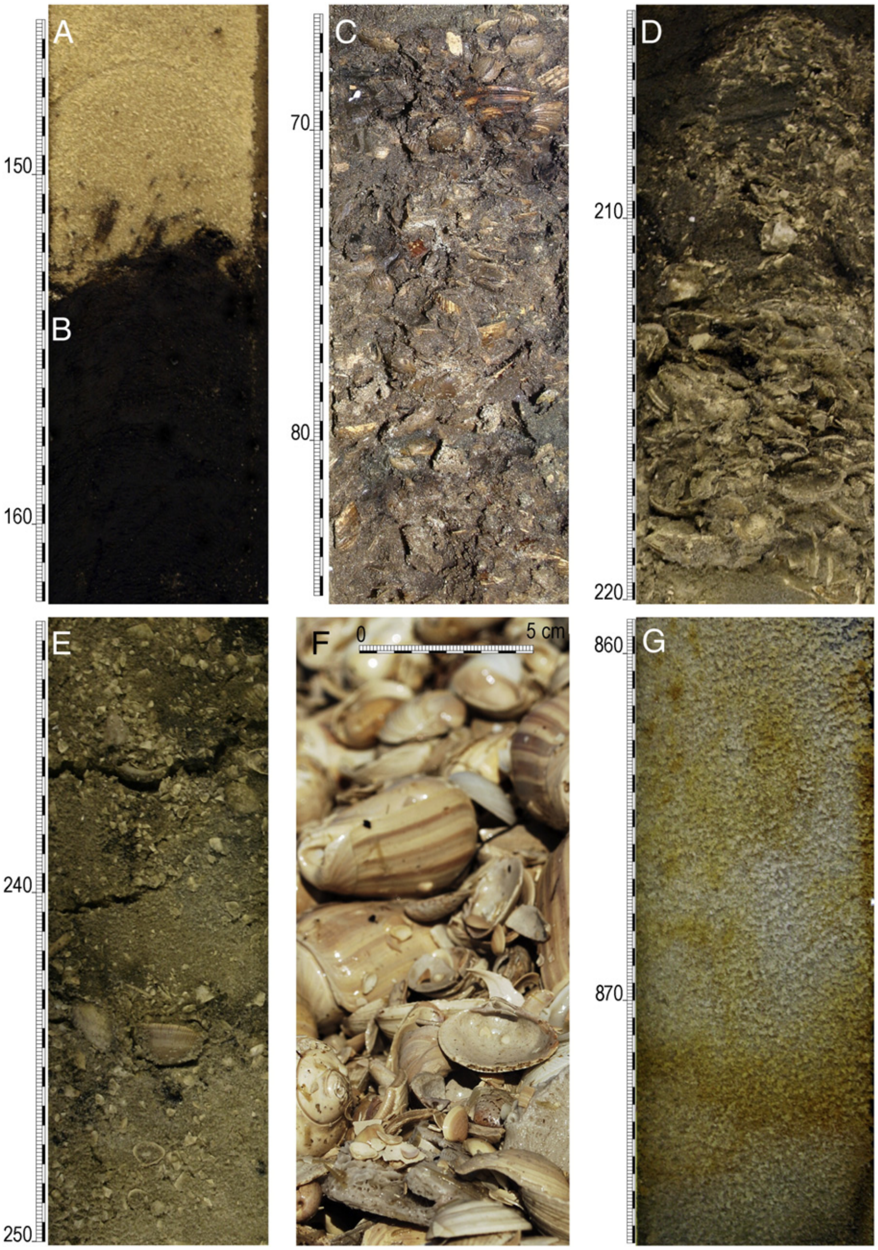


Fig. 6. Photographs of typical sediments for Holocene facies associations and Pleistocene substrate in the Jaguaruna–Laguna palaeo-bay. The ruler scale is given in centimetres. A = aeolian dune, B = back-barrier, C = lagoon, D = tidal inlet channel, E = marine transgressive sandsheet, F = mix of marine fauna within marine transgressive sandsheet, and G = Pleistocene deposits.

dominated by species, such as *Tellina* sp., with a broad distribution in the open ocean, especially shallow marine nearshore sandy coasts and opens bays (Table 1, Fig. 7B). Also preserved in the transgressive sandsheet are common to rare disarticulated, fragmented specimens of the bivalve *C. orbicularis*, *D. punctata* and *Divaricella quadrisulcata*, the gastropods *Bulla striata*, *Olivancillaria urceu* and *Olivella* sp., cirripede crustaceans such as *Balanus* sp., and echinoderms, such as *E. emarginata* end *Lytechinus variegatus* (Table 1, Fig. 6E). The ^{14}C ages of the whole and articulated *A. brasiliana* shells at the base of the transgressive sandsheet deposits in the Camacho sector indicate that the deposition of this facies association began between 8100 and 7800 cal BP (Fig. 4).

The sedimentary succession continues upward with the inlet channel facies association, which shows a maximum thickness of 2.3 m and a lateral extension of approximately 5 km. This association composed of fine sand with a dense concentration of whole and fragmented shells (Fig. 6D). The base of this association is marked by a sharp increase in shell concentration (more than 50%), whereas the terrigenous fraction shows a fining upward general trend. The shells from the base are whole, disarticulated, and fragmented, showing chaotic spatial distribution (with shells being oriented sometimes convex-up and other times convex-down). These characteristics suggest cut-and-fill processes within the inlet channel with reworking by waves and flood tide currents. Shells from *A. brasiliana* are abundant, whereas *B. striata*, *O. urceus*, *Olivella* sp., *D. punctata*, *D. quadrisulcata*, and fragments of the echinoderm *E. emarginata* are common to rare (Table 1). The obtained ^{14}C ages indicate that the inlet channel depositional processes were active since ~5700 cal BP, during the mid-Holocene maximum sea-level (Fig. 4). An increase in the packing and nesting degree of whole shells towards the top of inlet channel deposits is representative of the coverage of palaeo-inlet channel deposits by the flood-tide delta as a result of the successive abandonment and northward migration of the inlet. The passage to flood-tide delta facies is marked by a surface containing

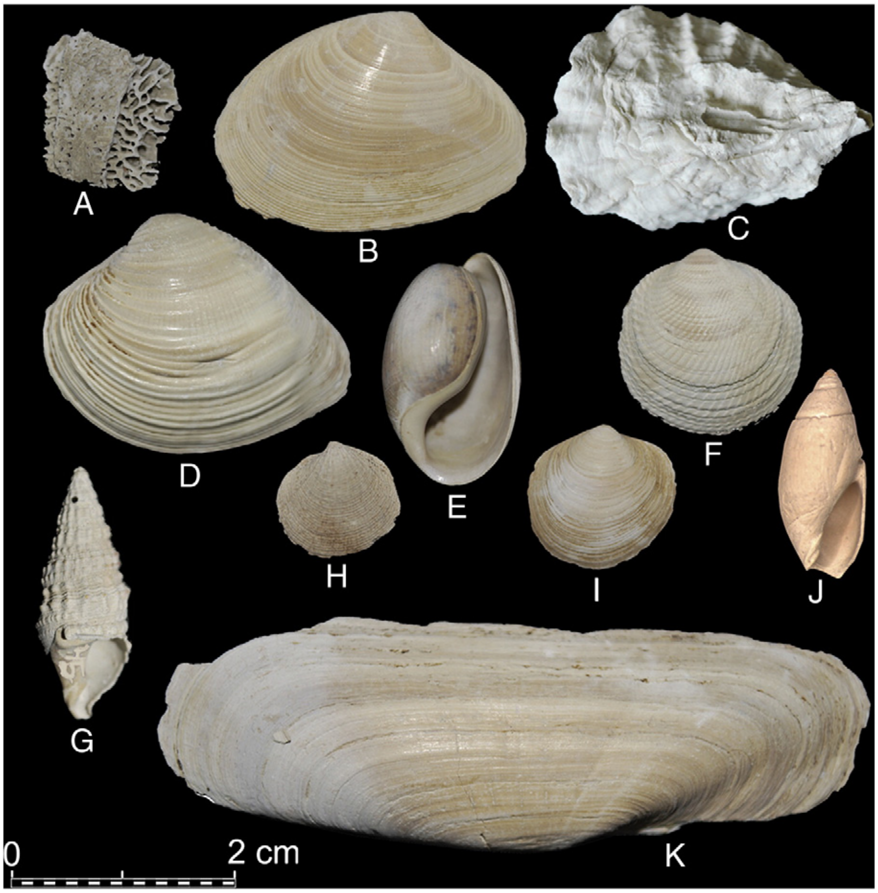


Fig. 7. Photographs depicting some of the selected macrofossils preserved in the facies associations. A = *Encope emarginata*, B = *Tellina* sp., C = *Crassostrea* sp., D = *Anomalocardia brasiliana*, E = *Bulla striata*, F = *Divaricella quadrisulcata*, G = *Cerithium eburneum*, H = *Codakia orbicularis*, I = *Diplodonta punctata*, J = *Olivella* sp., K = *Tagelus plebeius*.

disarticulated *A. brasiliana* concave upward valves, which may represent up to 95% of macrofossils, combined with rare remnants of *B. striata* (Table 1, Fig. 7E). The dominance of whole disarticulated shells with concave-up orientation suggests a reworking of the water/sediment interface by the combined actions of tidal currents and wind-driven waves. The ages of the shells in the flood-tide delta deposits, determined to be between 4360 and 2165 cal BP, become gradually younger towards the northeast (Fig. 4). This information confirms the interpretation based on morphological maps, according to which the successive re-openings of the Camacho inlet experienced lateral migration to the northeast (Klein et al., 1998; Giannini, 2002).

The flood-tidal delta facies is overlaid by a sharp contact with fine to very fine sand facies with plant material or root casts preserved, attributed to the back-barrier facies association (Fig. 4). In its most external portion, the Camacho back-barrier deposition is topped by an aeolian facies association, up to 2 m in thickness (Fig. 4). This association is composed of massive yellowish well sorted fine sand, with a grainsize distribution that has positive skewness and are sometimes associated with roots in situ (Fig. 6A). The aeolian deposits commonly occur as restricted lateral distribution, related to the displacement of aeolian dunes on silted areas of the lagoon system next to the Garopaba do Sul and Camacho lagoons.

3.2.3. Depositional succession in the Rio do Meio tombolo

The stratigraphic section in the Rio do Meio shows four facies associations (Fig. 5). The deposits at the base correspond to a tombolo facies association composed of light grey well-to-moderately sorted very fine sand. These deposits show a minimum thickness of 3 m and lateral continuity along the entire Rio do Meio back-barrier. The deposits result from the formation of a tombolo elongated toward northwest in the hydrodynamic shadow zone protected by rocky headlands from the direct action of dominant swells from the southeast. Thus, the rocky headlands, Costão do Ilhote Point and Santa Marta Cape, served as a stabilisation point for the initial accretion of the tombolo. A transgressive sandsheet facies association, measuring as much as 1.0 m in thickness, covers the tombolo deposits in a sharp contact (Fig. 5). This association is composed of fine-to-medium sand and contains a mix of whole and fragmented shells that is similar to that observed in other sectors. The shells include abundant disarticulated *Tellina* sp., as well as common fragments of *B. striata*, *D. quadrisulcata* and rare fragments of *A. brasiliana* and *Tivela* sp. (Table 1, Fig. 7). The contact between the transgressive sandsheet and the lagoon is gradual and shows an upward increase in bioturbation abundance. The lagoon facies association is formed by fine sand containing fragmented and whole shells. The whole shells represent as much as 50% of the deposit, are well-preserved, articulated and closed, with abundant specimens of the bivalve *A. brasiliana* and common specimens of *Crassostrea* sp. and *T. plebeius* (Table 1). Occasionally fragmented *Tellina* sp. and *B. striata*, two species from open ocean and shallow marine environments subject to the action of sea waves (Mendes, 1993; Pitoni, 1993; Rios, 1994) can be observed in this association facies. While *Nucula semiornata* and *Heliobia* sp. (Table 1), both of which are species reported to have a broad distribution in lagoon/estuarine systems, are found in a lower percentage (10%). In the top 15 cm of the lagoon facies association, only disarticulated *A. brasiliana* shells are found, and there is an upward increase (>50%) in the proportion of whole and packed valves. The ages of these shells indicate that the lagoon system has been present in this sector since ~5500 cal BP (Fig. 5). This finding indicates that the tombolo already existed during the Holocene marine transgression and early sea-level highstand, when diffractive wave processes set up by the island obstacle (e.g., rocky headlands) engendered the rapid proto-tombolo growth bayward. On the top, the Rio do Meio sedimentary succession is completed by the back-barrier facies association (Fig. 5) composed of clayey very fine sand deposits, up to 1 m thick, with abundant organic material and roots (total organic matter content of 10–15%), which was probably derived from a marsh similar to what exists in the area today. The sharp passage from lagoon to back-barrier facies associations reflects rapid segmentation and consequent restriction of the lagoon system, when the Santa Marta and Camacho lagoons were separated by the tombolo accretion.

3.2.4. Depositional succession in the Campos Verdes strandplain

The stratigraphic and sedimentological information combined with optically stimulated luminescence (OSL) dating published by Tanaka et al. (2009) permitted the identification of the three facies associations in the Campos Verdes plain: tombolo, beach ridges, and aeolian dunes. In the most SW portion of the plain, without beach ridges situated on the Santa Marta lagoon margin, deposits of well-sorted fine sand with dispersed disarticulated and fragmented *A. brasiliana* shell concentrations are dominant. These deposits, which exhibit an OSL age of 4912 ± 270 yr, correspond to the tombolo feature that may have played a role in pinning the beach ridges. The lateral change toward the northeast for the beach ridges facies association is represented by the appearance of massive or plain-parallel stratified fine sand, which is grey in the base transitioning to light grey and to whitish on top. The OSL ages (4000 to 2000 yr) obtained from beach ridges support the interpretation that the sets of ridges were formed after tombolo sedimentation and under intense sedimentary dynamics that may have been favoured by inlet processes. During the moments of coastline stabilisation or erosion, on the Campos Verdes plain, there was the initiation and migration toward the SW of the parabolic aeolian dunes.

4. Discussion

4.1. Geomorphological evolution

The results described in this study permit a discussion of geomorphological evolution after ~8000 cal BP from a bay system to a lagoon system. This evolution reflects the interplay of various forcing factors that contributed to the bay–lagoon development and can be differentiated into four geomorphological sectors, with each one corresponding to a major depositional feature: (1) a drowning bay (Garopaba do Sul); (2) an inlet channel, in migrating to the northeast (Camacho); (3) a tombolo (Rio do Meio); and (4) a strandplain (Campos Verdes) prograding to the north quadrants. The geomorphological evolution can be divided in to three phases (Fig. 8) that were controlled by regional variations in relative sea-level, antecedent morphology and sedimentary supply.

4.1.1. Holocene marine transgression (Phase 1 — Fig. 8A)

The stratigraphic sections through the Holocene sedimentary succession indicate that between 8000 and 5700 cal BP, during increase in sea-level rise rates, the low coastal areas were flooded, forming a bay system (Fig. 8A) that was initially filled by transgressive sandsheets (Figs. 3–5). GPR transects (~10.5 km) were collected by Fornari (2010) adjacent to the cross-section and show that the transgressive sandsheet facies lies unconformably over the homogeneous and massive radar facies; these facies were later interpreted as late Pleistocene substrates. This interpretation is also supported by the facies analysis results combined with luminescence and ^{14}C dates published by Giannini et al. (2007) and Amaral et al. (2011). The transgressive sandsheet deposit corresponds to the initial marine flooding surface and was generated as relative sea-level rose more quickly than the input of sediments, prior to the complete development of the Holocene barrier island that now separates the lagoon from the open sea. This bay was bounded on its outer part to the southwest and northeast by Pleistocene deposits and only semi-enclosed by a set of islands, represented by rocky headlands (Costão do Ilhote Point, Santa Marta Cape, Galheta Point and Ilhota Point). With this configuration, it was subject to sea waves and without influence of fresh water.

According to Nascimento (2011), the base of the Holocene sedimentary succession in the Tubarão River delta consists of very fine sand dominated by a variety of marine fauna (e.g., *B. striata*, *Tellina* sp., *O. urceu*) and formed around ~6000 cal BP. These data suggest that the bay covered the entire area of the delta plain before being constructed by the Tubarão River landward. The bay embraced the area of the present Garopaba do Sul, Camacho and Santa Marta lagoons, as well the Laranjal Lake. To the southwest, the palaeo-bay branched into the Sangão and Riachinho flooded incised valleys, where it acquired a more wave-protected character. Based on the Garopaba do Sul, Camacho and Rio do Meio cross-sections (Figs. 3–5), a bay formed with a southwest–northeast length of 30 km and was open to direct ocean influence favoured the fetch of the waves, which eroded part of the marine Pleistocene deposits and the palaeo-dunes. The influence of the ocean waves also reworked the bay bottom sediments, as suggested by preserved macrofossils in the transgressive sandsheet in which an abundance of articulated, disarticulated, and fragmented shells from marine bivalves, gastropods, crustaceans, and echinoderm species were found distributed throughout the sand matrix.

4.1.2. Holocene sea-level highstand (Phase 2 — Fig. 8B)

The change of depositional systems from a bay to a lagoon reduced both the hydrodynamic energy and the marine sedimentary supply. This change characterises the second phase of geomorphological evolution, which occurred between the PMT, prior to the maximum Holocene highstand, ~5700 cal BP and 2500 cal BP (Fig. 8B). The rate of sea-level rise did not allow enough time for the complete removal of Pleistocene deposits, and part of the sand eroded from these deposits did not leave the coastal system; in this way, and with the decreasing in the relative sea-level rise, this sand may be introduced into the longshore drift circulation, thereby providing sediment for the continued growth of the spits and tombolos linked to rocky headlands. Simultaneously with the continuous accumulation of sediments in the bay, the Holocene proto-barrier – in pinning on the Pleistocene marine terrace (to the southwest) and spit accretion from rocky headlands (to the northeast) – isolated the bay from the ocean and gradually gave rise to the lagoon water body, as indicated on the geomorphological map (Fig. 8B). In this phase, the influence of coastal marine waters and sediments became restricted to the inlet channel and adjacent areas, where a series of flood-tide deltas formed. The inlet channel deposits document a change from a transgressive open-marine environment to a lagoon as the development of a back-barrier environment occurred (Figs. 3–5).

The deposits from Phase 2 record these changes by the increased concentration of whole, articulated, closed, and in situ shells, with a reduction in the relative percentage of marine molluscs and an accentuated dominance of *A. brasiliana*. The restriction of circulation and marine water supply to the interior of the bay and the development of a lagoon system conditioned by restricted fetch led to a decrease in wave energy, thereby allowing better preservation of fossil molluscs in lagoon facies. These deposits are well represented in the Garopaba do Sul sector (Fig. 3), where the sedimentary filling was facilitated by the availability of sands from the Pleistocene marine terrace at the rear, and controlled the location of the coastal barrier initiation. This sand supply contributed to the relatively rapid emergence and fragmentation of the Garopaba do Sul lagoon and the individualisation of Lake Laranjal. During this phase, the inlet channel developed a series of

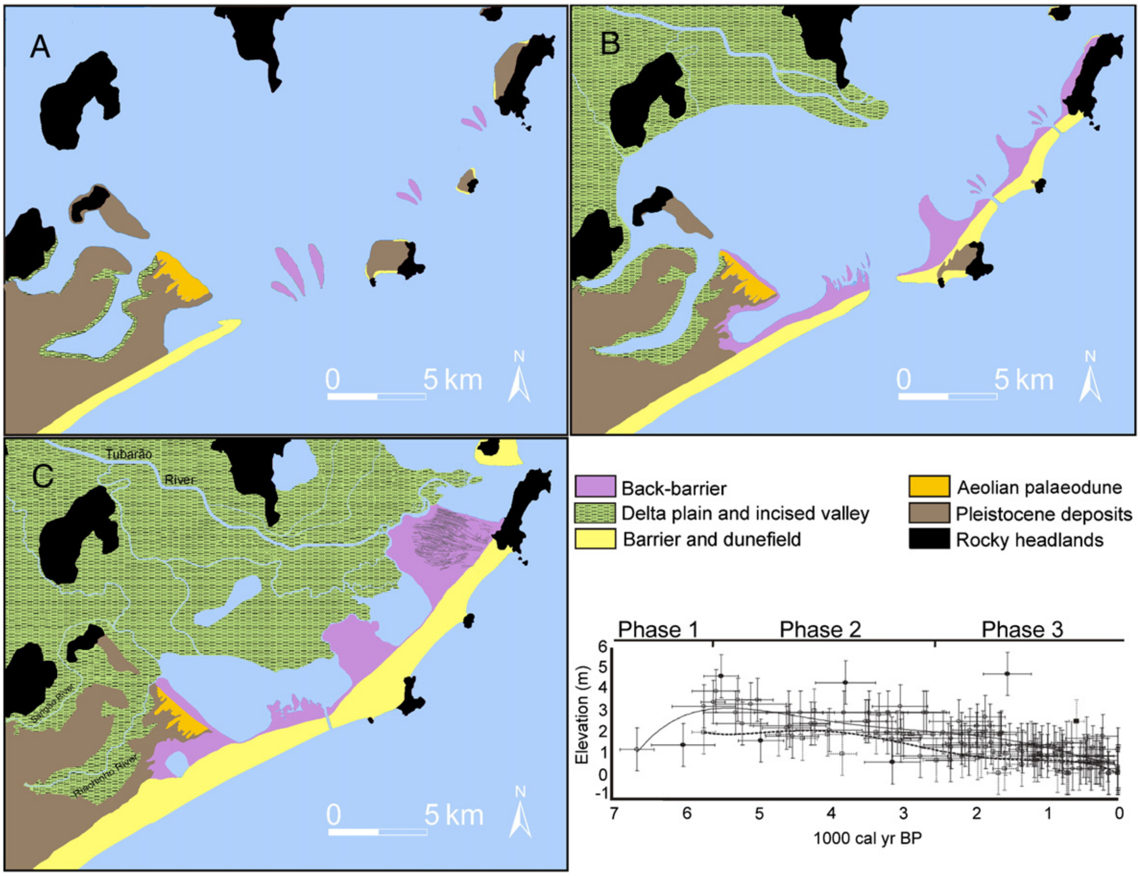


Fig. 8. The geomorphological evolution of a Holocene bay to a lagoon system reveals three phases: A) Phase 1 (8000–5700 cal BP), consisting of bay formation with the deposition of a marine transgressive sandsheet; B) Phase 2 (5700–2500 cal BP) with gradual restriction of the open ocean, when a Holocene barrier grew, until pinning in the edges of Pleistocene deposits and, promoted the development of a low-energy back-barrier lagoon, thereby favouring the initial progradation of the Tubarão River delta. C) Phase 3 (2500–Present), with further restriction of marine influence associated with the widening of Holocene barrier and shoaling of the inlet channel, resulting in the extension of the back-barrier facies and the maximum advance of a fluvial delta.

flood-tide deltas (Figs. 4 and 8B), with each one being successively incorporated to the back-barrier as the channel was periodically closed and re-opened further northeast under the influence of regional net longshore drift. Increasingly younger fossil mollusc ages to the northeast in Camacho inlet channel and flood-tide delta facies (Fig. 4) confirm this channel migration, which eroded the underlying deposits and may have destroyed part of the Holocene sedimentary succession in this sector. The overlying migrating inlet channel facies by the flood-tide delta facies characterises the transition from the dominance of waves and confined tidal currents in the throat of the inlet channel to the dominance of wind-driven waves in back-barrier areas next to the attached flood-tide delta. The age of the flood-tide delta facies, 5700 to 2000 cal BP (Fig. 4), indicates that the inlet channel continued to supply sediments to the back-barrier after the Holocene marine transgression. The addition of flood-tide delta sediments provided a greater volume of sediments and contributed to the restriction of marine sedimentary dynamics inside the lagoon. These processes occurred concomitantly with the emergence of a shallow proto-tombolo or sand spit in the Rio do Meio and Campos Verdes, thereby initiating the segmentation of the lagoon system and the formation of the strandplain in the northeast portion of the system (Fig. 8B). In addition to the successive filling and migration of the inlet and the emergence of prominent submerged features, the silting of the palaeo-bay was intensified by the progradation of the Tubarão River delta system along the west flank of the lagoon (Fig. 8B). The restriction of marine circulation contributed to this progradation through the formation of elongate deltaic lobes in the most nested areas of the lagoon, such as near Rio do Meio. A radiocarbon age of ~4500 cal BP obtained from the deltaic facies by Nascimento (2011) confirms that the progradation of the Tubarão River delta occurred concomitantly with the formation of the lagoon system, after ~5700 cal BP. In addition, the landward environmental changes in the bay–lagoon were dominated by Tubarão River sediment delivery, because relative sea-level began to fall during the Holocene.

4.1.3. Holocene back-barrier (Phase 3 — Fig. 8C)

The last phase of geomorphological evolution developed under a progressive decline of the relative sea-level since the mid-Holocene highstand (Fig. 8C). This phase is represented by the continuation of back-barrier accretion mechanisms, such as lateral filling and northward migration of the throat channel until its present position, and by the advance of the active aeolian dunefields on the outer lagoon margin. The sand from flood-tide deltas is incorporated into the lagoon margins after the inlet closes and the back-barrier wider and extending into the shallowing lagoon, which is a mechanism also discussed by Leatherman (1979) and Mallinson et al. (2010).

During this phase, the maximum widening of the Holocene barrier occurred due to the blockade of longshore drift by the rocky promontories and the sedimentary reworking by wind-driven waves and currents along the outer lagoon margins. The stabilisation of the barrier and back-barrier complex was marked by the installation of salt marsh, the restriction of the marine influence inside the lagoons and the reduction of sedimentary input as the deltaic front of the Tubarão River began to migrate to the northeast (Nascimento, 2011).

4.2. Mechanisms for the geomorphological and sedimentological transition from bay to lagoon

The Holocene sedimentary record of morphology changes, facies association, and chronology of the sedimentary fill of the palaeo-bay, which is currently occupied by lagoons (Garopaba do Sul, Camacho and Santa Marta) and a lake (Laranjal), add important details to the conceptual model of coastal geomorphological evolution, especially of lagoon systems. In particular, our data suggest that the transgressive sedimentary filling began with the formation of a bay that was subject to direct oceanic influences, rather than (and/or before) the configuration of a transgressive barrier, as proposed by many models in the literature (Galloway and Hobday, 1983; Leatherman, 1983; Evans et al., 1985; Oertel, 1985; Boyd et al., 1992; Dalrymple et al., 1992; Cooper, 1994; Morton, 1994; Roy et al., 1994) including that of the Holocene evolution of other barriers and lagoons in Southern Brazil (Lessa et al., 2000; Dillenburg et al., 2004; Souza, 2005; Travessas et al., 2005; Dillenburg et al., 2009; Hesp et al., 2009). Holocene relative sea-level rise and inherited morphology were the prime forcing factors determining the formation of a bay that was directly connected to the ocean before initiation of barrier–lagoon sedimentation around ~5700 cal BP. A mid-Holocene highstand 2.1 m above the current sea level lasted from 5916 to5587 cal BP and, rapidly drowned the low coastal areas, creating a transgressive system until ~5700 cal BP (Fig. 8). The complete drowning created a wide bay (~30 km) semi-closed by a set of islands, represented by rocky headlands (Costão do Ilhote Point, Santa Marta Cape, Galheta Point and Ilhota Point) associated with Pleistocene deposits and without the influence of a freshwater environment. The bay was directly linked with marine-sourced sediments that resulted in the deposition of a marine transgressive sandsheet with a maximum thickness of ~4 m. (Figs. 3–5). In contrast to other cases of Holocene sedimentary succession of the Southern Brazil (Lessa et al., 2000; Souza, 2005; Travessas et al., 2005; Dillenburg et al., 2009), the sedimentary succession of lagoon deposits beneath transgressive barrier (e.g., shoreface sands or shelf sands and muds) were not found directly overlying the Pleistocene deposits. In the study area, the marine transgressive sandsheet reflects the point when the rate of accommodation space creation decreased but had not yet balanced the sediment supply. This interpretation is mainly based on radiocarbon ages of more than ~5700 cal BP (Fig. 8) and suggests the deposition of a transgressive facies prior to the formation of the coastal barrier. During this initial transgressive phase, which occurred before the Holocene period of relative sea-level stabilisation, the sedimentary input was not sufficient to fill the accommodation space, and the geomorphology was represented by a bay depositional system.

With the configuration of a barrier soon thereafter the maximum relative sea-level (around 5700 cal BP), the bay system changed to a lagoon system (Fig. 8B), subsequently submitted to sea-level fall and increase of sediment supply; succumbed to the aggradational back-barrier setting. This phase was controlled by the sedimentary dynamics of local longshore transport and created a variety of features, such as the development of the barrier and diminishing marine influence, the formation of the inlet channels and flood-tide deltas deposits that provide the major volume of sediments to lagoon and the tombolo elongation from rocky headlands, resulting in lagoon fragmentation. Our study shows that the set of morphological features restricted the circulation and the marine supply and, enabled the dominance of large fluvial sediment supply within the inner bay–lagoon, (Fig. 8C). In fact, the extensive and relatively recent (<5000 cal BP) progradation of the Tubarão River delta has dominated the sedimentological and geomorphological changes in the inner portion of the present lagoon system (Nascimento, 2011). In the outer portion, at the dunefield inner border, the aeolian dunes migration has been an important factor in the silting of the lagoon and lake margins.

Another issue addressed in this study is the inherited morphology of the Pleistocene surface (marine terrace, palaeo-dunes and tombolo) and rocky headlands partly determines the geomorphological development during the Holocene. The mentioned pre-existing features sometimes acted as a sedimentary source and sometimes acted as a substrate or stabilisation point for marine transgressive and/or highstand sedimentation.

5. Conclusions

The Jaguaruna–Laguna palaeo–bay sedimentary record covers the period since ~8000 cal BP and consists as much as approximately 15 m of a vertical succession including, transgressive sandsheet, lagoon, inlet channel, flood-tide deltas, tombolo, strandplain, back-barrier, and aeolian dunes. This study demonstrates that the geomorphological analysis combined with sediment cores, macrofossils content and radiocarbon chronology permits the interpretation and determination of the sedimentological processes responsible for the transition from bay to lagoon system. The facies associations were dominantly controlled by relative sea-level, local sedimentary processes and sediment supply. Inherited morphology, conversely, could have been important in the external bay configuration.

The geomorphological evolution from a bay system to a lagoon system is divided into three phases. These phases differ from previous geomorphological evolution models of coastal lagoons, mainly in that the initial phase (8000–5700 cal BP) of sedimentary filling is characterised by the deposition of basal transgressive sandsheets that mark the formation of a bay susceptible to open sea and storm-related erosional processes. The transgressive sandsheets that unconformably overlie the antecedent Pleistocene substrate were probably deposited during the transgression terminus and before the formation of a barrier and the Holocene sea-level maximum. These sandsheets have an average thickness of 2 m and are composed of moderately- to well-sorted fine-to-medium quartzose sand with a dense concentration of macrofossils (70% facies association) and a lack of sedimentary structures due to strong bioturbation. The fauna elements within the transgressive sandsheet contain a variety of marine fauna (e.g., *Tellina* sp., *C. orbicularis*, *D. punctata*, *D. quadrisulcata*, *O. urceu* and echinoderms, such as *E. emarginata* and *L. variegatus*) that live in the sand of the marine nearshore and are broadly distributed in marine environments that are subject to a high-energy wave regimes and currents.

This analysis of the geomorphological and sedimentological evolution of the Jaguaruna–Laguna palaeo-bay, which is presently occupied by lagoons, residual lakes and a deltaic plain, has added new data and interpretations to the current models of coastal lagoon evolution on the southern coast of Brazil. This work provides a framework for other wave-dominated coastal regions in the Southern Hemisphere with similar morphologies and histories of sea-level variation. Additionally, this finding makes the lagoon system at Jaguaruna–Laguna the first sedimentary archive to provide a detailed understanding of the development and preservation of a bay succession in southern Brazil. Furthermore, this result can act as a key for recognising bay systems in the geological record.

Acknowledgements

The authors would like to thank Dr. Francisco Sekiguchi Buchmann and Dra. Juliana Moraes Leme for their help with macrofossils analyses. Acknowledgement is also made to Dr. Paulo de Blasis for aid in the field work, Dr. Luiz Pessenda for his assistance with radio carbon measurements. We thank the Fundação de Amparo à Pesquisa do Estado de São Paulo for the PhD Scholarship (04/13191-0) to Milene Fornari and by financial support to this research (processes 04/11038-0 and 05/51034-2), as well as to Editor (John T. Wells) and two referees of *Marine Geology* (Dr. Gerardo Perillo and a anonymous referee) for the their suggestions to improve the paper.

References

Amaral, P.G.C., Giannini, P.C.F., Sylvestre, F., Pessenda, L.C., 2011. Paleoenvironmental reconstruction of a Late Quaternary lagoon system in southern Brazil (Jaguaruna region, Santa Catarina state) based on multi-proxy analysis. Journal of Quaternary Science 27, 181–191.

Angulo, R.J., Giannini, P.C.F., Suguio, K., Pessenda, L.C.R., 1999. Relative sea-level changes during the last 5500 years in the Laguna–Imbituba region (Santa Catarina, Brazil), based on vermetid ^{14}C ages. Marine Geology 159, 323–339.

Angulo, R.J., Souza, M.C., Reimer, P., Sasaoka, S.K., 2005. Reservoir effect of the southern and southeastern Brazilian coast. Radiocarbon 47, 67–73.

Angulo, R.J., Lessa, G.C., Souza, M.C., 2006. A critical review of the mid- to late Holocene sea-level fluctuations on the eastern Brazilian coastline. Quaternary Science Reviews 25, 486–506.

Angulo, R.J., Lessa, G.C., Souza, M.C., 2009. The Holocene barrier systems of Paranaguá and northern Santa Catarina coasts, southern Brazil. In: Dillenburg, S.R., Hesp, P. (Eds.), Geology of the Brazilian Coastal Barriers. Lecture Notes in Earth Sciences, 107. Springer-Verlag, Berlin, pp. 53–91.

Araújo, C.E.S., Franco, D., Melo, E., Pimenta, F., 2003. Wave regime characteristics of the southern Brazilian coast. International Conference on Coastal and Port Engineering in Developing Countries, COPEDEC VI, Colombo, Sri Lanka. Proceedings. Paper 97. CD-ROM.

Boehs, G., Absher, T.M., Cruz-Kaled, A.C., 2004. Composition and distribution of benthic molluscs on intertidal flats of Paranaguá Bay (Paraná, Brazil). Scientia Marina 68, 537–543.

Boyd, R., Dalrymple, R., Zaitlin, B.A., 1992. Classification of clastic coastal depositional environments. Sedimentary Geology 80, 139–150.

Carrasco, A.R., Ferreira, Ó., Davidson, M., Matias, A., Dias, J.A., 2008. An evolutionary categorisation model for backbarrier environments. Marine Geology 251, 156–166.

Cooper, J.A.G., 1994. Lagoons and microtidal coasts. In: Carter, R., Woodroffe, C. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge Press, pp. 121–186.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62, 1130–1146.

Dillenburg, S.R., 1996. Oscilações holocênicas do nível relativo do mar registradas na sucessão de fácies lagunares na região da laguna de Tramandaí, RS. Pesquisas 23, 17–24.

Dillenburg, S.R., Tomazelli, L.J., Barboza, E.G., 2004. Barrier evolution and placer formation at Bujuru Southern Brazil. Marine Geology 203, 43–56.

Dillenburg, S.R., Barboza, E.G., Tomazelli, L.J., Ayup-Zouain, R.N., Hesp, P.A., Clerot, L.C.P., 2009. The Holocene coastal barriers of Rio Grande do Sul. In: Dillenburg, S.R., Hesp, P. (Eds.), Geology of the Brazilian Coastal Barriers. Lecture Notes in Earth Sciences, 107. Springer-Verlag, Berlin, pp. 53–91.

Evans, M.W., Hine, A.C., Belknap, D.F., Davis Jr., R.A., 1985. Bedrock control on barrier island development, Pinellas County, Florida. Marine Geology 63, 263–283.

Folk, R.L., Ward, W.C., 1957. Brazos river bar: a study in the significance of size parameters. Journal of Sedimentary Petrology 27, 3–27.

Fornari, M., 2010. Evolução sedimentar holocênica da retrobarreira na região de Jaguaruna-Laguna, Santa Catarina. São Paulo. Ph.D.thesis. Universidade de São Paulo, São Paulo, 290 pp.

Galloway, W.E., Hobday, D.K., 1983. Terrigenous Clastic Depositional Systems. Springer, Berlin. (489 pp).

Giannini, P.C.F., 2002. Complexo lagunar centro-sul catarinense. Sítios Geológicos e Paleontológicos do Brasil. In: Schobbenhaus, C., Campos, D.A., Queiroz, E.T., Winge, M., Berbert-Born, M. (Eds.), DNPM, SIGEP – Comissão Brasileira de Sítios Geológicos e Paleontológicos, pp. 213–222 (Web site: www.unb/br/ig/sigep).

Giannini, P.C.F., Sawakuchi, A.O., Martinho, C.T., Tatumi, S.H., 2007. Eolian depositional episodes controlled by Late Quaternary relative sea level changes on the Imbituba–Laguna coastal zone (southern Brazil). Marine Geology 237, 143–168.

Goodfellow, B.W., Stephenson, W.J., 2005. Beach morphodynamics in a strong-wind bay: a low-energy environment? Marine Geology 214, 101–116.

Hesp, P.A., Giannini, P.C.F., Martinho, C.T., Silva, G.M., Asp, N.E., 2009. The Holocene barrier systems of the Santa Catarina coast, southern Brazil. In: Dillenburg, S.R., Hesp, P. (Eds.), Geology of the Brazilian Coastal Barriers. Lecture Notes in Earth Sciences, 107. Springer-Verlag, Berlin, pp. 93–133.

Isla, F.I., 1989. Holocene sea-level fluctuations in the Southern Hemisphere. Quaternary Science Reviews 8, 359–368.

Jackson, N., Nordstrom, K., Eliot, E., Masselink, G., 2002. ‘Low energy’ sandy beaches in marine and estuarine environments: a review. Geomorphology 48, 147–162.

Kidwell, S.M., 1991. The stratigraphy of shell concentrations. In: Allison, P.A., Briggs, D.E.G. (Eds.), Taphonomy: Releasing the Data Locked in the Fossil Record. Plenum, New York, pp. 211–290.

Kjerfve, B., 1994. Coastal Lagoon Processes. Elsevier Oceanography Series, Amsterdam. (577 p).

Klein, A.H.F., Schettini, C.A.F., Carvalho, J.L.B., Diehl, F.P., 1998. Implications of inlet stabilization on the Camacho Lagoon, southern Brazil. Journal of Coastal Research 26, 150–155.

Klein, A.H.F., Krueger, J., Signorin, M., Araujo, R.S., Freitas Neto, D., 2010. Storm surges on the coast of Santa Catarina, southern Brazil. Storm Surges Congress, Hamburg, Germany, vol.1, p. 7.

Leatherman, S.P., 1979. Migration of Assateague Island, Maryland, by inlet and overwash processes. Geology 7, 104–107.

Leatherman, S.P., 1983. Barrier dynamics and landward migration with Holocene sea-level rise. Nature 301, 415–417.

Lessa, G.C., Meyers, S.D., Marone, E., 1998. Holocene stratigraphy in Paranaguá bay estuary, southern Brazil. Journal of Sedimentary Research 68, 1060–1076.

Lessa, G.C., Angulo, R.J., Giannini, P.C.F., Araújo, A.D., 2000. Stratigraphy and Holocene evolution of a regressive barrier in south Brazil. Marine Geology 165, 87–108.

Mallinson, D.J., Smith, C.W., Culver, S.J., Riggs, S.R., Ames, D., 2010. Geological characteristics and spatial distribution of paleo-inlet channels beneath the Outer Banks barrier islands, North Carolina, USA. Estuarine, Coastal and Shelf Science 88, 175–189.

Marriner, N., Goiran, J.P., Morhange, C., 2008. Alexander the Great's tombolos at Tyre and Alexandria, eastern Mediterranean. Geomorphology 100, 347–400.

Martinho, C.T., Giannini, P.C.F., Sawakuchi, A.O., Hesp, P.A., 2006. Morphological and depositional facies of transgressive dunefields in the Imbituba–Jaguaruna region, Santa Catarina State, Southern Brazil. Journal of Coastal Research Special Issue 39.

Mendes, I.L.V., 1993. Malacofauna, paleoecologia e biostratigrafia de sedimentos holocêncios da planície costeira de Imbituba e Imaruí, Santa Catarina, Brasil. Ph.D. thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre, 309 pp.

Morton, R.A., 1994. Texas barriers. In: Davis Jr., R.A. (Ed.), Geology of Holocene Barrier Island Systems. Springer-Verlag, Berlin, pp. 75–114.

Nascimento, D.R. Jr., 2011. Evolução sedimentar holocênica do delta do rio Tubarão, Estado de Santa Catarina. Ph.D. Thesis, University of São Paulo, 230 pp. (in Portuguese).

Nordstrom, K.F., Jackson, N.L., Sherman, D.J., Allen, J.R., 1996. Hydrodynamics and beach change on a micro-tidal lagoon shoreline. In: Nordstrom, K.F., Roman, C.T. (Eds.), Estuarine Shores: Evolution, Environments and Human Alterations. Wiley, Sussex, pp. 213–232.

Oertel, G.F., 1985. The barrier island system. Marine Geology 63, 1–18.

Pitoni, V.L.L., 1993. Moluscos Cenozóicos de sub-superfície em Imaruí, Santa Catarina, Brasil: paleoecologia, transgressões e regressões. Ph.D.thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre, 269 pp.

Rios, E.B., 1994. Seashells of Brasil, second ed. Fundação Universidade do Rio Grande, Rio Grande.

Roy, P.S., Cowell, P.J., Ferland, M.A., Thom, B.G., 1994. Wave-dominated coasts. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution, Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 121–186.

Siegle, E., Asp, N.E., 2007. Wave refraction and longshore transport patterns along the southern Santa Catarina coast. Brazilian Journal of Oceanography 55, 109–120.

Sloss, C.R., Jones, B.G., McClennen, C.E., de Carli, J., Price, D.M., 2006. The geomorphological evolution of a wave-dominated barrier estuary: Burrill Lake, New South Wales, Australia. Sedimentary Geology 187, 229–249.

Sloss, C.R., Jones, B.G., Switzer, A.D., Nichol, S., Clement, A.J.H., Nicholas, A.W., 2010. The Holocene infill of Lake Conjola, a narrow incised valley system on the southeast coast of Australia. Quaternary International 221, 23–35.

Souza, M.C., 2005. Estratigrafia e evolução das barreiras holocênicas paranaenses, sul do Brasil. Ph.D.thesis. Universidade Federal do Paraná, Curitiba, 100 pp.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised calib 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Switzer, A.D., Sloss, C.R., Jones, B.G., Bristow, C.S., 2010. Geomorphic evidence for mid–late Holocene higher sea level from southeastern Australia. Quaternary International 221, 13–22.

Tanaka, A.P.B., Giannini, P.C.F., Fornari, M., Nascimento Jr., D.R., Sawakuchi, A.O., Rodrigues, S.I., Leal-Menezes, P.M., Deblasis, P.A.D., Porsani, J.L., 2009. A planície costeira holocênica de Campos Verdes (Laguna, SC): evolução sedimentar inferida a partir de georradar (GPR), granulometria e minerais pesados. Revista Brasileira de Geociências 39, 750–766.

Timmons, E.A., Rodriguez, A.B., Matheus, C.R., DeWitt, Regina, 2010. Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA. Marine Geology 278, 100–114.

Travessas, F.A., Dillenburg, S.R., Clerot, L.C.P., 2005. Stratigraphy and evolution of the Holocene barrier of Rio Grande do Sul between Tramandaí and Cidreira (RS). Boletim Paranaense de Geociências 57, 57–73.

Troiani, B.T., Simms, A.R., Dellapenna, T., Piper, E., Yokoyama, Y., 2011. The importance of sea-level and climate change, including changing wind energy, on the evolution of a coastal estuary: Copano Bay, Texas. Marine Geology 280, 1–19.

Zenkovich, V.P., 1967. Processes of Coastal Development. Oliver & Boyd, Edinburgh-London. (London, 739 pp.).