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Chronostratigraphy and radiocarbon age inversion in the Holocene regressive barrier of Paraná, southern Brazil

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ABSTRACT

Twenty-two ^{14}C datings were performed at the central sector of the Paraná coast to define Holocene regressive barrier evolution. The barrier Pleistocene substratum was ascribed an age between 40 400 and 30 000 yr BP, but it can also represent the penultimate sea level highstand during marine isotope stage 5e. The Holocene barrier samples provided ages between 8542–8279 and 2987–2751 cal yr BP, and showed at least six age inversions that were related to age differences between in situ or low-distance transported shells or trunk fragments, and high-distance transported vegetal debris, wood fragments and organic matter samples. The regressive Holocene barrier age was 4402–4135 cal yr BP near the base, and 2987–2751 cal yr BP near the top. Most of the vegetal remains were transported by ebb tidal currents from the estuaries to the inner shelf below wave base level during the mid-Holocene highstand; they were transported onshore by storm waves and littoral currents during the sea level lowering after the sea level maximum, and were deposited mainly as middle shoreface swaley cross-stratification facies.

1. Introduction

Radiocarbon dating of samples from coastal regions has been used for many different purposes worldwide. It has been used on Brazilian coastal regions to determine paleo-sea levels (a compilation of which is presented in Angulo et al., 2006) and to distinguish Holocene from Pleistocene barriers (e.g., Suguio and Martin, 1978; Martin et al., 1979/80, 1988, 1997, Dominguez et al., 1990; Angulo et al., 2002). Systemic radiocarbon dating has also contributed to the understanding of deltaic (e.g., Dominguez et al., 1981; Martin et al., 1983, 1984; Dominguez and Wanless, 1991) and barrier depositional system evolution (e.g., Suguio et al., 1976; Suguio and Martin, 1978; Bittencourt et al., 1979; Vilas Boas et al., 1979; Martin et al., 1979; Martin et al., 1979/80; Bittencourt et al., 1983; Suguio et al., 1985; Martin et al., 1988, Martin et al., 1996, 1997; Bezerra et al., 2003; Buynevich et al., 2005 and a recent book by Dillenburg and Hesp, 2008, that present a synthesis of Holocene barrier evolution of different Brazilian coastal sectors).

Many difficulties related to the interpretation of radiocarbon age result from the dating of diverse samples, which include heterogeneous terrestrial remains (trunks, wood fragments, vegetal debris and organic mud) and coastal marine debris (shells, shell fragments, corals and calcareous algae), either in situ or transported, from natural (beach, lagoon and reef) or archaeological (shell midden) deposits. Some authors stress that the problem of interpretation is biased due to sample contamination (Flexor and Martin, 1979; Angulo and Pessenda, 1997), but little attention was given to the problem of dating transported material (Isla and Espinosa, 1998; Angulo et al., 1999, 2002; Rodriguez et al., 2000).

At the Paraná coast in southern Brazil, most of the dated shells were sampled from paleolagoonal sediments (Angulo et al., 2006). At the Holocene barriers of Paraná, the dated samples correspond mainly to vegetal debris because they were collected at the upper part of the barrier where the highly permeable sandy sediment, which is associated with acidic soil and ground water, leads to dissolution of carbonate shells, therefore only shell moulds are usually found. Carbonate dissolution occurs above lower groundwater where oxidant conditions prevail. Below lower groundwater level, the shells are well preserved, including organic mollusk tissues. At two sand quarries in the Paraná regressive barrier, abundant shells, vegetal debris and organic mud at different stratigraphic intervals were dated (Fig. 1).

The aims of this paper are to discuss problems related to ^{14}C age interpretation of materials of different nature, to present a chronological

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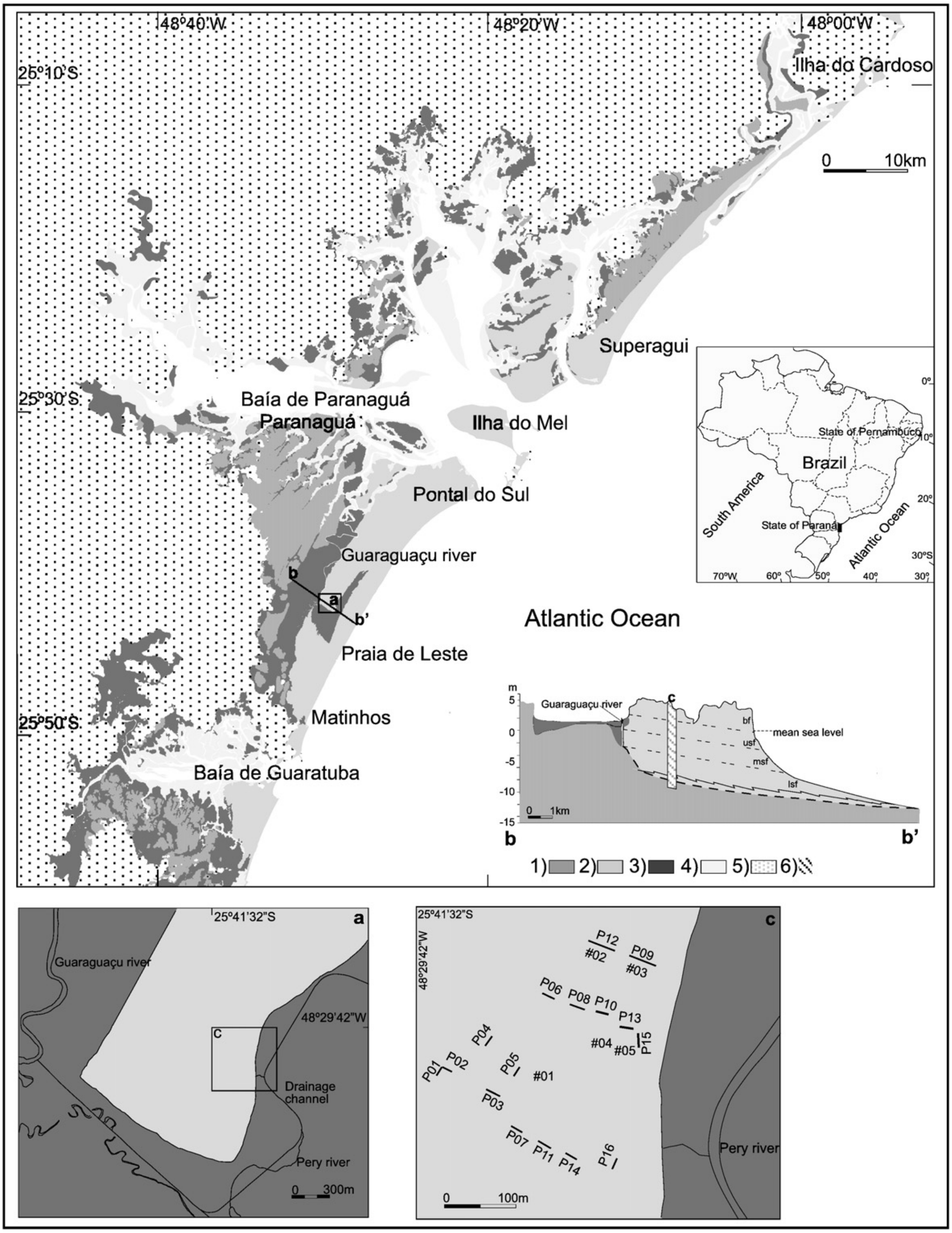


Fig. 1. Location of the study area: (1) Pleistocene barrier; (2) Holocene barrier; (3) paleolagoonal sediments; (4) present tidal flat; (5) other units; (6) sand quarries.

characterization of the regressive barrier of the central sector of the Paraná coast and to interpret the cause of age inversion in its stratigraphic record. This paper is mainly based on the results of the PhD dissertation of Souza (2005).

2. Materials and methods

The work was based on the description of 16 surface stratigraphic profiles and on the evaluation of samples taken from five vibrocorer drillings (Figs. 1 and 2). The outcrop descriptions and drillings were performed when the sand quarries were being exploited and the groundwater level was lowered by pumping. This provided an excellent opportunity to describe facies that were only accessible in former work by cores (Lessa et al., 2000). Presently, the quarries are filled with water and only the upper parts of the profiles are above the water level.

There were 22 samples that were taken and dated from outcrops and cores (Fig. 2); these samples included juvenile and adult shells, shell fragments, vegetal debris, wood remains and organic mud. Nineteen of the samples were dated by the conventional radiocarbon method at the Nuclear Energy Center for Agriculture of the University of São Paulo (CENA-USP), while the other three samples were dated by AMS (Accelerator Mass Spectrometer) at the Geochron Laboratories of

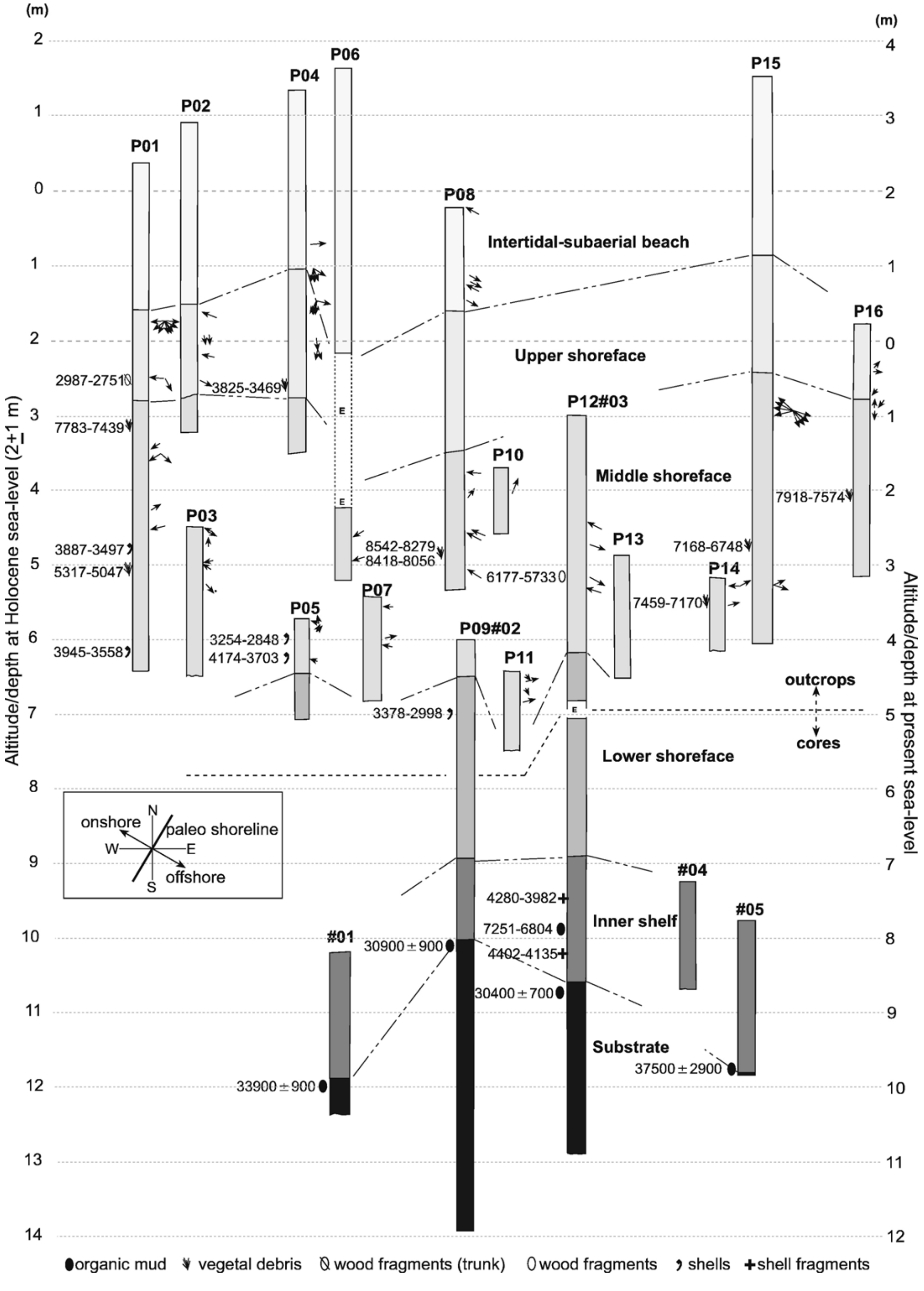


Fig. 2. Schematic stratigraphic profiles of the Holocene regressive barrier at Praia de Leste.

Krueger Enterprises Inc, Cambridge MA, USA. The results were calibrated using the Calib Radiocarbon Calibration 5.0 program (Stuiver and Reimer, 1986) and were corrected to a ΔR of 8 ± 17 yr, as defined in Angulo et al. (2005) for southern Brazil. Ages over 30 000 yr BP were not calibrated, because such values fall beyond the range of the calibration program.

3. Results

According to the obtained ages, the 22 dated samples were grouped in the Pleistocene (ages between 37 500 ± 2900 and 30 900 ± 900 yr BP) and Holocene (ages between 8542–8279 and 2987–2751 cal yr BP) (Tables 1 and 2).

The Pleistocene samples correspond to massive organic mud lying between depths of 8 and 10 m below the present mean sea level, with occasional shell fragments and vegetal debris (Fig. 2). This mud layer corresponds to the upper part of the Pleistocene substratum immediately below the Holocene barrier limit (Fig. 3). The characteristics of this layer, mud and fine to very fine sand sediments with bioturbated wavy and linsen lamination underlying the organic mud layer enclosing fresh water Thecamoebia (*Centropyxis aculeata*) and brackish water and mangrove affinity

Table 1
Radiocarbon datings of the Pleistocene substratum

Location	Depth[a]	Sample id[b]	Conventional ^{14}C yr BP[c]	δ^{13}C	Sample material
#02	8.2–8.1	CENA-475	30900±900	−22.30	Organic mud
#03	8.8–8.7	CENA-476	30400±700	−25.00	Organic mud
#05	9.8–9.7	CENA-369	37500±2900	−25.70	Organic mud
#01	10.1–10.0	CENA-368	33900±900	−26.00	Organic mud, vegetal debris, shell fragments

[a] Related to the present mean sea level.
[b] CENA — Centro de Energia Nuclear na Agricultura.
[c] δ^{13}C corrected.

foraminifera (*Blysmasphaera brasiliensis*) species, suggest that it is a lagoonal facies (Fig. 4).

Table 2
Radiocarbon datings of the Holocene barrier

Location	Depth (m)[(a)(b)]	Sample id[c]	Conventional ^{14}C yr BP[d]	cal yr BP[e]	δ^{13}C	Sample material
P01	0.5	CENA-364	2750±60	2987–2751	−26.80	Wood fragment (trunk)
P01	1.2–1.1	CENA-365	6750±90	7783–7439	−27.60	Vegetal debris
P04	1.0–0.7	CENA-370	3380±60	3825–3469	−28.60	Vegetal debris
P16	2.2–2.1	CENA-358	6860±80	7918–7574	−27.50	Vegetal debris
P01	2.8–2.75	CENA-380	3770±70	3887–3497	+1.10	Young and adult shells[f]
P15	2.8–2.75	CENA-301	6090±80	7168–6748	−20.05	Vegetal debris
P08	2.85–2.8	CENA-362	7580±80	8542–8279	−27.90	Vegetal debris
P08	2.85–2.8	CENA-363	7470±80	8418–8056	−27.50	Vegetal debris
P01	3.3–3.2	GX-29115[g]	4540±40	5317–5047	−25.60	Vegetal debris
P12	3.2–3.1	CENA-432	5160±70	6177–5733	−28.70	Wood fragments
P14	3.5–3.4	CENA-360	6410±80	7459–7170	−28.00	Vegetal debris
P01	4.3	CENA-366	3810±70	3945–3558	+0.50	*Anomalocardia brasiliana* shells
P05	4.4	CENA-300	3960±80	4174–3703	+0.99	*Tivela foresti* shell with periostracum
P05	4.0	CENA-385	3240±70	3254–2848	−0.40	*Amiantis purpuratus* shell
P09	5.0	CENA-473	3360±70	3378–2998	−0.90	*Tivela foresti* shell; shell fragments[(g)]
#03	7.67	GX-30703[g]	4100±40	4280–3982	−0.10	*Strigilla* sp. shell fragments
#03	7.9–7.8	CENA-499	6150±80	7251–6804	−25.30	Organic mud
#03	8.30	GX-30704[g]	4190±40	4402–4135	−2.80	*Tellina* sp. Shell fragments

[a] Related to the present mean sea level.
[b] Paleo-depth during inferred barrier sediment deposition time (4402–4135 to 2987–2751 cal yr BP) was estimated by considering a paleo sea level 2.0±1.0 m above present mean sea level (Angulo et al., 2006).
[c] CENA — Centro de Energia Nuclear na Agricultura, GX — Geochron Labs.
[d] δ^{13}C corrected.
[e] Calibrated age.
[f] With adult and young shells of *Divaricella quadrisulcata*, *Tivela isabelleana* and *Tivela fulminata*, and fragments of *Anadara* sp, *Tivela* sp, *Chione* sp or *Anomalocardia brasiliana*, *Divaricella quadrisulcata*, Ostreidae, Echinodermata (probably *Mellita quinquesperforata*).
[g] AMS datings.

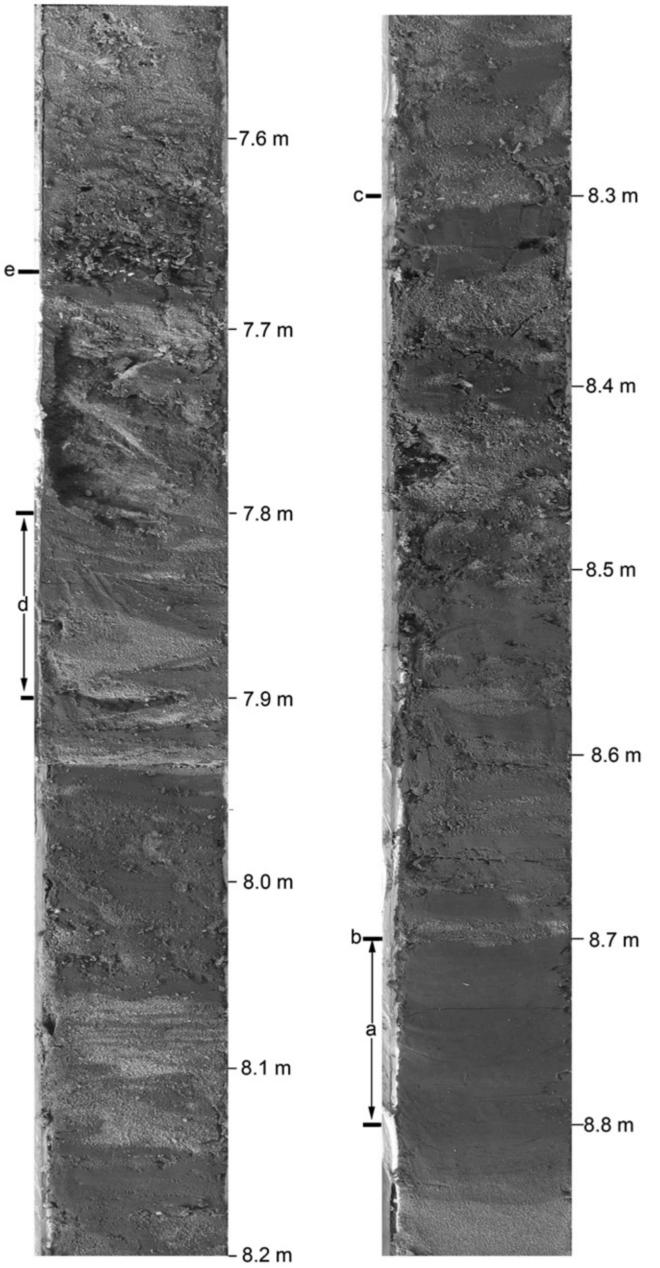


Fig. 3. Core #03 section: a) organic mud, 30400±700 conventional ^{14}C yr BP; b) Pleistocene–Holocene boundary; c) *Tellina* sp. shell fragments, 4402–4135 cal yr BP; d) organic mud, 7251–6804 cal yr BP; e) *Strigilla* sp. shell fragments, 4280–3982 cal yr BP (for location, see Fig. 2).

The Holocene samples correspond to mollusk shells and shell fragments (7 samples), vegetal debris (8 samples), wood and trunk fragments (2 samples) and organic mud (1 sample) collected from depths between 1.1 m and 8.1 m below the present mean sea level, encompassing sediments deposited from shoreface to the inner shelf (Fig. 2). The dating results indicate two main groups of samples: (a) the shell and shell fragments from the middle to lower shoreface and inner shelf with ages ranging between 4402–4135 and 3254–2848 cal yr BP, and (b) those consisting of vegetal debris, trunk and wooden fragments from the upper to middle shoreface, with ages between 8542–8279 and 2987–2751 cal yr BP (Figs. 2 and 5).

The age distribution reveals at least six age inversions in the stratigraphic profiles. Inversions in five cases are characterized by ages from vegetal remains/shell pair samples (2 at profile P01, 1 at P04/P04, 1 at P08/P09#02, 1 at P12#03, Fig. 2). In one case, the inversion is characterized by an organic mud/shell pair (at the profile P12/#03 lower part, Fig. 2).

Two of the mollusk shells, classified as *Tivela foresti* (CENA-300) and *Amiantis purpuratus* (CENA-385), show articulated valves with preserved ligament and periostracum. The periostracum and the

Fig. 4. Pleistocene wavy and linsen facies (core#02) (for location, see Fig. 2).

ligament that maintained the valves articulated after specimen death are organic tissues that decompose within a few weeks after exposure to oxidant conditions. Therefore, the preservation of these tissues indicates little or no transportation and quick burial (Fig. 6). The two other shell samples are composed of several very fragile young and adult shells, some of them articulated, with no abrasion marks, which again indicate little or no transportation (CENA-380 and CENA-473; Fig. 7). One sample is a trunk fragment with preserved cortex that indicates little transportation (CENA-364, Fig. 8). These characteristics suggest a short time between specimen death, deposition and burial. Otherwise, wood fragments show rounded corners that indicate long transport and reworking (Fig. 9). The abraded wood fragments and other vegetal debris were deposited in swaley cross-stratification generated by storm waves (Figs. 10, 11 and 12) and sigmoidal cross-stratification generated by coastal currents (Fig. 13), which also suggest transport and reworking.

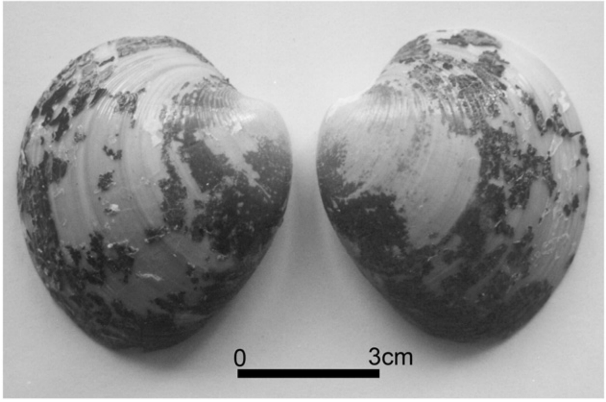


Fig. 6. *Amiantis purpuratus* specimen with articulate valves and preserved periostracum (3254–2848 cal yr BP, CENA-385; periostracum partially damaged after exposure of the sample to oxidant conditions; for location see Fig. 2).

All inversions are related to older age from vegetal debris, organic mud or wooden fragment samples compared with the younger ages from shell fragments. These results suggest that vegetal debris and organic matter, as the abraded wooden fragments, were transported and that the terrestrial organisms' times of death were older than the times of deposition.

4. Discussion

The facies that occurred at 8 to 12 m depth below present sea level, from where the Pleistocene samples (40 400 to 30 000 yr BP) were

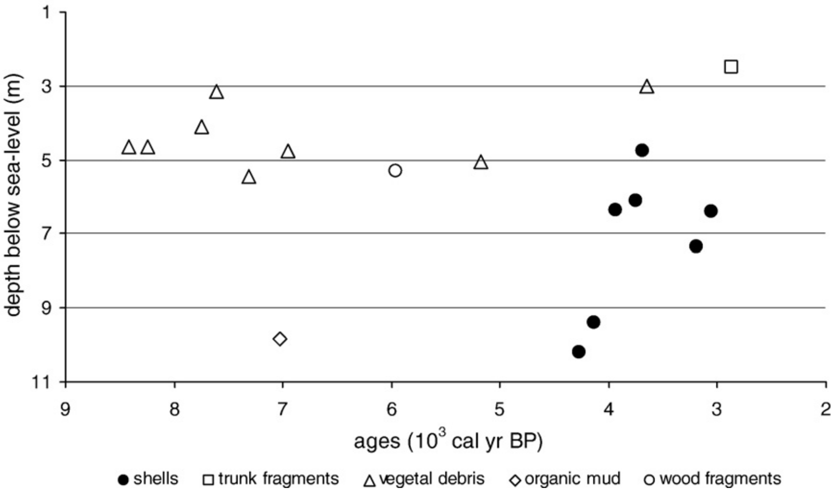


Fig. 5. Relationship between ages and depths of samples from the Holocene regressive barrier.

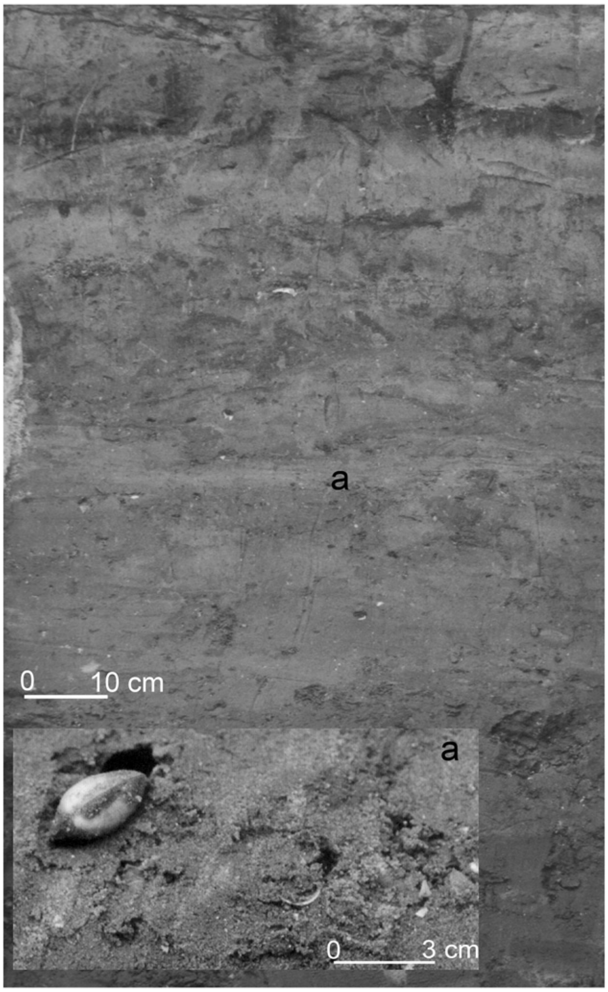


Fig. 7. Fragile articulate valves *Tivela foresti* juvenile specimen recovered from lower shoreface facies (3378–2998 cal yr BP, CENA-473; for location, see Fig. 2).

taken, were interpreted to be lagoonal. Lagoonal facies at these depths imply that the sea level at that time was similar to or about 10 m lower than the present sea level. However, according the most accepted global eustatic curves, the paleo-sea level 30 000 to 40 000 yr BP was at least 45 m lower than the present level (Pirazzoli, 1996; Lambeck and Chappell, 2001, Waelbroeck et al., 2002, Peltier and Fairbanks, 2006). Two explanations can be given for this contradiction. One is that the samples are contaminated by new carbon. In that case, the lagoonal sediments could correspond to isotope stage 5e deposits, which border the most landward barrier Holocene deposits (Fig. 1) and are widely exposed along the eastern Brazilian coast (Martin et al., 1979/80; Suguio et al., 1980; Martin et al., 1982; Martin and Suguio, 1989; Martin et al., 1996, 1997; Angulo et al., 2002). The other explanation is that the samples are not contaminated and sea level during that period was higher than proposed. Recent work on the southern Brazilian inner continental shelf Klein (2006) and Mahiques et al. (2007) suggest that the sea level at that time could have been about 10 m below the present level. Further work is necessary to resolve this issue.

On the central portion of the Holocene regressive barrier of Paraná, radiocarbon ages of shells and trunk fragment samples would represent the ages of regressive barrier formation that correspond to 4402–4135 cal yr BP near the barrier base and 2987–2751 cal yr BP near the top (Fig. 2). On the Paraná coast, the sea level at 7500 yr BP would have been similar to the present current level, with a maximum of 3.0±1 m between 7000 and 5000 yr BP and a lowering until the present (Angulo et al., 2006). The barrier ages fit with the sea level curve and correspond to the lowering that followed the Holocene sea level maximum (Fig. 14).

The abraded wooden fragments, vegetal debris and organic mud give ages that are hundred to thousands of years older than the shells (Fig. 5). These age differences suggest that vegetal remains were deposited hundreds or thousands of years after the vegetal specimens died. The vegetal remains correspond to terrestrial vascular plants and they were frequently found to be associated with swaley cross-stratification (Fig. 15). Such stratification was interpreted to be the result of oscillating fluxes induced by storm waves with an important NW unidirectional traction component that was normal to the paleo-coastline (Figs. 2 and 16). The vegetal remains could have been transported from the near estuaries to the inner shelf when the sea level was similar to or higher than the present one. In the shoreface and inner shelf Holocene barrier regressive facies, the foraminifera and ostracod assemblage indicate a shallow marine environment, but there some estuarine species were also found that would have been transported from the estuaries to the inner shelf (Sousa et al., 2000) in the same way as the vegetal remains. The vegetal remains were probably transported by ebb tidal currents though the Paranaguá and Guaratuba paleoestuaries, which were larger than present (Fig. 1), to the inner shelf, between 7500 and 5000 yr BP, when the sea level was similar to or higher than the present one (Fig. 14). The remains were probably deposited in the inner shelf beyond the storm wave base level. After the highstand, the progressive sea level lowering promotes reworking of the vegetal remains by storm waves. Paleocurrents measured in the lower and middle shoreface facies, where the vegetal remains were deposited, indicate preferential landward directions (Figs. 15 and 16) and swaley cross-stratification suggests storm wave action.

Stapor and Stone (2004) and Otvos (2005) describe similar inversions on the Gulf of Mexico Holocene barriers and, in a manner similar to that of the Paraná barrier, they were interpreted as having originated from non-transported and onshore transported materials during barrier development.

The discussion above points out that the radiocarbon age inversions observed in the Holocene regressive barrier of the Paraná coast result from dating diverse material, such as articulated shells without transport and intensely transported wood fragments. Datings of transported materials have been used to characterize barrier formation ages and depositional environments (e.g. Suguio et al., 1976; Suguio and Martin, 1978; Bittencourt et al., 1979; Martin et al., 1979, 1979/80, 1983, 1988, 1996, 1997; Souza et al., 2001; Angulo et al., 2002; Bezerra et al., 2003; Dillenburg et al., 2004; Buynevich et al., 2005; Dillenburg and Hesp, 2008) and to determine paleo-sea levels (for a discussion see Angulo et al., 2006). However, it must be stressed that transported materials give only maximum ages, and that their

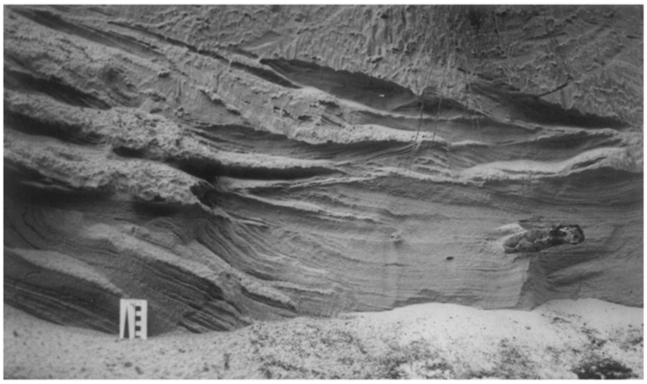


Fig. 8. Trunk fragment with preserved cortex sampled from upper shoreface through cross-stratified sand facies (2987–2751 cal yr BP, CENA-364; for location, see Fig. 2).

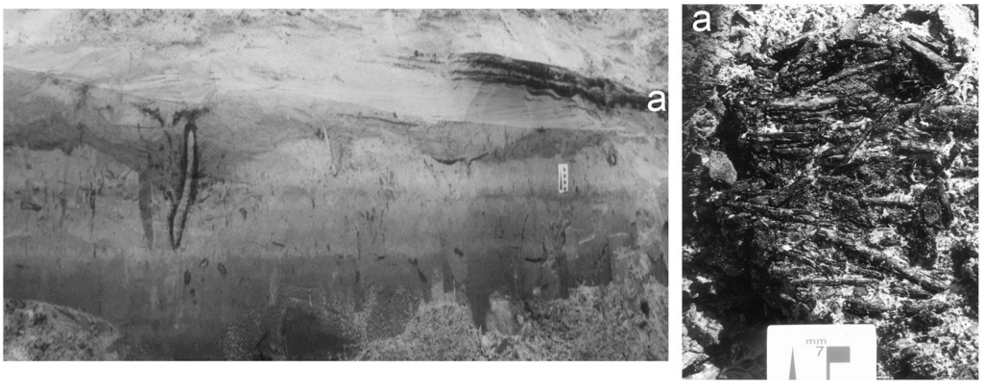


Fig. 9. Wood fragments rounded by abrasion (a — top view) from middle shoreface swaley cross-stratified facies (6177–5733 cal yr BP, CENA-432) (for location, see Fig. 2).

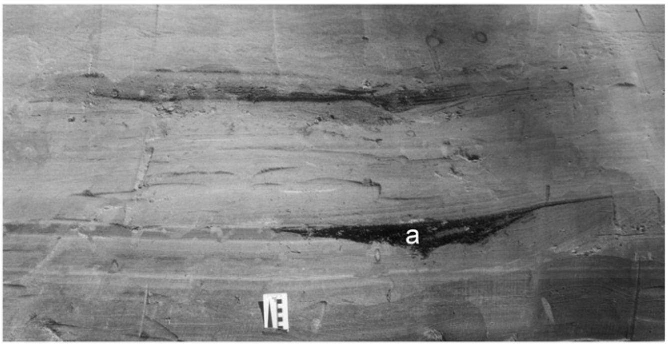


Fig. 10. Vegetal debris (a) sampled from middle shoreface swaley cross-stratification sand facies (5317–5047 cal yr BP, GX-29115) (for location, see Fig. 2).

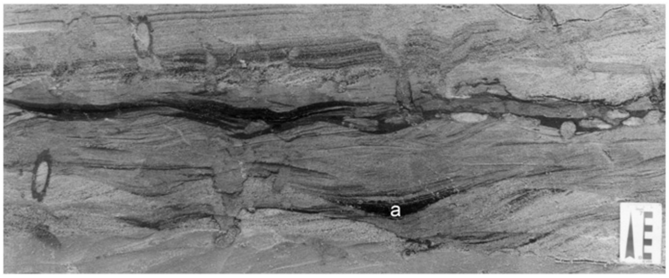


Fig. 11. Vegetal debris (a) sampled from middle shoreface swaley cross-stratification sand facies (8542–8279 cal yr BP, CENA-362 and 8418–8056 cal yr BP, CENA-363) (for location, see Fig. 2).

Fig. 12. Vegetal debris (a) sampled from middle shoreface swaley cross-stratification sand facies (7918–7574 cal yr BP, CENA-358) (for location, see Fig. 2).

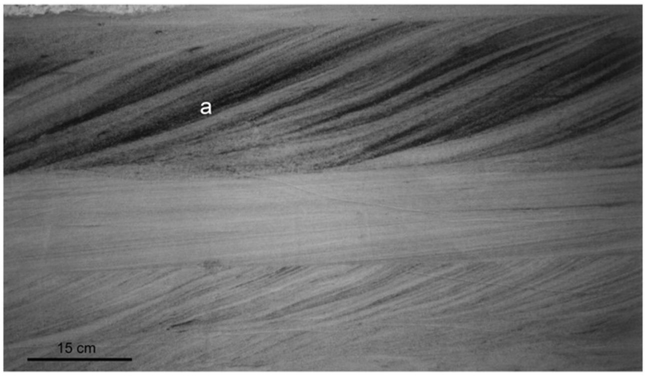


Fig. 13. Vegetal debris (a) sampled from upper shoreface sigmoidal cross-stratification sand facies (3825–3469 cal yr BP, CENA-370) (for location, see Fig. 2).

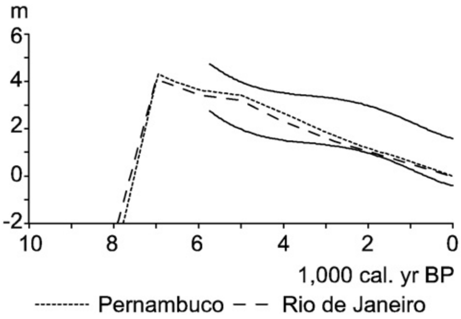


Fig. 14. Mid- to late-Holocene sea level envelope for eastern Brazilian coast between Pernambuco and Paraná, plotted with the paleo-sea level behavior predicted by geophysical simulations made by Milne et al. (2005, after Angulo et al., 2006; for location, see Fig. 1).

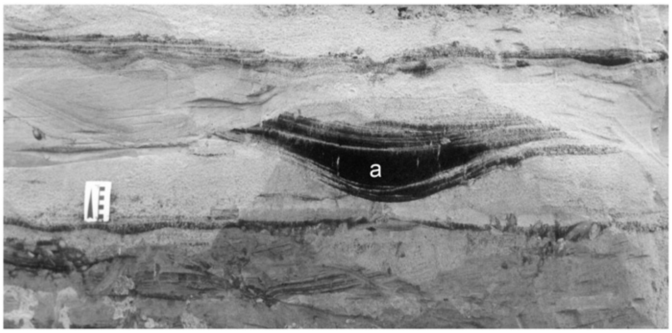
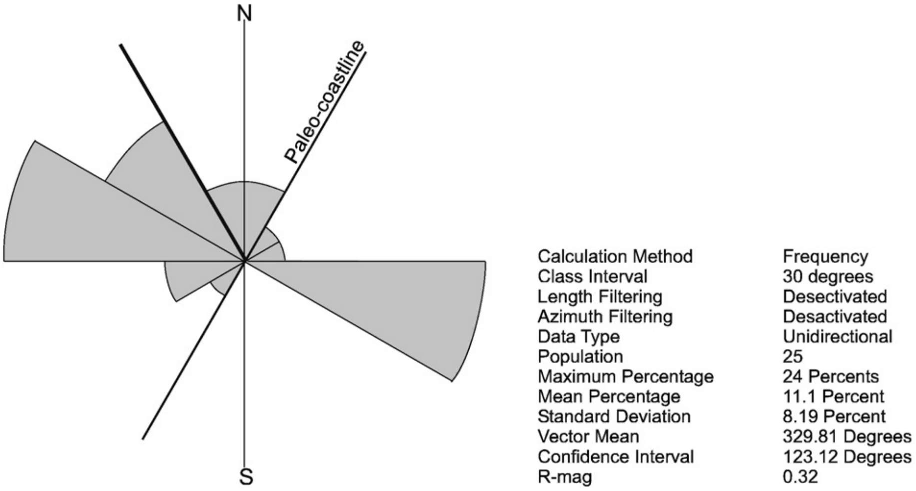


Fig. 15. Middle shoreface facies with swaley cross-stratification and vegetal debris (a).



Calculation Method	Frequency
Class Interval	30 degrees
Length Filtering	Desectivated
Azimuth Filtering	Desactivated
Data Type	Unidirectional
Population	25
Maximum Percentage	24 Percents
Mean Percentage	11.1 Percent
Standard Deviation	8.19 Percent
Vector Mean	329.81 Degrees
Confidence Interval	123.12 Degrees
R-mag	0.32

Fig. 16. Paleocurrents inferred from swaley cross-stratification showing preferential onshore sediment transport.

deposition environments can be very distinct from the environments in which the original organisms lived.

5. Conclusions

It's possible to conclude that: (a) 40 400 to 30 000 yr BP ^{14}C ages from lagoonal facies correspond to isotope stages 5e or 3. (b) The age inversions at the Holocene barrier stratigraphic profile were caused by dating in situ material or material that was transported over either short or long distances. (c) The more reliable ages of the Paraná Holocene regressive barrier at the studied sector, provided by in situ or short transported material, are 4402–4135 cal yr BP near the barrier base and 2987–2751 cal yr BP near the top. (d) The ^{14}C ages provided by vegetal debris with long transport are hundreds to thousands of years older than the barrier facies depositional time.

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