

# A critical review of mid- to late-Holocene sea-level fluctuations on the eastern Brazilian coastline

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## Abstract

The eastern coast of Brazil is 7000 km long and has been the subject of systematic paleo-sea-level investigations for more than 35 years. More than 1000 samples have been radiocarbon dated, and paleo-sea-level trends have been determined for 14 coastal sectors. These trends have in common a mid-Holocene sea-level maximum (PMT) above present sea-level and a subsequent fall to the present time. The time and elevation of the PMT, the time when relative sea-level rose above present mean sea-level, and the nature of late Holocene sea-level fall can, however, differ significantly. Discrepancies are observed not only between neighboring coastal sectors, but also between different studies in a same coastal sector. This paper discusses all the key radiocarbon-dated samples used to establish regional trends in relative sea-level on the eastern coast of Brazil. It is concluded that although many of the key sea-level indicators are imprecise (in time and space), there is widespread evidence (30% of the data set) for a progressive decline, possibly with uneven rates, of relative sea-level since the end of the PMT.

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## 1. Introduction

The eastern Brazilian coastline, between the parallels 5°S (State of Rio Grande do Norte) and 34°S (State of Rio Grande do Sul), is about 7000 km long and encompass about 60% of the Atlantic South American coast (from Argentina to Trinidad and Tobago) (Fig. 1a). Systematic studies of the paleo-sea-level in this region started in the mid-1960s, with more than 100 publications addressing the Holocene sea-level history published since then. These studies show that a mid-Holocene sea-level highstand occurred along the whole coast, followed by a drop to present time. However, several aspects of the relative sea-level history are problematic and debatable, given the poor quality of many paleo-sea-level indicators combined with

divergent approaches to their interpretations. Critical areas of debate during the last 7000 years include the different elevation of the highstand and the presence or absence of high-frequency sea-level oscillations. Resolving these issues is important since a well-tuned paleo-sea-level curve, or envelope, is necessary for the correct understanding and assessment of coastal and ocean processes, such as rates of sedimentation, net sediment-transport volumes and coastal erosion or progradation. It is also essential for the correct development of evolutionary models of coastal landscapes (barriers, estuaries and coral reefs), as well as the calibration of isostatic models.

This paper presents a comprehensive review of the paleo-sea-level indicators used to date to develop a new model of the Holocene sea-level trend along the eastern Brazilian coast. To achieve this we will review: (i) the timing when sea level first reached present mean sea-level (MSL) during the postglacial sea-level rise; (ii) the maximum elevation of sea level in the mid-Holocene

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and when it occurred; (iii) the nature of sea-level fall in the late Holocene and; (iv) the evidence for significant regional differences in the Holocene sea-level record. The work synthesizes a large amount of information on paleo-sea-level indicators previously published in Brazilian journals and conference proceedings of restricted circulation.

## 2. Chronology of relevant paleo-sea-level studies in Brazil

To help the understanding of the present debate on the Holocene Brazilian sea-level history, it is important to provide an insight on the succession of articles that led to the widely held Brazilian sea-level curve that is now the subject of this review.



Fig. 1. (a) Location of the sites from where dated paleo-sea-level indicators have been obtained along the eastern Brazilian coast. Insets show details in the coastal sectors of (b) Salvador, (c) Cananéia-Iguape, (d) State of Paraná and Itapoá, (e) Ilha de Santa Catarina and (f) Laguna.



Fig. 1. (Continued)

The first references to Holocene paleo-sea-levels in Brazil date back more than 100 years, with the works of Hartt (1870) and Branner (1902). In the 1940s, more detailed studies of the Brazilian sea-level oscillations were published by Lamego (1940), Bigarella (1946), Maack (1947, 1949) and Almeida (1955). In the 1960s, the first radiocarbon dates of biogenic limestone composed mainly by vermetids (Van Andel and Laborel, 1964), allowed for the earliest reliable temporal and spatial interpretations of paleo-sea-levels. Other pioneer radiocarbon dates for paleo-sea-level studies were made by Bigarella (1965, 1971), Bigarella and Sanches (1966), Delibrias and Laborel (1969) and Laborel (1969).

Bigarella (1965, 1971) compared the paleo-sea-level data from Brazil with Fairbridge's (1961) curve, which was understood at that time as a representation of the eustatic sea-level behavior. Delibrias and Laborel (1969) were the first to anticipate regional differences in the sea-level history, showing that, in contrast to sites in the Northern Hemisphere, a clear highstand at least 1 m higher than present existed in Brazil.

Pioneer outlines of the sea-level curves (from Cananéia coastal plain and Baía de Parataguá—Figs. 1c, d, 2 and 3), heavily laden with archeological information, were presented in the beginning of the 1970s by Martin and Suguio (1975) and Suguio et al. (1976). It is already

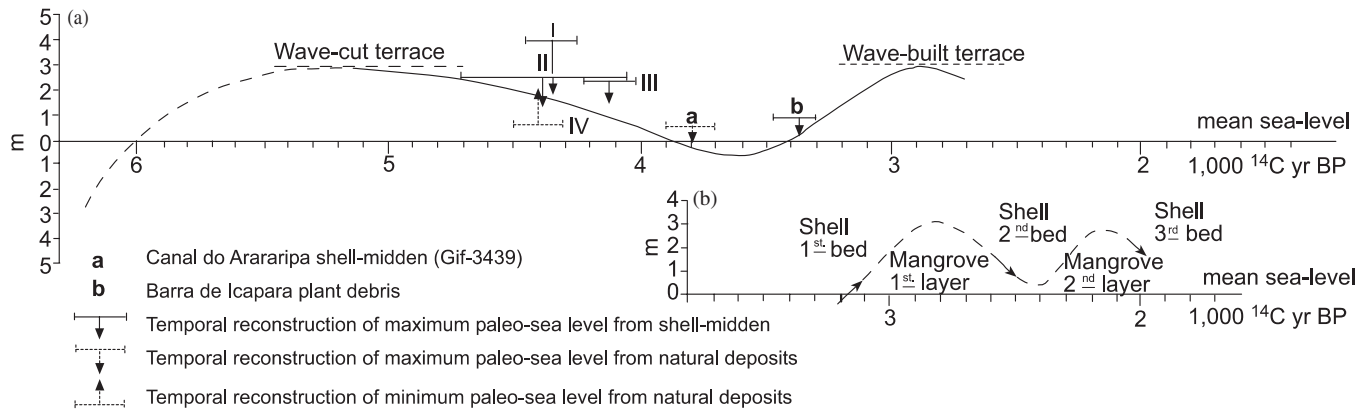


Fig. 2. (a) Sea-level changing scheme for the last 6000 years in Cananéia-Iguape region and (b) sea-level changing indicated by the shell-midden from Ilha das Rosas in Baía de Paranaguá (after Martin and Suguio, 1975). For location see Figs. 1c and d and details on the identified sample see Table 1.

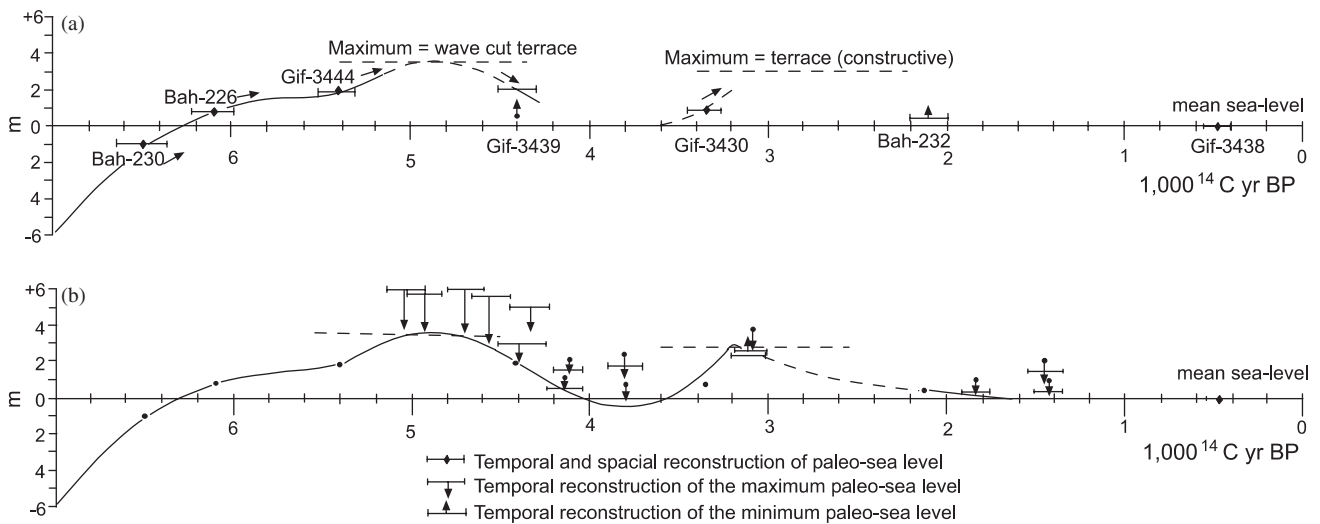


Fig. 3. Relative sea-level changes in the Cananéia-Iguape region: (a) information from geomorphologic and geological evidence and (b) additional information supplied by samples from shell-middens (after Suguio et al., 1976). For location see Fig. 1c.

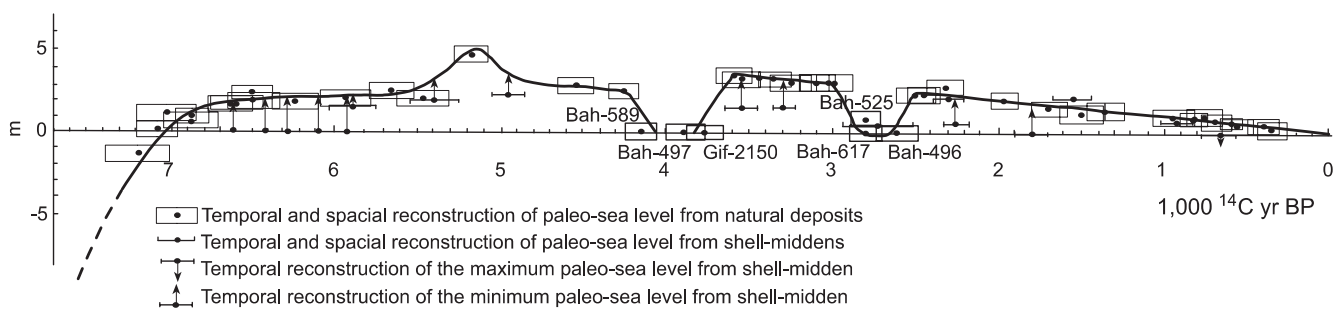


Fig. 4. Relative sea-level changes in the last 7000 years in the region around Salvador (after Martin et al., 1979/1980). For location see Fig. 1a and for details on the identified samples see Table 1.

observed in these curves the general shape of the commonly accepted Brazilian relative sea-level curve, with shell-midden indicating the periods of lower sea-level and the elevation of marine terraces indicating periods of higher sea-levels.

In the late 1970s, Martin et al. (1979/1980) published a curve that became the reference of the Brazilian Holocene sea-level behavior, with the two high-frequency oscillations and the highstand at 4.8 m above present MSL (Figs. 1a and 4). It is important to note,

however, that only six paleo-sea-level indicators, out of the total 52 used, have a clearly defined age and height relationship to a former sea level (see below).

In the mid-1980s, Suguio et al. (1985) compiled all published curves between the states of Alagoas and Santa Catarina (Fig. 1a), that in accordance with the authors, were the result of more than 700  $^{14}\text{C}$  dates. The papers by Martin et al. (1979/1980) and Suguio et al. (1985) were complementary, and grounded the concept of the high-frequency sea-level oscillations that has biased the interpretation of the coastal geomorphology in the country (see discussion below).

Other relevant studies discussing paleo-sea-level data and trends (Villwock et al., 1986; Dominguez et al., 1990; Angulo and Suguio, 1995; Angulo and Lessa, 1997; Lessa and Angulo, 1998; Tomazelli et al., 1998; Angulo et al., 1999) were published in the late 1980s and 1990s. With the exception of the work by Dominguez et al. (1990), all the other publications proposed alternative interpretations for the sea-level data and trends. For instance, Tomazelli et al. (1998) suggested that sea level has been rising in the last 2000 years, Angulo and Suguio (1995) questioned whether the geoid could cause the difference in the elevation of the postglacial sea-level maximum (PSLM) along the coast (as proposed by Martin et al., 1985), and Angulo and Lessa (1997) and Lessa and Angulo (1998) contested the existence of the high-frequency sea-level oscillations and the elevation of the Holocene sea-level maximum.

More recently Bezerra et al. (2003), based on 48 radiocarbon dates, showed that regional tectonics is largely controlling the relative sea-level variations in the State of Rio Grande do Norte (Fig. 1a). Finally, Martin et al. (2003) summarized 25 years of studies sustaining the sea-level behavior indicated by the base curve. In addition, corrections to account for the fluctuation of atmospheric  $\text{CO}_2$  through time was performed, and the curves were then plotted in calibrated years.

### 3. The data set

A considerable amount of contradictory information exists regarding the samples used for sea-level studies in Brazil, including their location, nature, ages, laboratory reference number and inferred paleo-sea-levels. This required an extensive search in more than 100 articles and technical reports where radiocarbon dates were originally published and first described. Whenever possible, contact was made with the authors or with the laboratory responsible for the radiocarbon datings. Some of the original data have, therefore, been corrected, and differ from those published elsewhere. Table 1 lists the paleo-sea-level data set, excluding samples older than 28,000 yr BP as well as samples obtained from archaeological debris (shell-middens). All

dates are calibrated after Stuiver and Reimer (1993), with calibrated dates using a two sigma age range. A regional reservoir effect of  $8 \pm 17$  years, determined by Angulo et al. (2005) for the south and southeastern Brazil, was attributed to all marine samples.

### 4. Discussion

Different paleo-sea-levels can be generated by (i) misinterpretations of the elevation of the paleo-sea-level, (ii) misinterpretations of the age of the paleo-level, (iii) leveling errors, (iv) dating errors caused by contamination, and (v) inclusion, or not, of time correction factors, such as carbon isotopic fractionation, variation of atmospheric  $^{14}\text{C}$  content through time and reservoir effects. Misinterpretations of the paleo-environment of deposition, misunderstanding of the vertical zonation of marine species, and the use of inappropriate or inadequate evolutionary models of coastal landscapes can also result in an incorrect reconstruction of paleo-sea-level. Age misinterpretations commonly occur when information on the paleo-sea-level and its time come from different sources (Angulo et al., 2002). An example is a beach-face sediment deposit with embedded shells. Dating of the shells provides a time control and the environment of deposition provides an elevation control. However, it often occurs that the age of reworked samples is taken as the age the sedimentary deposit from which it is derived.

The following sections review the main areas of debate in Brazilian sea-level research that, as will become apparent, revolve to a large degree around the identification and treatment of these various age and altitude issues.

#### 4.1. When did relative sea-level reach present mean sea-level in the postglacial transgression?

The timing of when relative sea-level rose above present MSL provides a useful datum to assess whether local or regional differences in the relative sea-level history exist in Brazil. Suguio et al. (1985), for example, noted that there appeared to be a northward delay of the time when this crossover occurred. This delay was also noted by Martin et al. (1985), who ascribed it to variations in the configuration of the geoid over Brazil during the late Holocene. Between the states of Rio de Janeiro and Paraná, where the coast is oblique to the geoid contour lines, a slight east–west geoidal shift would lower the elevation of the PSLM and diminish the amplitude of the subsequent sea-level fall (Fig. 5). Also as a consequence, the crossover time between Rio de Janeiro and Paraná would occur later than in the others coastal sectors (Figs. 4 and 6).

Although the age estimates provided for the relative mean sea crossing times appear precise, there are major age and altitude uncertainties associated with these estimates. These arise from the nature of the material dated and also from the interpretation of the paleo-environment from which these critical indicators are

derived. This is now illustrated through detailed consideration of the relevant data from two sites.

The MSL-crossing times have been established by Martin et al. (1985) and Suguio et al. (1985) at 6600 yr BP in Cananéia-Iguape (25°S), 6800 yr BP in Santos (24°S) and 7100 yr BP in Salvador (13°S) (Fig. 1a). In earlier papers, the MSL-crossing time in Cananéia was given as 6200 yr BP (Suguio et al., 1976) and 6900 yr BP (Martin et al., 1979b), whereas in Santos an age of 6400 yr BP (Martin et al., 1979b) was given. Two other samples from a coastal plain near Santos (Praia Grande), although indicating paleo-sea-levels higher than present, can also be used to infer an approximate time for the earliest MSL-crossing time, and will be discussed below.

In Cananéia-Iguape and Santos, the MSL-crossing time was determined by interpolating between the ages of different samples. The samples consist of transported wood fragments within muddy sediments (Suguio et al., 1976; Martin et al., 1979b). One was dated at  $6500 \pm 170$  yr BP (Bah-230, 7659–6949 cal yr BP), and would indicate a paleo-sea-level of  $-0.8 \pm 0.3$  m (Suguio et al., 1976) (Fig. 7a). The other sample provided an age of  $6100 \pm 130$  yr BP (Bah-226, 7248–6486 cal yr BP), and would indicate a paleo-sea-level of  $0.8 \pm 0.3$  m (Fig. 7b). Other similar indicators found in the states of São Paulo

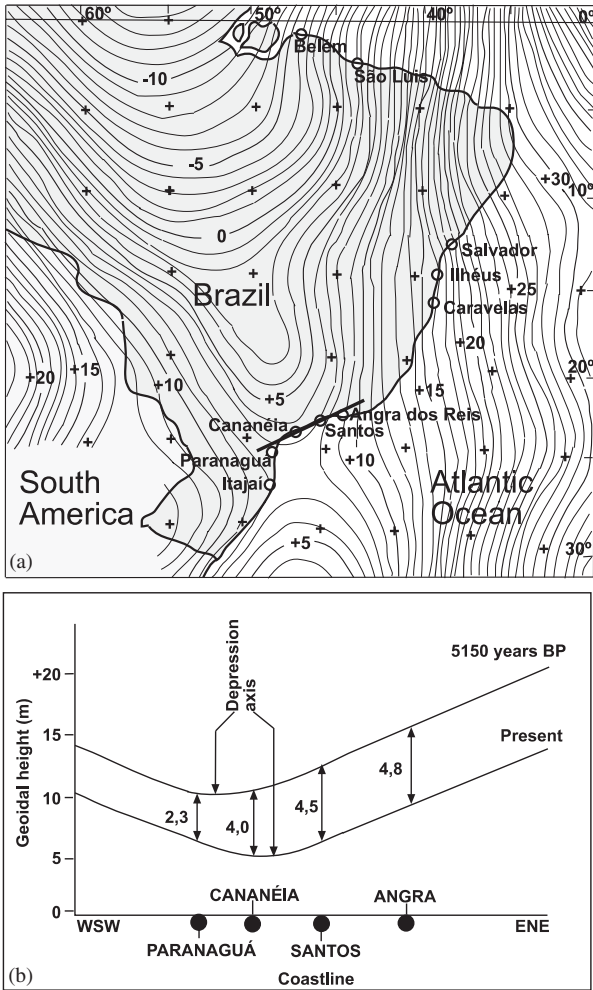


Fig. 5. (a) Geoidal chart of Brazil and (b) a cross section of the geoid today and a suggested one for the mid-Holocene with a lateral offset. Regional differences in the elevation of the postglacial sea-level maximum were ascribed to subsidence of the geoidal relief east of Cananéia, which was due to a slight displacement of the central depression (after Martin et al., 1985). The location of the profile in (b) is showing in (a).

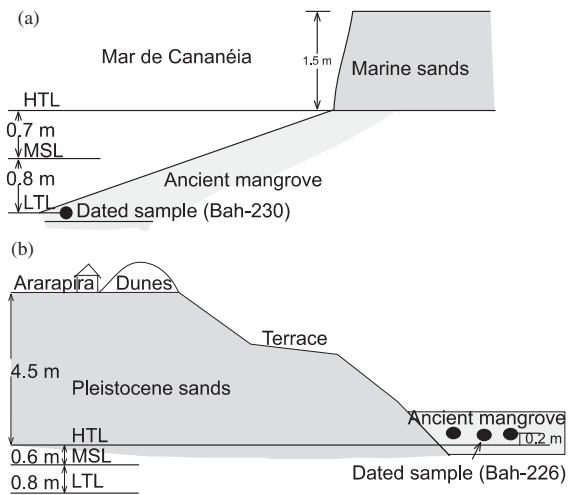


Fig. 7. Schematic cross sections of the sites where radiocarbon-dated samples were collected: (a) landward margin of Ilha Comprida and (b) Canal de Ararapira (after Suguio et al., 1976). For location see Fig. 1c.

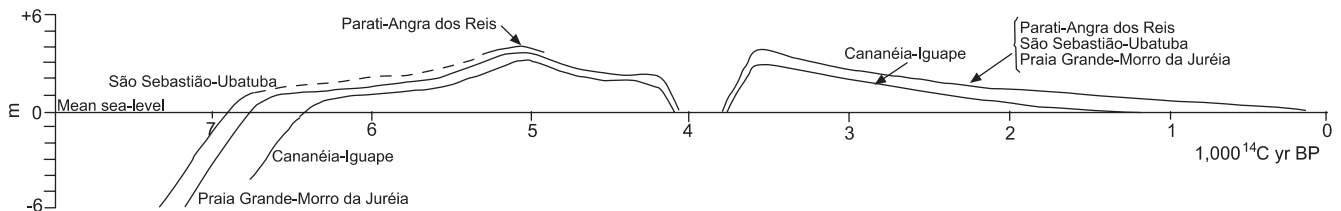


Fig. 6. Paleo-sea-level curves for three different sectors of the Brazilian coast between Angra dos Reis and Cananéia (after Martin et al., 1979b). For location see Fig. 1c.

and Rio de Janeiro support this MSL-crossing time (Martin et al., 1979b).

The problem with the determination of the MSL-crossing times above resides on the interpretation of the depositional environment. This interpretation was based on a flawed conceptual model of the evolution of the coastal plain (see Angulo and Lessa, 1997). For example, it is possible that the muddy sediments from where the samples were collected were indeed a paleo-estuarine deposit, but of sub-tidal elevation. This would indicate the lowest possible sea level at the time. It is also possible that the age of the deposit is much younger than the (transported) sample. In this case, both elevation and age controls are inadequate to indicate the MSL-crossing time.

The MSL-crossing time in Salvador was based on a single sample: a reworked shell embedded in a beach-rock indicating an elevation of  $0 \pm 0.5$  m at  $7095 \pm 125$  yr BP (Bah-571, 7792–7334 cal yr BP) (Bittencourt et al., 1978; Martin et al., 1979a). This altitude interpretation was based on primary sedimentary structures observed in the beach-rock. The authors inferred the age of the deposit by the age of transported samples, which can be much older than the deposit itself. In addition, Lessa and Angulo (1998) suggested that the depositional environment should be at least 1.5 m higher (see section 4.3.2). Therefore, problems associated with time and elevation control of this sample makes it also unsuitable for the determination of the crossover time in the region of Salvador.

The only in situ paleo-sea-level indicator in the whole data bank is the mangrove trunk found in living position in a trench dug on the coastal plain close to Santos (Fig. 8) (Martin and Suguio, 1978; Martin et al., 2003). The trunk was rooted into muddy sediments and buried

by marine sands, suggesting either a transgressive event or lateral barrier progradation. It rested  $2.0 \pm 0.5$  m above the level where modern mangrove trees grow and was dated to  $6480 \pm 75$  yr BP (Bah-327, 7557–7264 cal yr BP) and  $6250 \pm 130$  yr BP (Gif-3845, 7423–6803 cal yr BP) (Fig. 8). By incorporating these two paleo-sea-level reconstructions in the sea-level base curve of Salvador, Martin et al. (2003) suggested an MSL-crossing time at around 7550 cal yr BP.

It can be concluded that complex indicators indicate that sea level had already overtaken present MSL by 6600 yr BP (6900–7700 cal yr BP). However, the majority of these indicators are not sufficiently precise to establish regional differences in the MSL-crossing time. Consequently, there is also no indication that changes of the geoidal surface have occurred, as proposed by Angulo and Suguio (1995).

#### 4.2. The mid-Holocene highstand

References to the elevation of the mid-Holocene highstand in the eastern coast of Brazil can be found in several publications, including Suguio et al. (1985), Dominguez et al. (1990), Angulo and Suguio (1995), Angulo and Lessa (1997), Angulo et al. (1999), Souza et al. (2001) and Bezerra et al. (2003). The suggested elevations vary from a minimum of  $2.1 \pm 1.0$  m in Laguna (Angulo et al., 1999) to 5 m in Pernambuco (Dominguez et al., 1990) (Fig. 9). Suguio et al. (1985) suggested regional differences of 2.5 m amongst seven sites between Salvador in the north and Laguna in the south, and ascribed this difference, as stated in the previous section, to a shift of the geoidal relief (Martin et al., 1985; Suguio et al., 1985) (Fig. 5).

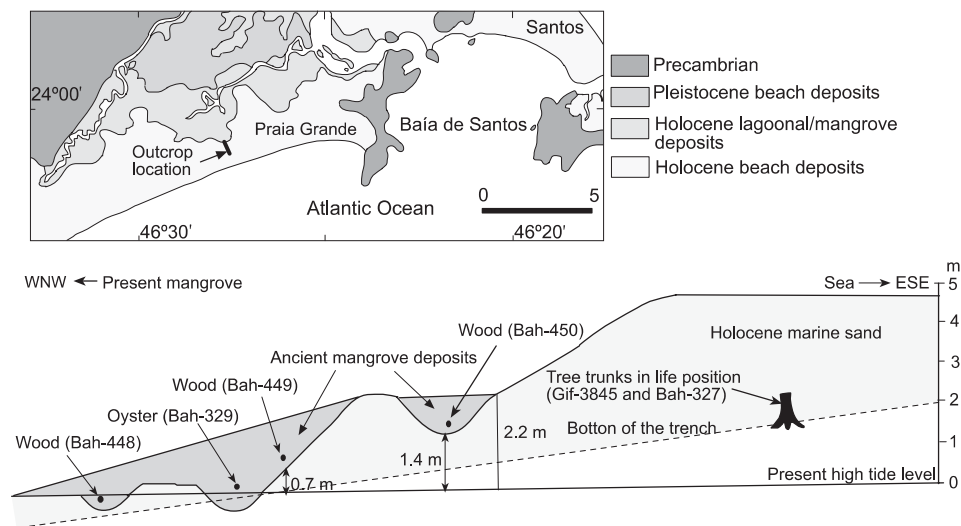


Fig. 8. Schematic profile of the Holocene terrace in Praia Grande, State of São Paulo showing the location of the tree trunk from where two samples with ages older than 6800 cal yr BP were collected. The profile also shows four other dated samples listed in Table 1 (after Martin and Suguio, 1978). For location see Fig. 1c.

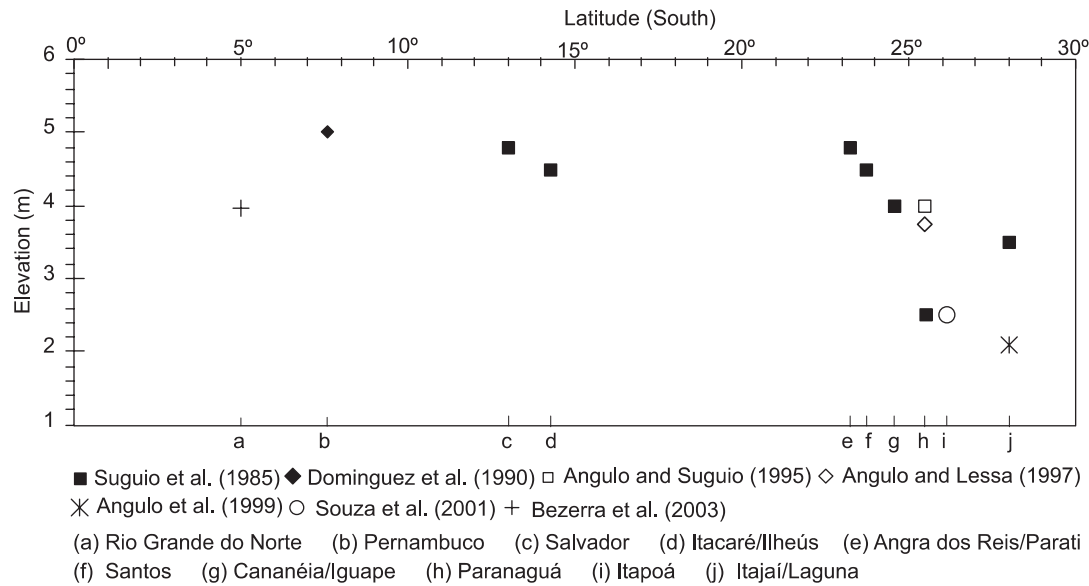


Fig. 9. Elevation of the Holocene highstand along the eastern coast of Brazil in accordance with different authors.

The time of the highstand varies between  $5195 \pm 110$  yr BP (Bah-567, 5783–5291 cal yr BP) (Martin et al., 1979a; Martin et al., 2003) and  $5410 \pm 80$  yr BP (CENA-179, 5916–5597 cal yr BP) (Angulo et al., 1999). All of the above ages and elevations were obtained with the elevation of coastal barriers, dating of oyster samples, and shell-rich sediment layers on beaches, that will be now discussed.

#### 4.2.1. Elevation of the mid-Holocene highstand inferred through the elevation of coastal barriers

Martin and Suguio (1978), Suguio and Martin (1978), Martin et al. (1979/1980, 1988a), Suguio et al. (1985) and Martin et al. (2003) suggest that the elevation of wave-built terraces (beach ridges) represent the MSL at the time of their deposition. They use this assumption to hypothesize the Holocene sea-level maximum in the coastal sectors between Itacaré and Laguna (Fig. 1a). Dominguez et al. (1990) also infer the elevation of the Holocene sea-level maximum on the basis of the elevation of a wave-built terrace.

As Angulo and Lessa (1997) pointed out, the elevation of the terraces are related to the elevations of the swash limit during storms, which in its turn depends on the wave spectrum, beach grain size and slope, the bathymetry of the nearshore and the tidal range. Roep (1986) showed that paleo-sea-levels in the Netherlands's coast should be 2–3 m below the surface of the wave-built terraces. Bigarella et al. (1961) showed that wave-built terraces with different elevations are associated with the present MSL along the coast of the State of Paraná, and indicated that the PSLM may have been 1–6 m below the average elevation of the inland-most part of the strandplain (Angulo, 1994). Therefore, we

consider that all the above paleo-sea-level interpretations based on the elevation of wave-built terraces are overestimated, whereas their margin of error is significantly underestimated.

In the Paranaguá region (Fig. 1a), Suguio et al. (1985) and Martin et al. (1988b) inferred the elevation of the Holocene highstand on the basis of the altitude of innermost part of the strandplain without indurated, organic-rich, dark-brown sands. It was then assumed that epigenetically enriched sediments were characteristic of Pleistocene deposits only. However, Angulo and Suguio (1995) and Angulo et al. (2002) showed that such indurated sands can also be Holocene. Angulo and Suguio (1995) re-evaluated the morphological boundary between the Pleistocene and Holocene strandplains, and the elevation of the highstand was then re-assessed at about 4 m (Fig. 10).

#### 4.2.2. Elevation of the mid-Holocene highstand inferred with shell-rich sediment layers

Inferences of the paleo-sea-level made by Martin and Suguio (1976, 1978, 1989), Suguio and Martin (1978) and Martin et al. (1979b,c, 2003) based on shell-rich sediment layers are questionable due to the inaccurate interpretation of the depositional environment.

For instance, close to Santos (Morro da Enseada, Fig. 1c), in a protected re-entrance of the coastline, the elevation of the transgression maximum has been inferred from shell-rich layers embedded in beach-rocks. Two samples obtained from the shelly layers were dated at  $5470 \pm 100$  yr BP (Bah-609, 6070–5600 cal yr BP) and  $3475 \pm 70$  yr BP (Bah-355, 3512–3162 cal yr BP) (Fig. 11). Martin and Suguio (1976) and Martin et al. (1979c) suggested that the shell-rich layers are analogous

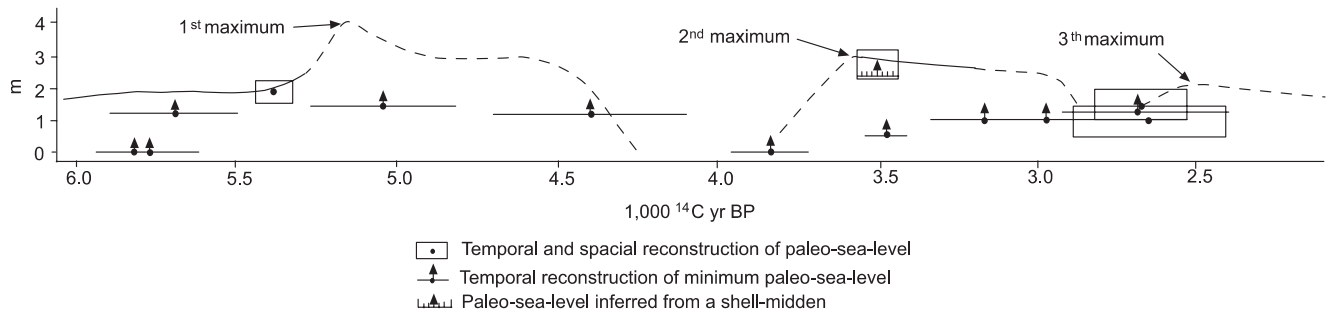


Fig. 10. Heights of the maximum relative sea-levels along the State of Paraná coastline during the last 6000 yr BP. The original curve for Parangá from Suguio et al. (1985) was elevated based on re-interpretation paleo-sea-level and the age of the coastal plain (after Angulo and Suguio, 1995). For location see Fig. 1a.

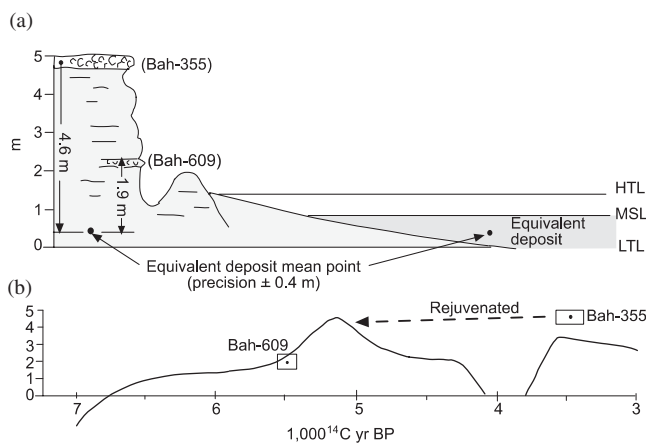


Fig. 11. (a) Schematic profile of the Morro da Enseada outcrop in the Bertioiga coastal plain with the location of the samples and (b) the position of the samples in relation to the Santos paleo-sea-level (after Martin et al., 1979c). For location see Fig. 1c and for details on the identified samples see Table 1.

to similar deposits found in the lower half of the beach profile, between MSL and low-tide level. The elevation difference between the shell layers on the present beach and on the outcrop suggests a sea-level maximum between  $4.0 \pm 0.5$  and  $4.6 \pm 0.4$  m (Martin and Suguio, 1976, 1978; Suguio and Martin, 1978; Martin et al., 1979c, 2003). Because the age  $3475 \pm 70$  yr BP was too young to be associated to the PSLM, and the  $\delta^{13}\text{C}$  was rather negative ( $-7.25\%$ ), Martin et al. (1979c) considered that the sample was contaminated (Fig. 11).

Martin et al. (1979c, 2003) interpreted the sedimentary sequence in the outcrop as transgressive in nature, suggesting that the top of the terrace was an environment analogous to the lower part of the present-day beach. The lower beach would have been elevated by the vertical accretion of a low-tide terrace. This is a rather uncommon coastline adaptation to a rising sea level, with no landward displacement of the shoreline indeed. If shoreline migration was impaired by the presence of a coastal relief with higher topographical gradients, the

morphological result would more likely be a drowned sandy body (Roy et al., 1995). Although we have not visited the area, we consider that the shell layer in question more probably represents an elevated part a pocket beach, and not an environment analogous to the lower beach face. Any inference of the paleo-sea-level using this evidence is therefore highly questionable.

#### 4.2.3. Elevation of the mid-Holocene highstand inferred from oyster samples

Because oyster can live in a wide range of elevation, they are of limited use as a paleo-sea-level indicator. Oyster samples were used to determine the elevation of the PSLM close to Angra dos Reis-Parati, Rio de Janeiro (Fig. 1a). Two in situ samples dated at  $5200 \pm 200$  yr BP (LJ-1364, 5982–5019 cal yr BP) and  $4800 \pm 200$  yr BP (LJ-970, 5558–4558 cal yr BP) (Martin and Suguio, 1978) indicate an elevation of 4.8 m. This sample was collected and dated by Danciger and Curray (pers. comm. in Delibrias and Laborel, 1969), who measured the samples' elevation as 4.8 m above MSL. As Laborel (1979, 1986) pointed out, the vertical zonation of a rocky cliff does not correspond to the hydrographic tide levels. Delibrias and Laborel (1969) observed “living *Ostrea* in wave beaten crevices, 3 m above mean above mean level” at Cabo Santo Agostinho (Fig. 1a), and concluded that oysters are particularly poor sea-level indicators and that, as a result, it is possible that the level given by Danciger and Curray is an overestimate. Therefore, the elevation of the PSLM around Angra dos Reis could have been lower than 4.8 m.

#### 4.2.4. Elevation of the mid-Holocene highstand inferred from vermetid samples

The most reliable inferences on the elevation of the Holocene highstand (Fig. 9) are given by the vermetids. In the region around Salvador, vermetid samples were collected at the entrance of Baía de Todos os Santos (Porto da Barra headland,  $13^\circ\text{S}$ , Fig. 1b), providing an age of  $5195 \pm 110$  yr BP (Bah-567, 5783–5291 cal yr BP)

and an inferred paleo-sea-level of  $4.7 \pm 0.5$  m (Martin et al., 1979a, 2003) or  $4.5 \pm 0.5$  m (Martin et al., 1979d) or  $4.8 \pm 0.5$  m (Suguio et al., 1985) (Table 1). Martin et al. (1979d) mentioned that the assessed paleo-sea-level could be slightly overestimated, because the site was exposed to the wave action. Nevertheless, the  $4.7 \pm 0.5$  m elevation is maintained by Martin et al. (2003) because although it “could at first be a source of controversy...information from other sectors of the Brazilian coast corroborates the timing and/or altitude of the maximum of the Holocene Transgression in the Salvador curve”.

It is worth pointing that at least 142 paleo-sea-level assessments have been published on the basis of vermetid (138 samples) or algae with vermetids (four samples) samples, amongst which only two, besides the sample from Salvador, indicated paleo-sea-levels higher than 4 m. A sample obtained in Gaibú provided an age of  $3870 \pm 170$  yr BP (Bah-1221, 4277–3397 cal yr BP) and indicated a paleo-sea-level of  $4.83 \pm 0.5$  m (Dominguez et al., 1990). The other, collected at Cabo de Santo Agostinho was dated at  $2010 \pm 160$  yr BP (Bah-1236, 1931–1246 cal yr BP) and indicated a paleo-sea-level of  $4.36 \pm 0.5$  m (Dominguez et al., 1990). We consider that these samples are exceptions, possibly due to the high wave action at the site and, as will be shown below, are outliers within the data set.

Another four vermetid samples have been used to establish the maximum PSML in the states of Paraná and Santa Catarina. In Morro de Caiobá (Fig. 1d), Angulo et al. (2002) collected two samples at an elevation  $3.6 \pm 1.0$  and  $3.5 \pm 1.0$  m above the level of occurrence of the polichaete *Phragmatopoma lapidosa*, whose upper living zone corresponds to the lower living limit of the vermetid *Petalonchus* (*Macrophragma*) *varians* (vermetids are no longer found in southern Brazil—Laborel, 1977; Angulo et al., 1999). The samples provide an age of  $4750 \pm 70$  yr BP (CENA-140, 5222–4826 cal yr BP) and  $5300 \pm 70$  yr BP (CENA-141, 5845–5513 cal yr BP), in agreement with the elevation suggested by Angulo and Lessa (1997) based on the elevation of the outermost part of the Pleistocene strandplain. In the State of Santa Catarina, two other vermetid samples were obtained by Angulo et al. (1999) from rocky headlands between Cabo de Santa Marta and Ponta de Itapirubá (Fig. 1f), at elevations of  $2.1 \pm 1.0$  and  $1.95 \pm 1.0$  m. The dating of these samples provided ages of  $5410 \pm 80$  yr BP (CENA-179, 5916–5597 cal yr BP) and  $4600 \pm 70$  yr BP (CENA-192, 4971–4577 cal yr BP).

All the evidence presented by the indicators above point out that the PSLM took place between 4900 yr BP (5100 cal yr BP) and 5400 yr BP (5700 cal yr BP), and reached an elevation between 3 and 4 m from the state of Pernambuco to the state of Paraná, and 2 m in the southern State of Santa Catarina.

#### 4.3. Late Holocene high-frequency oscillations of sea level

The existence of the high-frequency sea-level oscillations in Brazil after the PSLM has long been debated (Angulo and Lessa, 1997; Martin et al., 1998; Lessa and Angulo, 1998; Martin et al., 2003). It is hypothesized that these fluctuations had amplitudes of 3–4 m, and occurred between 4100–3800 and 3000–2700 yr BP (4200–3700 and 2700–2100 cal yr BP) (Suguio et al., 1985; Martin et al., 2003).

Evidence for the regressive events were presented in the first sea-level curve for the Cananéia-Iguape region published by Martin and Suguio (1975) (Fig. 4a). In this paper, two lines of evidence point to lower sea-levels between 4100 and 3800 yr BP (4200–3700 cal yr BP): the shell-midden at Canal do Ararapira (Fig. 2a) and a sample of plant detritus obtained from an outcrop close to Barra de Icapara (Fig. 2a). Another shell-midden, located in Ilha das Rosas (Baía de Paranaguá), provides evidence of a second oscillation (Fig. 2b).

Several indicators were subsequently presented to support the existence of these regressive events, and can be grouped into five classes: (a) shell-middens (from the regions of Salvador, Santos, Cananéia-Iguape and Baía de Guaratuba); (b) primary sedimentary structures in beach-rocks (from Salvador region); (c) detritus of beach vegetation (from Cananéia-Iguape region); (d) swamp deposits (from Rio do Fogo) and (e) truncation of beach ridges within the strandplains at Caravelas and at the mouth of the rivers Doce, Jequitinhonha and Paraíba do Sul. Amongst these, only the shells embedded in beach-rocks provide good-quality spatial and temporal control on former sea-level.

##### 4.3.1. Evidence of lower sea-levels derived from shell-middens

Shell-middens are the most numerous and perhaps the second most important evidence, following beach-rocks, of the short-term regressive episodes, and have been used extensively in the work of Martin and Suguio (1976, 1989, 1992), Martin et al. (1979a, b, 1986a, b, 1987, 1988a, b, 1996, 1997, 1998, 2003) and Suguio et al. (1980, 1985, 1986, 1992). These middens, especially in south Brazil, can be as long as 300 m, as wide as 60 m and taller than 30 m (Martin et al., 1986a, b; Gaspar, 2000). The potential of shell-middens for sea-level studies was anticipated by Laming-Empeaire (1968), and thoroughly discussed by Martin et al. (1986a, b). Laming-Empeaire (1968) mentioned the existence of several shell-middens that extend below present sea-level, and noted specifically the shell-middens of Ilha das Rosas (in Baía de Paranaguá, Fig. 1d) and Maratúá (close to Santos, Fig. 1c). Martin and Suguio (1975) and Martin et al. (1979a, 1986a, b, 2003), besides these middens, refer to others found at Canal de

Ararapira (in the Cananéia-Iguape region, Fig. 1c), at Pedra Oca (in the margins of Baía de Todos os Santos, Fig. 1b) and at Rio Boguaçu (inside Baía de Guaratuba, Fig. 1d), as evidence of paleo-sea-levels at or below the present level.

The two assumptions made by Laming-Emperaire (1968), Martin and Suguio (1976) and Martin et al. (1986a, b, 1987, 2003) in the use the middens as paleo-sea-level indicators are that they are a remnant, or waste dumps, of campsites, and as such, their base (i.e., its initial stages) would have to be originally above the spring high-tide level at the time of construction. Angulo and Lessa (1997) questioned the validity of the historic sea-level data obtained from shell-middens, given the various possibilities that could have led an unknown culture to initiate a mound underwater. Recent archaeological studies (Gaspar, 1998, 2000; Fish et al., 2000; Nadal de Masi, 2001; Gaspar et al., 2002) indicate that shell-middens were structures with multiple functions, with a complex and hierarchical spatial distribution that resulted from a socially planned effort. Amongst others, one of the reasons for erecting a midden would be the creation of an important topographical reference in the landscape. Gaspar (1998) reported that some middens were used as living sites, others were dumpsites and still others were burying grounds. Hence, although initially sound, the idea that shell-middens are the daily life remains of pre-historic people accumulated on dry ground must be re-evaluated.

Furthermore, the nature of the midden's substrate and the midden's complex internal structure bring in additional complexity to the assessment of the original substrate elevation and paleo-sea-levels. Detailed stratigraphic studies of shell-middens reveal a highly complex internal structure, making it difficult to assess where the earliest layers are. The shell-middens of Ponta das Almas and Carniça I, studied by Hurt (1974) in the coast of Santa Catarina (Fig. 12), are good examples of such complexity. A detailed investigation of their internal structure reveal several discontinuous time lines, suggesting the merging of different smaller mounds that were initiated over different substrates (Fig. 12). Also, as the mound grew, slumping was probably a natural process. This indicates that, even if the original premises taken by Laming-Emperaire (1968), Martin and Suguio (1976) and Martin et al. (1986a, b, 1987, 2003) were correct, investigation and sampling of numerous detailed sections in the same midden are needed to identify its base. We have found no indication that any further evaluation of the shell-midden structures has been performed to assess their significance as paleo-sea-level indicators.

The  $\delta^{13}\text{C}$  of the mollusk shell samples obtained from shell-middens have also been used as evidence of late Holocene sea-level oscillations. Because  $\delta^{13}\text{C}$  values are higher in marine than in continental waters, the value

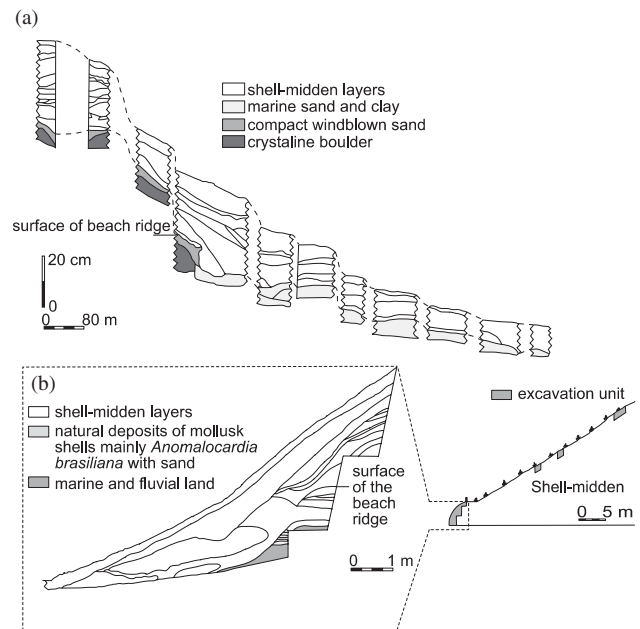


Fig. 12. Detailed scheme of internal structures of the shell-midden of (a) Ponta das Almas and (b) Carniça I (after Hurt, 1974). For location see Figs. 1e and f, respectively.

recorded in mollusk shells is an indication of the degree of marine (continental) influence in the paleo-environment (Martin et al., 1986a, b, 2003). Decreasing (increasing) value of  $\delta^{13}\text{C}$  has then been interpreted as a consequence of a fall (rise) of sea level, and a higher (smaller) degree of continental influence upon the estuary. Apart from possible relative sea-level changes, the degree of marine influence inside an estuary is also regulated by natural changes in the estuarine morphology during the sediment-infilling process (that can change the tidal range and excursion), and by natural fluctuations of the freshwater inflow due to climatic oscillations. Regarding the latter, Genz et al. (2003) and Pekárova et al. (2003) have shown that low-frequency (~30 years) hydrological cycles are associated with changes in the mean annual river discharge of up to 40% (as it is the case for rivers in the State of Bahia—Genz et al., 2003). These cycles can certainly impact the estuarine ecology, as indicated by Alber (2002). The shells collected by the primitive people belonged mostly to the species *Anomalocardia brasiliiana*, *Ostrea*, *Crassostrea* and *Modiolus* (Bigarella, 1950/51a, b; Emperaire and Laming, 1956; Laming-Emperaire, 1968; Hurt, 1974; Gaspar, 1998, 2000). The life-time of *A. brasiliiana* varies between 1 and 3 years (Boehs, 2000) and that of *Ostrea* and *Crassostrea* is around 20 years (Wakamatsu, 1973). This means that the life cycle of an estuarine mollusk may record short-lived alternation between drier and wetter periods and that the simple assumption that  $\delta^{13}\text{C}$  values can be used to reconstruct changes in relative sea-level is open to doubt.

#### 4.3.2. Evidence of lower sea-level derived from primary sediment structures in beach-rocks

Six samples (Bah-589, Bah-497, Gif-2150, Bah-617, Bah-525 and Bah-496—Table 1) of bivalve shells obtained from beach-rocks in the northern coast of Bahia also were used as evidence for the secondary oscillations of the paleo-sea-level (Martin et al. (1979/1980). Radiocarbon dating of reworked shells provided a time control, whereas primary sedimentary structures within the beach-rocks defined the environment of deposition, with their elevation relative to a present analog defining the paleo-sea-level (Martin et al., 1979a; Flexor and Martin, 1979). These six samples constituted the only evidence, with both time and space controls, of lower sea-levels in the proposed intervals for the secondary oscillations. Martin et al. (2003, Fig. 7 page 107) included another three, non-referenced, samples in the 4100–3800 yr BP time interval, besides removing one sample from the time interval between 2900 and 2700 yr BP.

Based on the textural characteristic of the deposit (a conglomerate, as will be shown below), Flexor and Martin (1979) and Martin et al. (1979a) suggested that deposition occurred in the lower part of the higher beach (Fig. 13). The authors mention that the beach-rock is located approximately at the level of the change in slope on the modern beach (beach step), therefore indicating a similar environment of deposition, or a paleo-sea-level close to the present one. Flexor and Martin's (1979) interpretation of the environment of deposition of the dated shells was based on a morphosedimentary model that sub-divided the beach in four zones, accounting for variations in sediment texture and sedimentary structures (Fig. 13). This model shows the same lateral variation of the beach structures as the Reineck and Singh's (1973) model, although changes in the sedimentary structures occur at different elevations along the profile. For example, the transition between plane-parallel and cross-stratified laminations occurs above the low water level in the model of Flexor and Martin (1979), whereas it is below low water level in the model of Reineck and Singh (1973). Cross-stratified laminations are rather difficult to form on the beach

face, since supercritical flows of the wave swash tend to destroy any cross-stratified laminations produced by a short lived (half tidal cycle), weaker longitudinal flow (see, e.g., Reineck and Singh, 1973; Short, 1984).

In the field site, we have observed two beach-rocks with different matrices on the beach face (Fig. 14). The lower beach-rock is observed from about MLWS to MHWS, and is composed of fine and medium sand displaying trough-cross stratification suggesting a northward-directed paleo-flow. This deposit is interpreted as a nearshore deposit, and indicates a paleo-sea-level at least 1.5 m above the modern one. The upper beach-rock is observed above MSL, and is composed of tabular beds of shell rich, poorly sorted conglomerate up to 20 cm thick, interfingering fine to medium sand layers showing a 4–6° dip, and with seaward inclined plane-parallel laminations. The dated shells mentioned above almost certainly originated from the conglomerate deposit within the upper beach-rock, which is arranged as a seaward inclined surface. We interpret this as a lower beach-face deposit that indicates a sea level at least 1.5 m above present. Therefore, the strongest piece of evidence sustaining secondary sea-level oscillations actually indicates the opposite, i.e., higher sea-levels at the time of the oscillations. In addition, because the

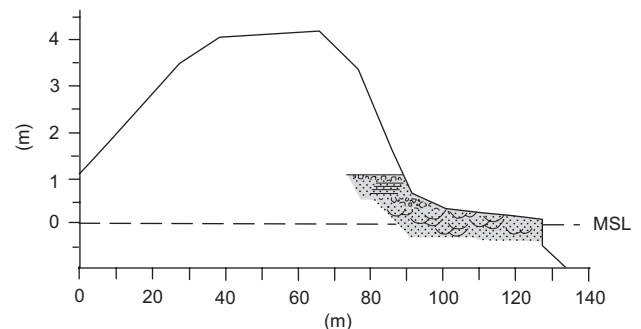


Fig. 14. Cross section of the beach-face south of Arembepé and beach-rock exposures with their primary sedimentary structures identified. The lower beach-rock has trough cross-bed structures, whereas the upper beach-rock, with tabular beds of conglomerates interfingering with plane-parallel laminations of sand (after Lessa and Angulo, 1998). For location see Fig. 1b.

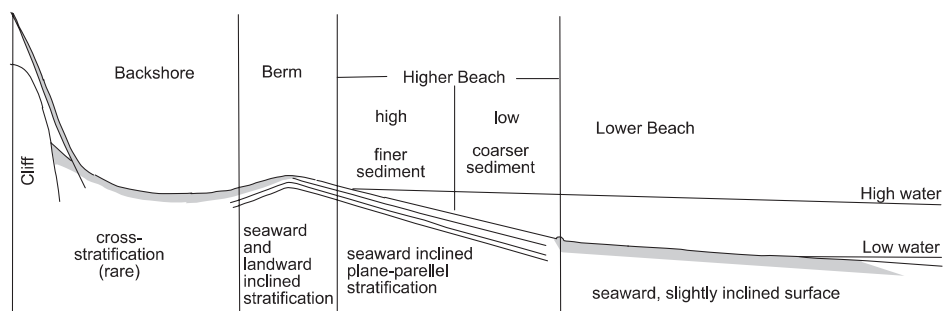


Fig. 13. Schematic beach profile and variations in the sedimentary structures and sediment textures (after Flexor and Martin, 1979).

shells are reworked, they can only indicate the oldest possible age for the formation of the sedimentary deposit (Lessa and Angulo, 1998).

#### 4.3.3. Evidence of lower sea-level derived from vegetal detritus embedded in beach deposits

Martin and Suguio (1975) have found evidence for the 4100–3800 yr BP (4200–3700 cal yr BP) oscillation in a 2–3 cm thick accumulation of plant debris at Barra de Icapara (Figs. 1c and 15a). This debris, dated at  $3370 \pm 100$  yr BP (Gif-3430, 3857–3382 cal yr BP), was interpreted as part of an upper-beach sediment deposit, at a level close to a berm crest. The reasoning behind the interpretation was that debris normally accumulates close to the high-water mark. Because the samples were collected 0.3 m above the present high water level, the paleo-sea-level would have been  $0.3 \pm 0.2$  m (Suguio et al., 1976),  $0.5 \pm 0.3$  m (Suguio and Martin, 1978) or  $0.6 \pm 0.3$  m (Suguio et al., 1980).

The plant debris was covered by a 3 m thick layer of sand with plane-parallel, sub-horizontal stratification and low-angle cross-stratification characteristic of beach face. In accordance with Martin and Suguio (1975), the surface associated with the detritus would have been

buried by foreshore sands in the following transgression (Figs. 15b and c), and then capped by the upper part of the sand sequence during the subsequent regression (Fig. 15d). This evolutionary model is rather implausible given the erosion associated with the ravinement surface during a transgressive episode. It is more likely, based on the sedimentary structures we have observed in the outcrop at the site, that these debris were deposited somewhere in the lower half of the beach face, and are therefore indicative of a higher, and not a lower, paleo-sea-level. In addition, as with the shells from the beach-rock, the dated samples are reworked and only indicate the oldest possible age for the formation of the sedimentary deposit.

#### 4.3.4. Evidence of lower sea-level derived from “mangrove” swamp deposit

Another evidence for the 4100–3800 yr BP (4200–3700 cal yr BP) oscillation is a mangrove swamp deposit from Rio do Fogo region in NE Brazil (Fig. 1a) (Martin et al. (2003)). A layer of muddy sediments with wood fragments and shells of *Lucina pectinata* outcrops on the beach face between low- and high-tide levels. The deposit, positioned slightly below the upper surface of modern mangrove swamp, was interpreted as a mangrove deposit and a relative sea-level slightly below the present level at the time of deposition. A wood fragment from this outcrop was dated at 4200–4096 cal yr BP (Martin et al., 2003).

Bezerra et al. (2003) suggest that, between 4200 and 2100 cal yr BP, sea level was continuously low (2 to –1 m) (Fig. 16), along a 200 km long stretch of coastline in Rio Grande do Norte (including Rio do Fogo). A sample of peat apparently obtained from the same outcrop visited by Martin et al. (2003) was dated at  $3550 \pm 60$  yr BP (BETA-121263, 3580–3320 cal yr BP), and would indicate a paleo-sea-level of  $0.2 \pm 1.0$  m. Bezerra et al. (2003) argue that the paleo-sea-level behavior during the late Holocene in this coast has been largely influenced by tectonics and possibly wind-wave patterns. Therefore, the peat (or mangrove deposit by Martin et al., 2003) deposit cannot be used to endorse the existence of high-frequency oscillations.

#### 4.3.5. Evidence of paleo-sea-levels higher than present at the time of the suggested regressions (4200–3700 and 2700–2100 cal yr BP)

Several paleo-sea level indicators pointing to sea level higher than present in the intervals of the proposed high-frequency oscillations, have been published in the literature (Table 1 and Fig. 17). Forty-six in situ, more reliable indicators are carbonate algae, corals, vermetids and oysters, whilst 38 less reliable indicators are related to wood fragments and mollusk shells (normally *A. brasiliensis*) in paleo-estuarine sediments and plant detritus and shells in barrier sediments (Table 1).

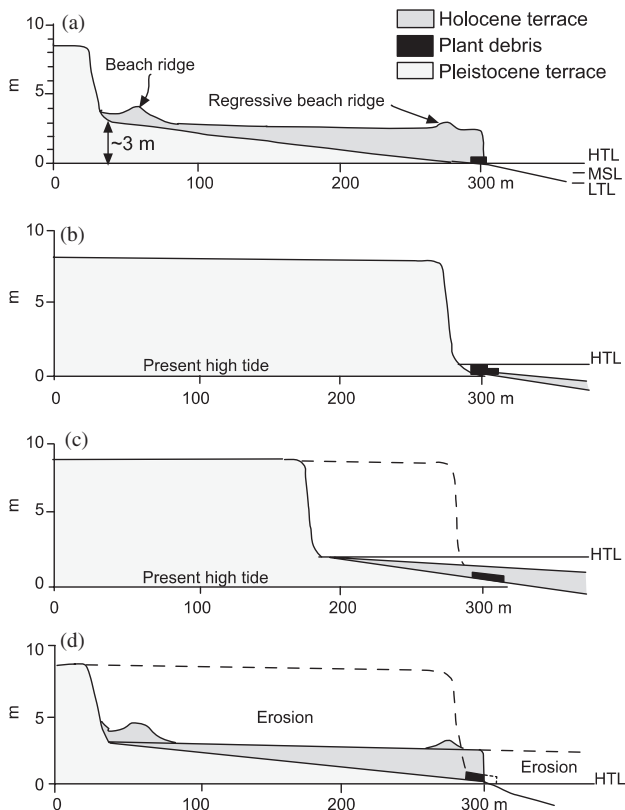


Fig. 15. Schematic cross sections of Barra de Icapara south of state of São Paulo: (a) present stage, (b) plant debris deposited during the transgressive period, (c) plant debris fossilization stage and (d) present erosion of Holocene terrace (after Martin and Suguio, 1975). For location see Fig. 1c.

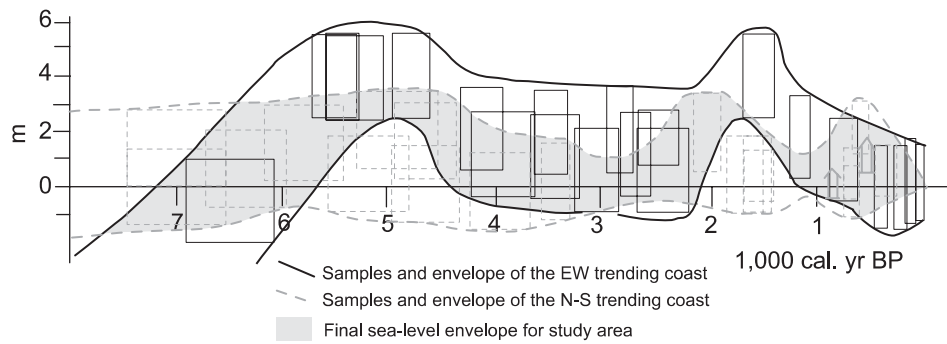


Fig. 16. Sea-level envelopes for two coastal sectors in the State of Rio Grande do Norte (after Bezerra et al., 2003).

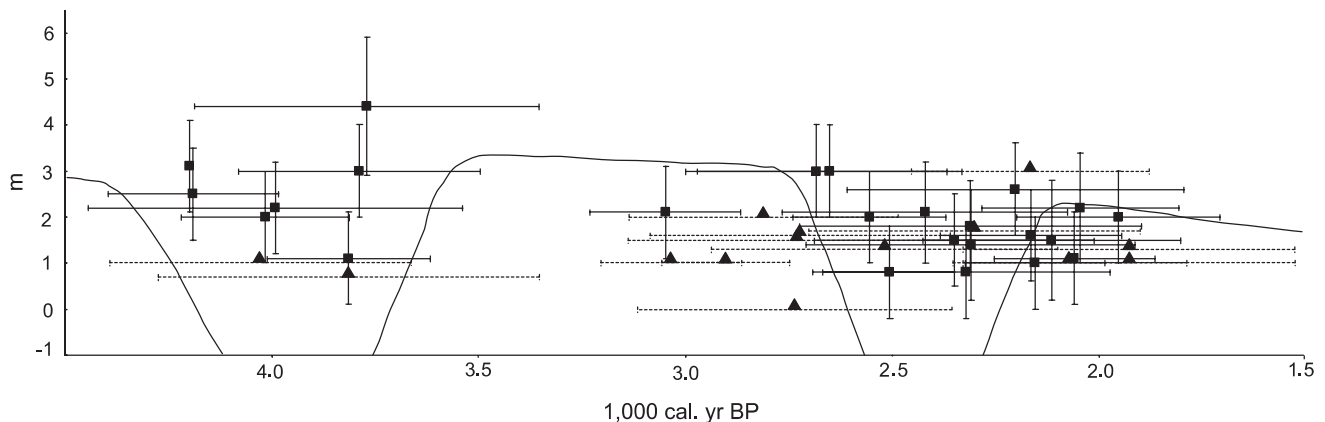


Fig. 17. Distribution of more reliable paleo-sea-level indicators showing higher sea-levels during the time of the supposed negative high-frequency oscillations: (i) algae, corals, oysters and vermetid that indicate a minimum paleo-sea-levels (triangle and dashed line); and (ii) vermetids that indicate paleo-sea-levels with margin of error of  $\pm 1.0$  m (squares and full line).

Fourteen paleo-sea-levels between  $0.8 \pm 1.0$  and  $4.4 \pm 1.0$  m are indicated for the interval 4200–3700 cal yr BP, whereas 21 paleo-levels between  $0.8 \pm 1.0$  and  $3.0 \pm 1.0$  m exist for the interval 2700–2100 cal yr BP.

In Cananéia, Ybert et al. (2003) found, by means of diatoms, that “the study area was occupied by a lagoon from at least 4900 up to ca. 3470 cal yr BP” when “sea-level was at least 1.2–2 m higher than at present”. The region subsequently underwent a “continuous fall of the sea-level”.

Regarding the above discussion it is concluded that none of the paleo-sea-level indicators used to support the high-frequency sea-level oscillations, with amplitudes of more than 1 m, are reliable or have been correctly interpreted. On the other hand, there are several reliable indicators that sustain a higher-than present paleo-sea-level in the time interval of the suggested oscillations.

## 5. Final remarks

The discussions above show that a significant part of the data set used to investigate crucial points of the

Brazilian sea-level history in the Holocene are problematic as sea-level indicators. The great majority of the data analyzed (amounting to about 70% of the data set) are either non-conclusive or have been misinterpreted. This has led to several doubtful or erroneous paleo-sea-level results. At this point, we believe that a good approximation of a general sea-level history can be best achieved with the use of vermetids, which provide the most reliable estimate of age and elevation of former sea level.

Vermetid possesses several attributes that make them ideal for paleo-sea-level reconstruction. Laborel (1979, 1986) indicated that reefs of the vermetid *Petalococonchus* (*Macrophragma*) *varians* could be used to assess paleo-sea-levels with a precision of  $\pm 0.1$  to  $\pm 1.0$  m along the Brazilian coast, depending on the wave-energy level of the coast (higher waves imply in less precision). Angulo et al. (1999), after considering three other sources of errors in the evaluation of the paleo-sea-level with fossil vermetid (remains may not correspond to the upper limit of the formation, changes in the hydrodynamic characteristics of the coast through time, and reference used to assess the vertical displacement of the vermetid reef), suggested that a precision of  $\pm 1$  m should always be used.

Based on the existing data, it is not possible to suggest that the elevation of the Holocene highstand has been significantly different along the Brazilian coast between Pernambuco (8°S) and Paraná (26°S), because the margins of error of the paleo-sea-level indicators are larger than the suggested elevation differences. A regional difference is only detectable in the south of the State of Santa Catarina (28°S). Hence, when dealing with the calibrated vermetid radiocarbon datings, data from the two regions were separated in order to define regional trends (Fig. 18). Eight possible outliers were identified in Fig. 18 (samples Bah-1129, Bah-1152, Bah-1221, Bah-711, Bah-567, Bah-1586, Bah-1236 and GX-14061). These outliers plot outside the 2 standard deviation envelope around the MSL trend for their respective regions, calculated by a 5th-order polynomial

(Fig. 18). With the removal of these outliers from the data set a new trend is then drawn for both regions (Fig. 19).

The highstand elevation does not appear to have exceeded 4m to the north of Santa Catarina, where maximum Holocene sea level was about 2.1m. This highstand may have lasted for a couple of hundreds of years between 5000 and 5800 cal yr BP, without the distinct peak (Fig. 4) that characterizes the sea-level curves in Martin et al. (2003). Similar elevations for the PSLM are indicated in South Africa (3.5 m, Ramsay and Cooper, 2002), northeastern Australia (1.7 m, Larcombe et al., 1995), southeast Australia (2 m, Baker et al., 2001) and south Australia (1–3 m Belperio et al., 2002), suggesting that broadly similar hydro-isostatic adjustments (Chappell et al., 1982) may have occurred

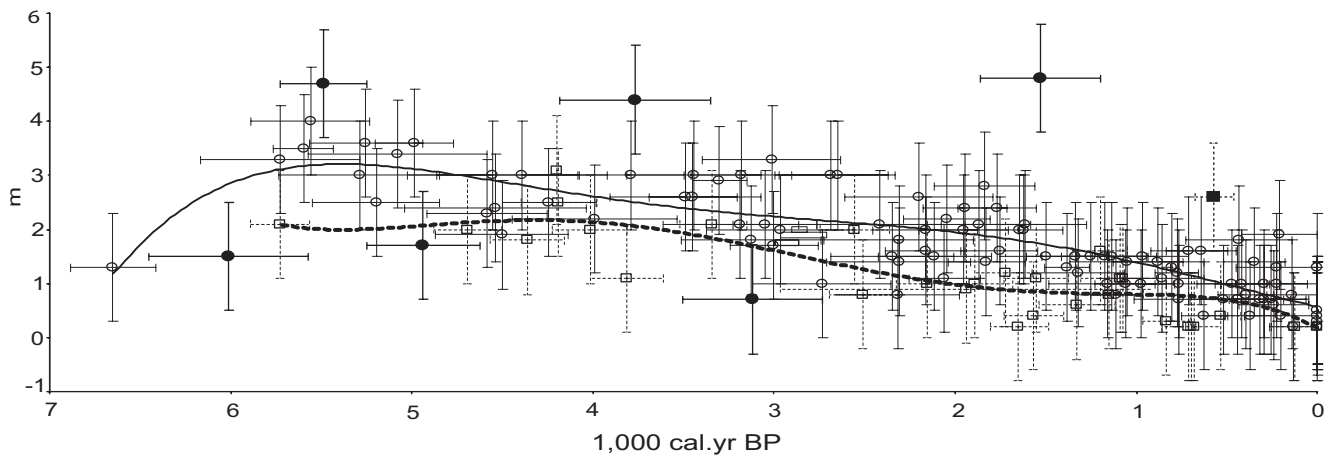


Fig. 18. Scatter of the vermetid samples dated along the Eastern Brazilian coast with their margin of error. A 5th-order polynomial was fit within the indicators with vertical margins of error, showing an average paleo-sea-level trend. Data from the southern State of Santa Catarina are identified by empty squares and dashed lines, whereas the remaining data have empty circles and solid lines. Outliers within the data set are shown with full circles and squares.

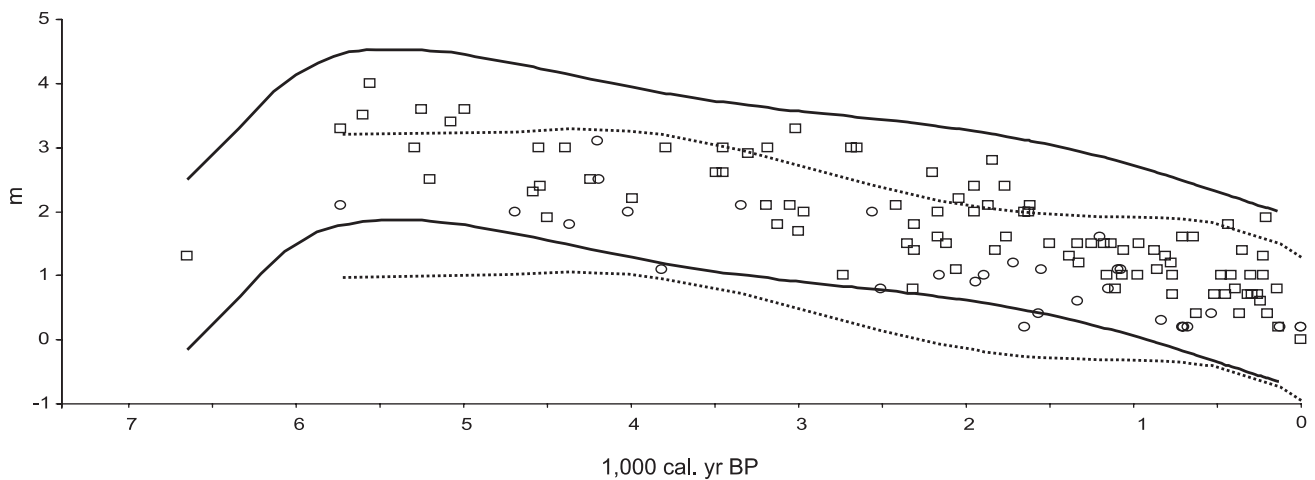


Fig. 19. Sea-level envelop and paleo-sea-level reconstructions for the Brazilian coast north 28° (solid line and squares) and south of 28° (dashed line and circles), based on vermetid samples and with outliers removed.

throughout the Southern Hemisphere, as predicted by global isostatic models (Clark et al., 1978; Lambeck and Nakada, 1990; Fleming et al., 1998; Peltier, 1999; Milne et al., 2005). For the South American coast, model results by Milne et al. (2005) suggest that the highstand occurred at 7000 cal yr BP, reaching ~4 m in Pernambuco and Rio de Janeiro (Fig. 20a), and ~2.5 m in Santa Catarina (Fig. 20b). The model suggests a period of relative sea stabilization between 7000 and 5000 cal yr BP falling steadily after then. The time of the predicted highstand departs from that suggested by the data (between 5000 and 5800 cal yr BP, Fig. 19). This difference is ascribed to the presence of only one sample older than 6000 cal yr BP in the data set (Fig. 18), and cannot be taken as representative. If the sample is removed, the predicted paleo-sea-level older than 5800 cal yr BP becomes a fine extension of the observed trend (Fig. 20).

It is not possible to affirm that the MSL-crossing time occurred at different times along the coast. Information obtained from vermetids allows us to suggest that the MSL-crossing time occurred as late as 6500 cal yr BP. On the other hand, information derived from wood debris and shell samples embedded in coastal-plain sediments, indicate that the MSL-crossing time took place as early as 7550 cal yr BP. This last date agrees well with the crossover time predicted by Milne et al. (2005) (Fig. 20), which we suggest can be taken as a reference for the relative sea-level variation in the last 10,000 cal yr BP.

There is no reason to assume any Holocene change of the geoid in eastern Brazil, as advocated by Martin et al. (1985) and implied by Martin et al. (2003). Differences between paleo-sea-level trends in Brazil only occur in areas undergoing localized tectonic subsidence, which is the case of the State of Para, in north Brazil (Fig. 1a) (Behling et al., 2001; Cohen et al., 2005; Souza Filho et al., in press), State of Rio Grande do Norte (Bezerra et al., 2003) and the surroundings of Baía de Todos os Santos (Martin et al., 1984a; Carvalho, 2000). In the

State of Pará, sea level may have never been higher than the current one throughout the Holocene (Souza Filho et al. in press).

According with the data set, but differently to what is suggested by the geophysical simulation, sea level apparently withstood an elevation between 2 and 3 m until about 2000 cal yr BP, as suggested by the envelope in Fig. 19 and by diatom data from Cananéia (Ybert et al., 2003). Coincidentally, higher mid-Holocene sea-level was sustained up to 2500 yr BP in Australia as suggested by Chappell (1983), Larcombe et al. (1995) and Lessa and Masselink (2005). Uneven rates of sea-level fall in the late Holocene, with higher rates in the last 2000 years, would have important implications to the understanding of the evolution of the coastline, as it could impact the rate of shore-normal sediment transfer from the inner-shelf toward the shoreline.

The evidence for high-frequency (300–600 years) sea-level oscillations in the late Holocene are inconsistent, as initially discussed by Angulo and Lessa (1997) and Lessa and Angulo (1998), and are contradicted by the widespread evidence of higher paleo-sea-levels in the time period of the alleged oscillations (4200–3700 and 2700–2100 cal yr BP) (Fig. 17). In Rio Grande do Norte, Bezerra et al. (2003) found no record of the oscillations in the expected time frames, a disagreement that was ascribed to recent tectonism or changes in the wind/wave climate. In fact, the paleo-sea-level patterns observed in two sectors of a 300 km long coastal zone differ significantly (Fig. 16), and suggests important tectonic controls (the area is well known for its seismic activity—DeMets et al., 1990; Bezerra and Vita-Finzi, 2000).

The secondary oscillations in Brazil are suggested to have occurred along a latitudinal span of about 25°, between Rio Grande do Norte in the north and Laguna in the south (Suguio et al., 1985; Martin et al., 2003). These oscillations, with an amplitude of 5 m extending over such a large area, would be characterized by rise and fall rates between 16 and 32 mm/year, which is three

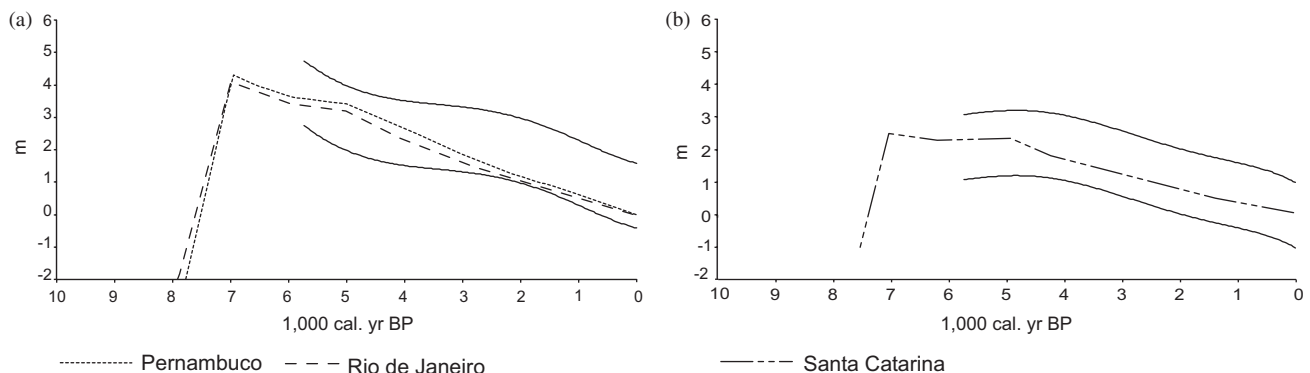


Fig. 20. Sea level envelopes for the region between Pernambuco and Paraná (a), and the southern State of Santa Catarina (b), plotted with the paleo-sea-level behavior predicted by the geophysical simulations made by Milne et al. (2005).

times higher than the suggested rising rates (10 mm/year) of the fastest sea-level rise period (15000–8000 cal yr BP) in far-field sites (Fleming et al., 1998). Such oscillations would be expected to leave records in neighboring regions, either to the north or south of the established limits. An inspection of other published curves in South America shows that there is hardly any coincidence with the paleo-sea-level pattern proposed in Argentina or in Suriname (Fig. 21).

Throughout the Southern Hemisphere there appears to be a broadly consistent sea-level trend, with a smooth or gently oscillating decline of sea level after a Holocene maximum between 2 and 3.5 m. It cannot be ruled out, however, that the late Holocene sea-level fall in Brazil underwent small-scale (few decimeters) oscillations, such as those proposed by Baker et al. (2001) for SE Australia. However, to test this hypothesis we need to develop more precise indicators. A clear example of the limited resolution of current approaches is that the youngest samples of vermetids suggest paleo-sea-levels between 0 and 1 m in the last 500 years (Fig. 18). Although current MSL is within the margin of error of all these samples, the mean position is clearly over-estimated. This may also be the case for the Suriname curve in Fig. 21.

The proposition of secondary sea-level oscillations along the Brazilian coast in the late Holocene has caused problems in the interpretation of the coastal geomor-

phology and the sedimentary record, especially due to the premise that such oscillations would be able to develop new strandplain or barrier/lagoon systems. At the time when the chronology of the coastal landscape was first being uncovered, and in the light of the then recently proposed sea-level curves, some Brazilian researchers mistakenly interpreted the Pleistocene barriers/strandplains as of Holocene age, associated with Holocene highstand. In the same way, the real Holocene highstand barrier/strandplains were interpreted as resulting from a transgression at 3700 cal yr BP (Martin and Suguio, 1976; Maia et al., 1984; Muehe and Ignarra, 1984; Neto, 1984; Perrin, 1984; Turcq et al., 1986; Muehe and Corrêa, 1988). More recently, Gómez et al. (2005) argued, on the basis of a single radiocarbon date obtained from an underwater sedimentary deposit in Bahía Blanca estuary (Argentina, Fig. 1a), that large scale late Holocene sea-level oscillations also occurred in Argentina, thereby contradicting the majority of the studies conducted in that country to date.

Although more than 1000 radiocarbon dates from the Brazilian coast exist and many hundreds of paleo-sea-level assessments have been performed, at present we can say that the Brazilian Holocene sea-level history is still far from complete. The current data set suggests a progressive decline, with uneven rates, of the relative sea-level since the mid-Holocene highstand. Higher resolution studies of the sedimentary record (especially

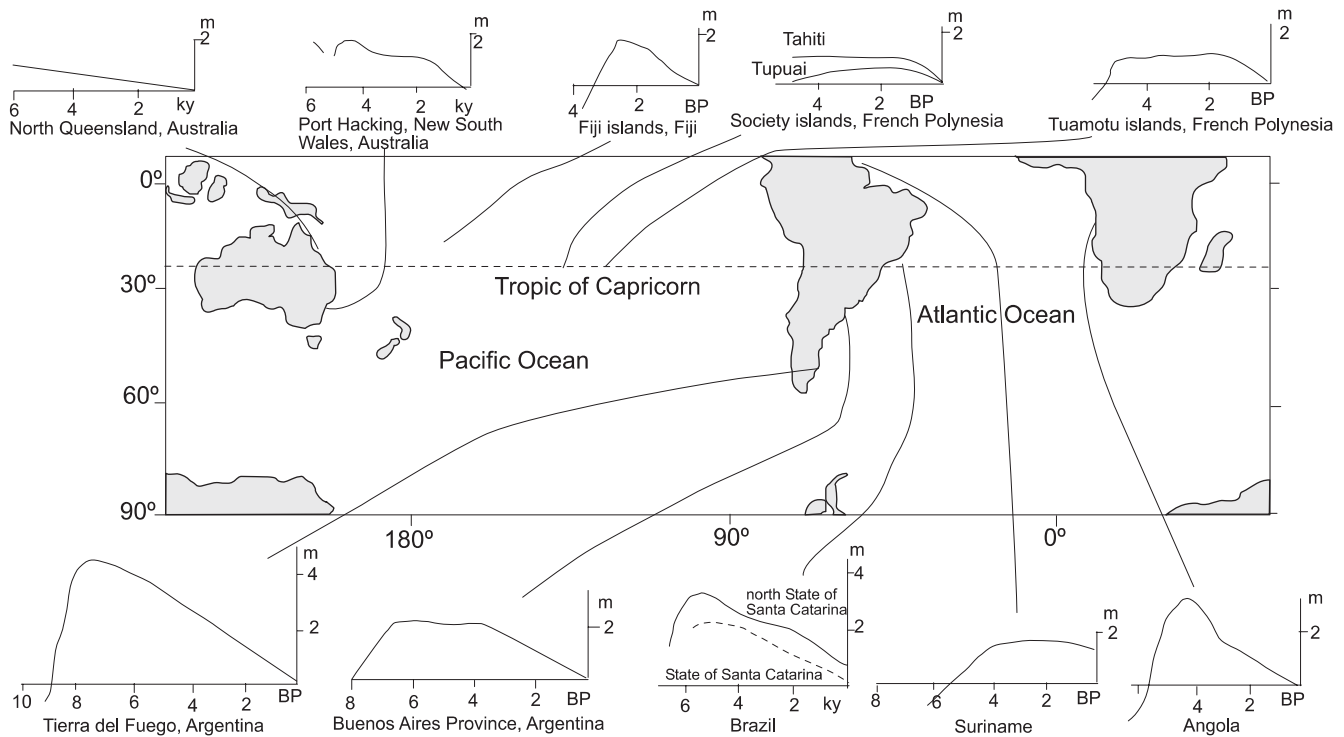


Fig. 21. Sea-level curves for the last 6000 years in the Southern Hemisphere. All curves present similar elevations and show a gradual decline of sea-level after the highstand, modified from Isla (1989) and Angulo and Lessa (1997). The curves from southeast Australia and Brazil were drawn with calibrated years, the other curves with <sup>14</sup>C years BP.

biogenic formations) are necessary to obtain a clearer picture of the regional differences and possible small scale oscillations as those found by Baker et al. (2001) in SE Australia. Perhaps even more important are investigations on the continental shelf, due to a complete lack of sound information on the sea-level history prior to 7000 years ago.

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### Appendix A. Supplementary Materials

The online version of this article contains additional supplementary data. Please visit [doi:10.1016/j.quascir-ev.2005.03.008](https://doi.org/10.1016/j.quascir-ev.2005.03.008).

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