ELSEVIER

Marine Geology 159 (1999) 323–339

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.nl/locate/margeo

Relative sea-level changes in the last 5500 years in southern Brazil (Laguna–Imbituba region, Santa Catarina State) based on vermetid ^{14}C ages

Rodolfo J. Angulo [a,*], Paulo C.F. Giannini [b,1], Kenitiro Suguio [b,2], Luiz C.R. Pessenda [c,3]

[a] Departamento de Geologia, Universidade Federal do Paraná, Caixa Postal 19001, 81531-990 Curitiba (PR), Brazil
[b] Instituto de Geociências, Universidade de São Paulo, Caixa Postal 11348, 05422-970 São Paulo (SP), Brazil
[c] Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Caixa Postal 96, 13400-970 Piracicaba (SP), Brazil

Received 10 March 1998; accepted 1 December 1998

Abstract

Twenty-six new radiocarbon dates from vermetid shells collected in the southernmost sector of the Brazilian rocky coast presented dates ranging from 5410 ± 80 to 190 ± 65 years B.P., with associated paleosea levels varying from $+2.10$ m to $+0.20$ m above present sea level. The overall suggested trend of the relative sea level (RSL), declining until at least 190 years B.P., is somewhat contradictory to a proposed RSL rise in the last 1000 years in southern Brazil. The data also seem to undermine a more widely accepted RSL trend that suggests that at least two negative RSL oscillations occurred between 4100 and 3800 years B.P. and between 3000 and 2700 years B.P. The maximum elevation of the RSL in the Holocene in southern Brazil was possibly lower than that observed in most of the Brazilian eastern coast. Discrepancies between ancient sea levels of similar ages are attributed to coincidental methodological problems, to imprecisions in determining past relative sea levels and to possible changes in the geomorphology and wave climate close to shore during the last 5000 years. A general trend of increasing $\delta^{18}O$ with a reduction in age in the studied samples may suggest a gradual reduction of water temperature in the region during the same period.

Keywords: holocene; paleosea level; southern Brazil; vermetid; sea level changes; ^{14}C ages

1. Introduction

The construction of relative sea level (RSL) curves for the late Pleistocene and Holocene, using relatively accurate paleo RSL indicators, has shown to be an essential tool for understanding the evolutionary history of coastal regions in the Quaternary.

Amongst several existing ancient RSL indicators on the Brazilian coast, one of the most reliable is represented by the remains of an incrustant arago-

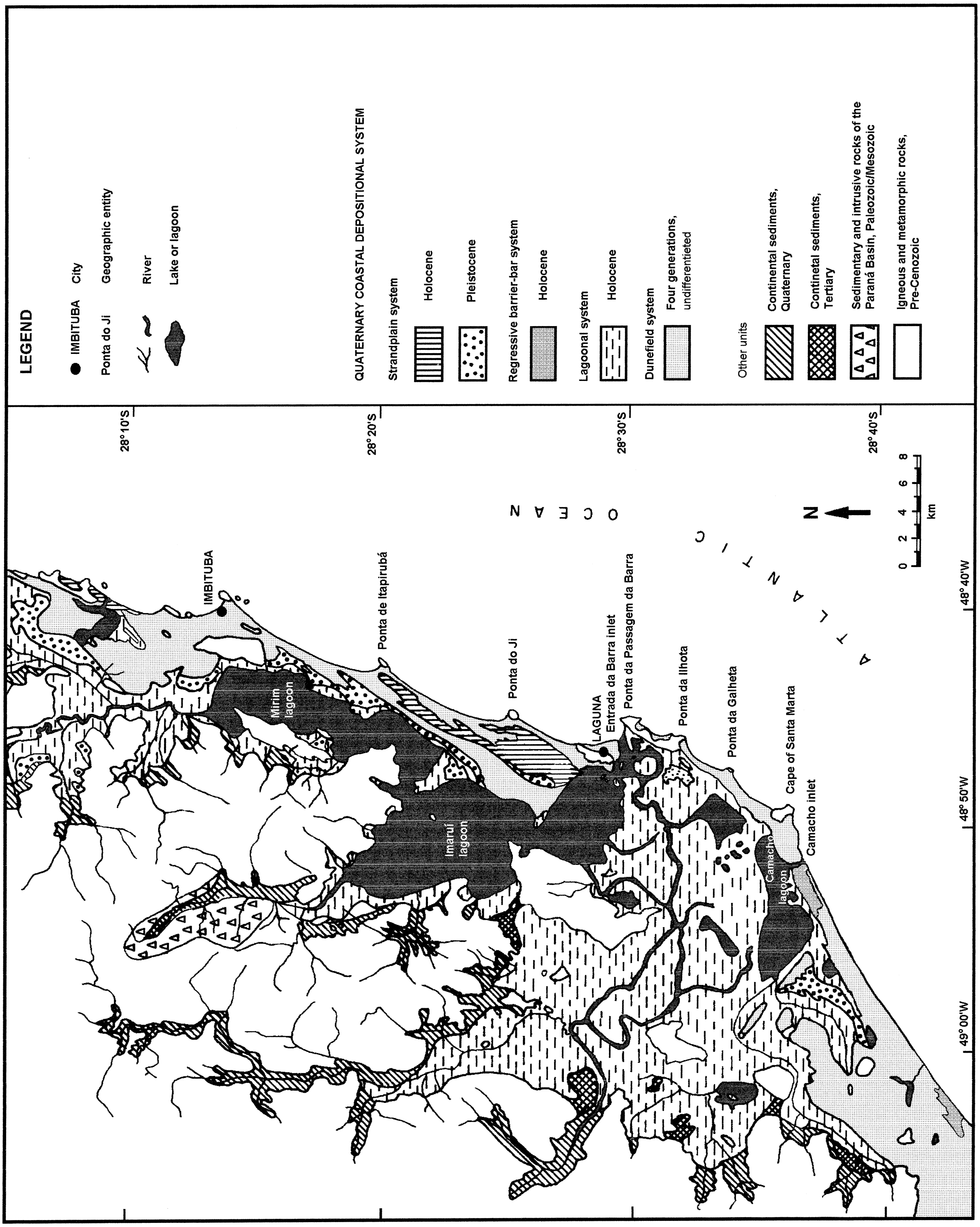
* Corresponding author. Fax: +55-41-266-2393; E-mail: angulo@geologia.ufpr.br
[1] Fax: +55-11-818-4129; E-mail: pcgianni@usp.br.
[2] Fax: +55-11-818-4129.
[3] Tel.: +55-19-433-51-22; E-mail: pessenda@cena.usp.br.

0025-3227/99/$ - see front matter
PII: S0025-3227(98)00204-7

Fig. 1. Location map. Study area encircled.

nitic gastropod, the vermetid *Petaloconchus* (*Macrophragma*) *varians* (d'Orbigny) (Laborel, 1986; Angulo, 1993). This study aims to improve the understanding of the RSL changes in southern Brazil in

Fig. 2. Simplified map of the Quaternary depositional systems in the region of Laguna–Imbituba (SC), showing the sampled rocky headlands (modified from Giannini and Santos, 1994).


LEGEND
IMBITUBA City
Ponta do Ji Geographic entity
River
Lake or lagoon
QUATERNARY COASTAL DEPOSITIONAL SYSTEM
Strandplain system
Holocene
Pleistocene
Regressive barrier-bar system
Holocene
Lagoonal system
Holocene
Dunefield system
Four generations, undifferentieted
Other units
Continental sediments, Quaternary
Continetal sediments, Tertiary
Sedimentary and intrusive rocks of the Paraná Basin, Paleozoic/Mesozoic
Igneous and metamorphic rocks, Pre-Cenozoic
28°10'S
28°20'S
28°30'S
28°40'S
48°40'W
48°50'W
49°00'W
IMBITUBA
Ponta de Itapirubá
Ponta do Ji
LAGUNA
Entrada da Barra inlet
Ponta da Passagem da Barra
Ponta da Ilhota
Ponta da Galheta
Cape of Santa Marta
Camacho inlet
Mirim lagoon
Imaruí lagoon
Camacho lagoon
ATLANTIC OCEAN
N
0 2 4 6 8
km

the Holocene by providing a new set of 26 new radiocarbon ages of vermetid samples collected from the southernmost Santa Catarina State's rocky coast (Figs. 1 and 2).

2. Study area

2.1. Rocky coasts and headlands

The distribution of rocky coasts in southern Brazil is relevant in this article, not only because it controls the presence of the ancient RSL indicators used here, but also because it can indicate possible physiographical and structural partitioning of the region. Therefore, it's important for the recognition of coastal sectors with homogeneous neotectonic behavior and similar RSL changes.

According to the Lister et al. (1986) model for the Atlantic-type passive margins architecture, continental shelf off the study region could be formed by an alternation of transversal belts with two distinct morphostructural patterns, separated by transforming-transcurrent faults. Giannini (1993) assumed that, if this model is valid for the continental shelf and slope adjacent to Santa Catarina State (Fig. 3), the hypothesis of transfer zones in the northern and southern limits of Florianópolis paleostructural high (Pereira and Macedo, 1990) explains the structural differences between this high and the Santos and Pelotas marginal basins, neighbors to the north and south, respectively. The probable extension of these structural differences towards the west would explain the geomorphological partitioning of the coastal plain observed in the Santa Catarina State. On this aspect, the studied rock coast, comprised between the latitudes of Imbituba and Laguna, would be interpreted as the western structural extension of southern Florianópolis high (Giannini, 1993). Therefore, it would be inside a homogeneous tectono-structural sector. The following distinguishing geomorphological characteristics in this area would be the expressions of this structural partitioning: (1) the direction NNE of the coastline, changing abruptly to ENE south of Santa Marta Cape (Figs. 2 and 3); (2) the transition between scarped and indented coast north Santa Marta Cape, to wide, depositional coastal plains to the south (Fig. 2); (3) the narrowing and steeping of the inner continental shelf in the sector between Santa Marta Cape and Florianópolis–Itajaí (Fig. 3).

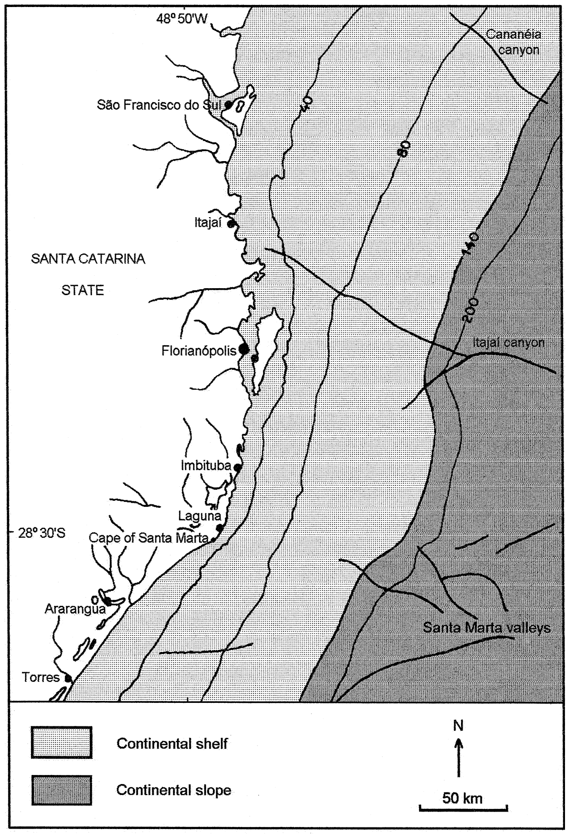


Fig. 3. Topographic map of the continental margin of Santa Catarina State (after Zembruscki, 1979). Limits of the Florianópolis paleoestructural high is approximately coincident with Itajaí canyon and Santa Marta valleys.

Two directional systems of fractures prevail in the area: the N30E and the N60E. These directions are possibly associated to more ancient faults of the crust (Trainini et al., 1978), that had several reactivation phases between the Eopaleozóic and the Tertiary (Horbach and Marimon, 1980). The system N30E is seemingly dominant in the rocks that outcrop close to the coast. Intrusions of basic to intermediate rock, linked to the magmatic flows of the Serra Geral Formation (Jurassic–Cretaceous of the Paraná Basin), form hives of dikes of same direction in the area between Florianópolis and Laguna (Castro and Castro, 1969; Morgental and Kirchner, 1983). Larger

Fig. 4. Panoramic view of the northern side of Ponta de Itapirubá. Sand of eolian paleodunes is observed on the right side. Notice the headlands with characteristic subvertical cliffs bordered by boulders.

part of the rocky coasts in the study area is formed by Late Proterozoic granitoids (leucogranites, granodiorites and monzonites). The N30E trend controls the orientation of the rocky headlands. The dominant geomorphological pattern of the rocky coasts is subvertical, sometimes stepping cliffs that are bordered by abrasion platforms at less than 20 m in elevation and by boulder seas and/or cobble beaches (Fig. 4). Most of the vermetid encrustations sampled on this work occur on vertical to slightly inclined walls and

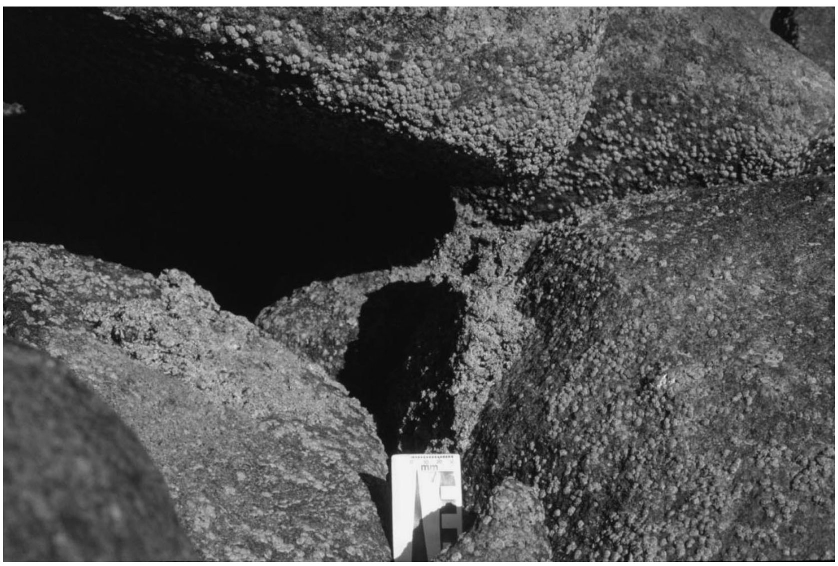


Fig. 5. Remains of vermetid tubes in the Ponta da Galheta, corresponding to sample 1 (1690 ± 90 years B.P.). The remains are found in the zone of *Chthamalus*.

Fig. 6. Concretioned formations of vermetid in the Ponta da Galheta, corresponding to sample 5 (2910 ± 70 years B.P.). This was the best-preserved formation sampled in the area.

in the lower part of metric-size boulders (Figs. 5 and 6).

2.2. Coastal plain

The geology of the coastal plain was subdivided into four main depositional systems (Giannini, 1993; Fig. 2): Holocene regressive barrier system, strandplain system, dunefield system and Holocene lagoonal system.

The Holocene regressive barrier system occurs south of Laguna and is associated with back-barrier lagoonal and paleolagoonal deposits. The strandplain system is composed of, at least, a late Pleistocene and a Holocene section, and is distinguished from the barrier system by the absence of a contiguous back-barrier lagoon. The Imaruí and Mirim lagoons (Fig. 2) that occur behind the Pleistocene strandplains are actually drowned river valleys, and not a water body isolated by the growth of a barrier (Giannini, 1993).

The Holocene lagoonal system reaches the open sea via two inlets: Camacho in the south and Entrada da Barra in the north. Aeolian deposits cover the barrier and the strandplain systems in most of the area. It comprises four transgressive phases, with ages varying from late Pleistocene to present (Giannini, 1993; Giannini and Suguio, 1994).

High-energy waves, as for the whole southeastern and southern Brazilian coast, come from the S and SE quadrants (Giannini, 1993). Modal wave height offshore Imbituba harbor (equivalent to 42% of the waves registered since the harbor construction in 1952) is 1.0 to 2.0 m (Porto de Imbituba, 1997). The astronomic tidal range in Imbituba harbor is 0.6 m at spring tide (DHN, 1989), but storm surges up to 1.5 m have been registered (Porto de Imbituba, 1997).

3. Methods

The 26 samples of fossilized vermetid tubes, collected between Cape of Santa Marta and Ponta de Itapirubá (Fig. 2), were subjected to air drying, mechanical cleaning with a wire brush (to extract the remains of present organisms such as barnacles and algae) and superficial chemical attack to eliminate eventual secondary carbonates incrusted in the vermetid tubes. The Radiocarbon Laboratory of the Center of Nuclear Energy in Agriculture (CENA), University of São Paulo (USP), Brazil, performed the ^{14}C datings. The dating method was of benzene synthesis and detection of ^{14}C by spectrometry of liquid scintillation (Pessenda and Camargo, 1991). The $\delta^{18}O$ values were obtained in the Laboratory of Environmental Isotopes of the University of Waterloo, Canada. The ages were corrected for the ^{13}C isotopic fractionating, but to maintain consistency with other published ^{14}C datings, the reservoir effect of the samples was not taken into consideration.

The determination of the paleosea level followed the method proposed by Laborel (1986), which adopts as reference the present level of occurrence of the living organisms.

The vermetid *P.* (*Macrophragma*) *varians* lives in the lower quarter of the intertidal area, between neap and springtides. However, as vermetids have disappeared in southern Brazil, the reference used in this work was the upper limit of *Phragmatopoma lapidosa* colonies, a polychaete which lives at a level equivalent to that of the vermetids (Paulo da Cunha Lana, CEM/UFPR, pers. comm.) (Fig. 7). When the level of *Phragmatopoma* was measured in rocky fissures, 0.15 m was added to the estimated paleosea level in order to compensate the superelevation of the upper limit observed for these situations.

Fig. 7. Aspect of well-developed colonies of *Phr. lapidosa* in the State of Paraná (to the north of the study area), similar to the Santa Catarina's ones. Approximate scale 1:180.

4. Results

Remains of fossil vermetid, all composed of tubes of *P.* (*Macrophragma*) *varians* (Fig. 8), were found at six headlands—Ponta de Itapirubá, Ponta do Ji, Ponta da Passagem da Barra, Ponta da Ilhota, Ponta da Galheta and Santa Marta Cape. The schematic profiles of the rock cliffs where the samples of vermetid tubes were obtained are presented in Fig. 9.

These vermetid remains correspond to relicts of concretional formations, preserved in specific places, sheltered from wave action and to the pluvial and run-off waters, frequently beneath metric boulders (Fig. 6). Most of the fossil remains are less than 10 cm thick, reaching up to 30 cm. The best-preserved formation was found in the Ponta da Galheta (Fig. 6).

The vermetids were found in coasts facing the N and NE quadrants, with the exception of the sampling stations Ponta da Galheta 2 and 3 (Fig. 2), that faced the S–SW quadrants. The results indicate that, in the study region, sea level was above the present elevation between 5410 $\pm$ 80 years B.P. and 190 $\pm$ 65 years B.P. (Table 1 and Fig. 10). The paleosea levels varied from $+2.10$ m to $+0.20$ m, with lower elevations towards younger ages. However, some samples did not follow this general behavior.

The oldest sample, dated at 5410 $\pm$ 80 years B.P., suggests a paleosea level of $+2.10 \pm 0.50$ m. No records were found for the periods between 5300 to 4700 years B.P. and 3800 to 3000 years B.P. Between 4600 and 3900 years B.P., three samples indicate paleosea levels higher than $+1.75$ m and one sample suggests a paleosea level of $+1.05$ m, but no trend can be observed. The majority of the samples fell in the interval between 2910 and 190

Fig. 8. Detail *P*. (*Macrophragma*) *varians* tubes in a sample of the Ponta do Ji.

years B.P. In this time interval, paleosea levels around +1.0 m are suggested to have occurred until 1580 ± 70 years B.P. (Fig. 10), after which paleolevels around +0.20 m became more common. Nevertheless, no definite trend was observed.

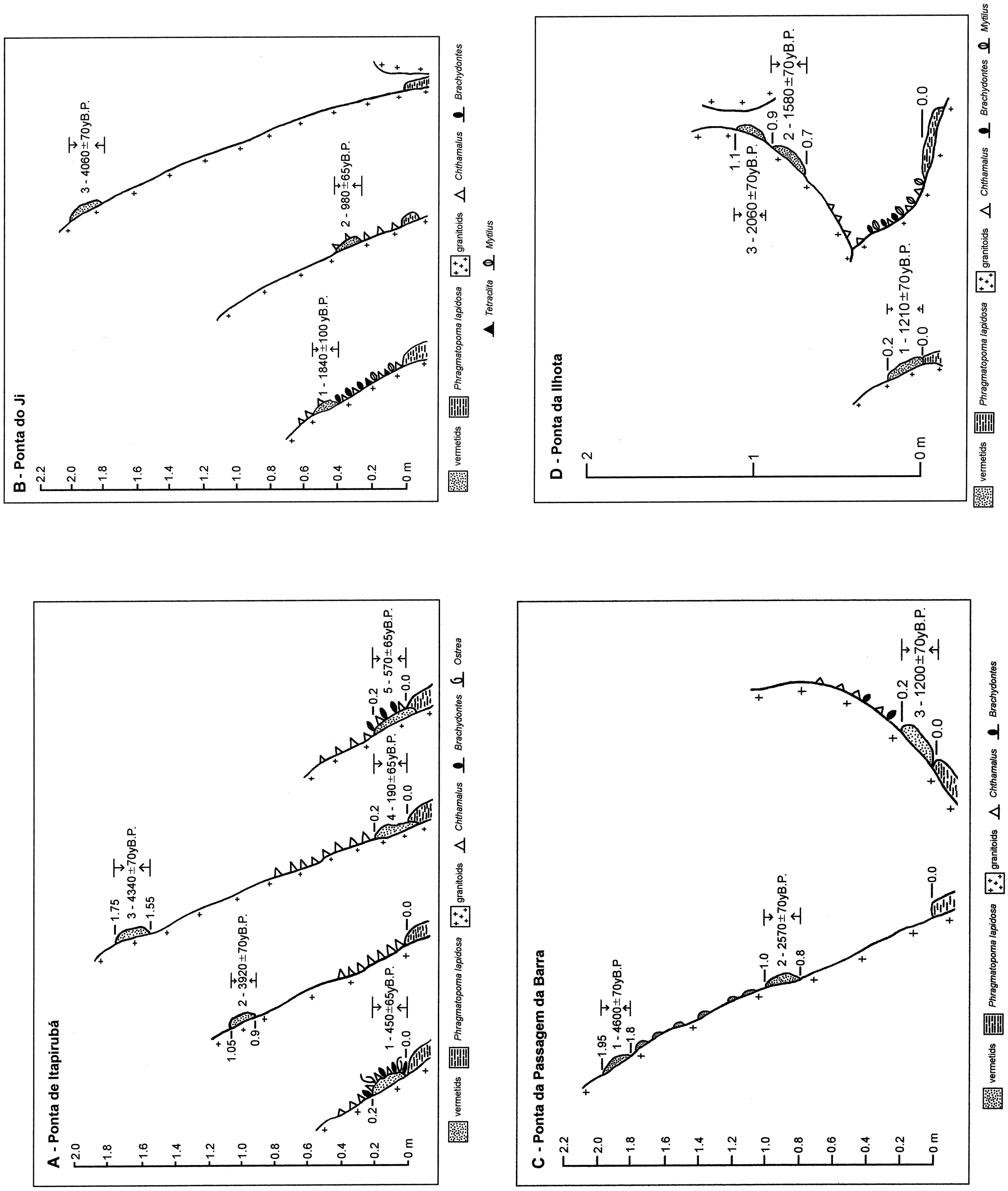
Significant differences of the estimated paleosea levels occurred between 2910 ± 70 and 1580 ± 70 years B.P., when it varied from a minimum of +0.35 m to a maximum of +2.0 m. Conversely, in the interval between 1370 ± 60 and 190 ± 65 years B.P., the estimated paleosea levels varied only between +0.20 m and +0.40 m.

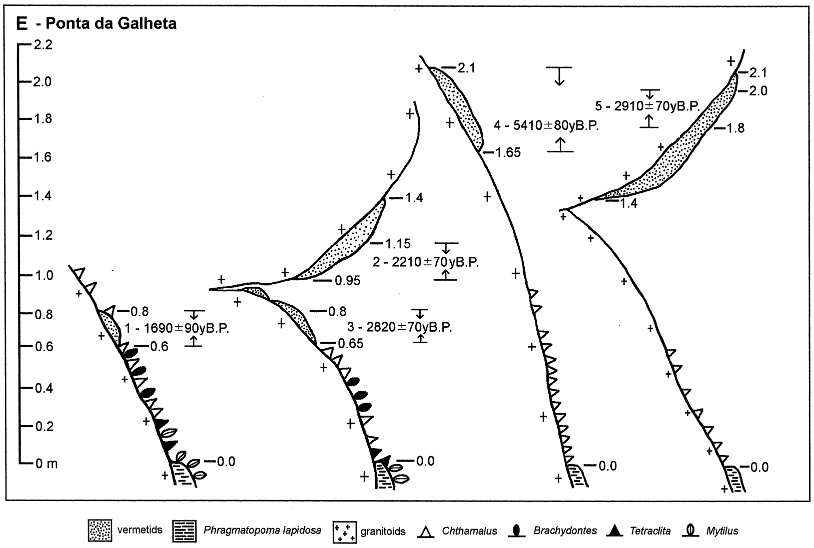
Values of $\delta^{18}O$ oscillated between +0.91‰ and −0.66‰, with higher values related to younger vermetid samples (Table 1). Despite this general inverse relationship between $\delta^{18}O$ values and ages of the vermetids, discrepant values of $\delta^{18}O$ were recorded for ages very close to each other, such as +0.91‰, −0.26‰ and −0.66‰ for tubes dated at 1180 ± 70, 1210 ± 70 and 1200 ± 70 years B.P., respectively.

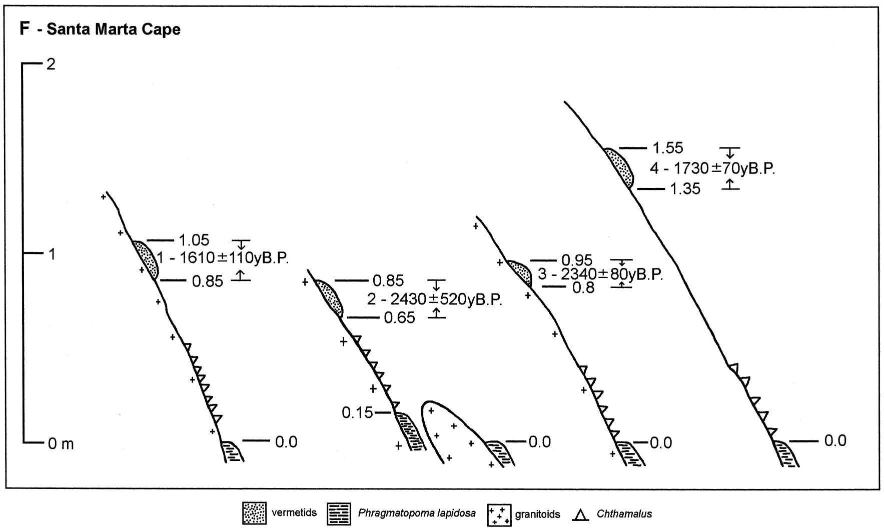
5. Discussion and conclusions

5.1. Discrepancies between paleolevels of similar age

The results show differences of up to 1.25 m in height between paleosea levels with similar ages (around 100 years apart), which pose a question about what factors could cause these discrepancies. A possible laboratory contamination, and consequent rejuvenation, of carbon in some of the samples must be discarded as a premise, since appropriate care was taken during the cleaning process. Additionally, the aragonite *Petaloconchus* tubes would be, according to Laborel (1986), less susceptible to contamination


A - Ponta de Itapirubá
1 - 450±65yB.P.
2 - 3920±70yB.P.
3 - 4340±70yB.P.
4 - 190±65yB.P.
5 - 570±65yB.P.
vermetids
Phragmatopoma lapidosa
granitoids
Chthamalus
Brachydontes
Ostrea
B - Ponta do Ji
1 - 1840±100yB.P.
2 - 980±65yB.P.
3 - 4060±70yB.P.
Tetraclita
Mytilus
C - Ponta da Passagem da Barra
1 - 4600±70yB.P
2 - 2570±70yB.P.
3 - 1200±70yB.P.
D - Ponta da Ilhota
1 - 1210±70yB.P.
2 - 1580±70yB.P.
3 - 2060±70yB.P.





than the calcite exoskeletons. The hypothesis that the differences between the elevations would be related to different degrees of wave action at the sampling points could be also rejected. All, but two samples, were obtained on coasts facing N and NE. However, the comparison of the elevation of these two samples (Ponta da Galheta 2 and 3) against the others shows no superelevation.

The most probable reason to explain the discrepancies between paleosea levels of similar age would be that the margin of error involved in determining paleosea levels from vermetid tubes is larger than previously presumed (0.5 to 1.0 m, in accordance with Laborel, 1986). The narrow vertical band (0.2 to 2.0 m) of occurrence of the *P.* (*Macrophragma*) *varians* (d'Orbigny), allows it to be considered a precise indicator of marine paleolevel (van Andel and Laborel, 1964; Delibrias and Laborel, 1969; Laborel, 1979, 1986). Laborel (1986) related the variations in the thickness of the vermetid bands to

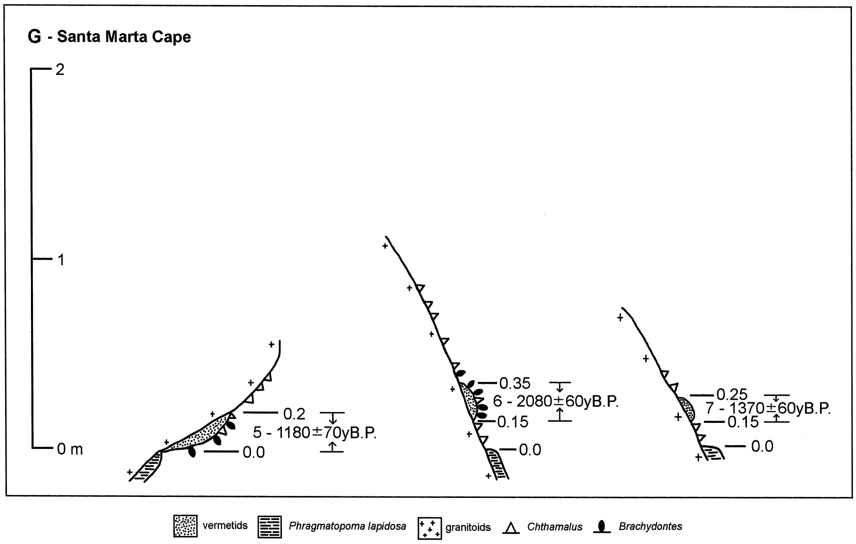


Fig. 9. Schematic profiles of the sites where vermetid tubes were sampled. (A) Ponta de Itapirubá. The sampling stations 3, 4 and 5 were more exposed to wave action than stations 1 and 2. (B) Ponta do Ji. Notice that in station 3, the *Phragmatopoma* incrustation was in a fissure between the cliff and a boulder. (C) Ponta da Passagem da Barra. Sample 3 was obtained under a boulder. This position favours preservation due to protection against rainfall. (D) Ponta da Ilhota. The *Phragmatopoma* incrustation was found beneath an inclined rock slab, which favours wave run up and superelevation of the *Phragmatopoma* upper limit. (E) Ponta da Galheta. Samples 2 and 5 were obtained under a boulder. (F and G) Santa Marta Cape. The *Phragmatopoma* colony associated with leveling of sample 2 was located in a rock fissure and was 0.15 m above the elevation of neighboring colonies. Sample 5 was taken from the base of a boulder.

wave height and tidal range, varying between ± 0.1 m and ± 1.0 m in the best (lower waves and smaller tidal ranges) and worst (higher waves and larger tidal ranges) scenarios. For the most common hydrodynamic conditions along the Brazilian coast, a precision of about ± 0.5 m was suggested by Laborel (1986), reaching ± 1.0 m in some extreme (high wave energy) cases. A margin of error between 0.5 m and 0.4 m has been adopted by several authors studying the paleosea level oscillations in Brazil (van Andel and Laborel, 1964; Delibrias and Laborel, 1969; Suguio and Martin, 1978; Martin et al., 1979a,b; Martin and Suguio, 1989; Angulo, 1989, 1992, 1994; Dominguez et al., 1990), also including this article.

Two factors would be involved in diminishing the accuracy of the vermetid tubes as sea level indicators, namely the imprecision in defining the vertical position of the studied sample in relation to the original colony's spread zone and possible changes in the wave climate and coastal geomorphology associated with a sea-level fall.

5.1.1. Imprecisions in the identification of the paleolevel

The upper limit of the fossilized vermetid tubes used as the paleolevel record might not correspond to the upper limit of the existing concretioned formation at the lifetime of the vermetids. This imprecision could provoke the underevaluation of the paleosea level, depending on how wide was the spread of the original occurrence of the vermetids. In the most unfavorable situation, in which the peak of the preserved concretioned formation corresponds to the base of the original formation, the underevaluation would be equal to the width of the formation during its lifetime (0.1 to 1.0 m).

Moreover, additional errors in the paleosea level determination can occur due to differences in the vertical distribution of the organism taken as reference, such as the colonies of *Phr. lapidosa*.

Measurements of the relative level of *Phragmatopoma* colonies in a rocky coast in Itapoá (Santa Catarina State, nearly 200 km to north from Imbituba) showed that the upper limit of well-devel-

Table 1
Radiocarbon datings from vermetid samples from Laguna–Imbituba region (Santa Catarina State, Brazil)

Local	Latitude (south)	Longitude (west)	Age (years B.P.)	Paleosea level (m)	$\delta^{18}O^{(1)}$ (‰)	$^{1}\delta^{13}C$ [a] (‰)	Lab. Ref. No.
Ponta de Itapirubá 1	28°20′18″	48°41′57″	450 ± 65	+0.20	−0.24	2.05	CENA 181
Ponta de Itapirubá 2	28°20′18″	48°41′57″	3920 ± 70	+1.05	0.51	2.54	CENA 182
Ponta de Itapirubá 3	28°20′18″	48°41′57″	4340 ± 70	+1.75	0.33	2.38	CENA 183
Ponta de Itapirubá 4	28°20′18″	48°41′57″	190 ± 65	+0.20	0.55	2.39	CENA 184
Ponta de Itapitubá 5	28°20′18″	48°41′57″	570 ± 65	+0.20	0.59	2.62	CENA 185
Ponta do Ji 1	28°25′25″	48°44′15″	1840 ± 100	+0.55	0.02	2.29	CENA 189
Ponta do Ji 2	28°25′25″	48°44′15″	980 ± 65	+0.40	0.40	2.18	CENA 190
Ponta do Ji 3	28°25′25″	48°44′15″	4060 ± 70	+2.00	−0.32	2.51	CENA 191
Ponta da Passagem da Barra 1	28°30′19″	48°44′45″	4600 ± 70	+1.95	−0.38	1.83	CENA 192
Ponta da Passagem da Barra 2	28°30′19″	48°44′45″	2570 ± 70	+1.00	−0.10	2.53	CENA 193
Ponta da Passagem da Barra 3	28°30′19″	48°44′45″	1200 ± 70	+0.20	−0.66	2.23	CENA 194
Ponta da Ilhota 1	28°32′10″	48°45′36″	1210 ± 70	+0.20	−0.26	2.10	CENA 186
Ponta da Ilhota 2	28°32′10″	48°45′36″	1580 ± 70	+1.05	−0.42	2.17	CENA 187
Ponta da Ilhota 3	28°32′10″	48°45′36″	2060 ± 70	+1.10	−0.47	1.81	CENA 188
Ponta da Galheta 1	28°34′00″	48°47′11″	1690 ± 90	+0.80	0.36	2.44	CENA 176
Ponta da Galheta 2	28°34′00″	48°47′11″	2210 ± 70	+1.15	−0.10	2.67	CENA 177
Ponta da Galheta 3	28°34′00″	48°47′11″	2820 ± 70	+0.75	−0.23	2.57	CENA 178
Ponta da Galheta 4	28°34′00″	48°47′11″	5410 ± 80	+2.10	−0.62	1.55	CENA 179
Ponta da Galheta 5	28°34′00″	48°47′11″	2910 ± 70	+2.00	−0.31	2.17	CENA 180
Cape of Santa Marta 1	28°36′18″	48°48′54″	1610 ± 110	+1.05	–	–	CENA 169
Cape of Santa Marta 2	28°36′18″	48°48′54″	2430 ± 520[b]	+0.85	0.90	2.96	CENA 170
Cape of Santa Marta 3	28°36′18″	48°48′54″	2340 ± 80	+0.95	–	1.86	CENA 171
Cape of Santa Marta 4	28°36′18″	48°48′54″	1730 ± 70	+1.55	–	1.95	CENA 172
Cape of Santa Marta 5	28°36′18″	48°48′54″	1180 ± 70	+0.20	0.91	2.76	CENA 173
Cape of Santa Marta 6	28°36′18″	48°48′54″	2080 ± 60	+0.35	−0.87	2.28	CENA 174
Cape of Santa Marta 7	28°36′18″	48°48′54″	1370 ± 60	+0.25	0.06	2.17	CENA 175

[a] Two $\delta^{13}C$ determinations were performed for the majority of the samples, and the indicated values correspond to the mean. The largest observed difference was equal to 1.12‰.
[b] The low analytical precision is due to, in this case, a small amount of sample mass.

oped colonies varied within 0.52 m, with higher colonies generally located on cliffs more exposed to wave action. Amongst the least developed colonies, a greater vertical spread of the upper limit was observed. In this case, differences in the upper limit of up to 2.06 m were measured, varying in average ±0.77 m in relation to the top of well-developed colonies. It is worth mentioning that we have utilized well-developed *Phragmatopoma* colonies as a reference level at every site, but Passagem da Barra 2 and 3.

In comparison with the vermetid, the *Phragmatopoma* colonies could, for example, colonize a vertically narrower or wider band as a result of variations in wave energy, slope of the substrate, isolation and competition between species, etc. As indicated by Laborel (1979), the upper limit of the colonies of *Phr. lapidosa* would correspond to the lower limit of the vermetid formation, and that the upper limit of the latter would coincide with the lower limit of *Tetraclita*, a common cirripede of the Brazilian coast (Fig. 11a). Therefore, in the regions studied by Laborel (1979), between Recife (8° south) and Ilha Grande (23° south) (Fig. 1), the vertical difference between the lower limit of *Tetraclita* and the upper limit of *Phragmatopoma* corresponds to the width of the vermetid formations.

In the study area, however, the lower limit of *Tetraclita* coincides with the upper limit of *Phragmatopoma* (Ponta do Ji 1; Ponta da Galheta 1, 2 and 3 and Ponta da Passagem da Barra 1; Fig. 11b), which supports the use of *Phragmatopoma* as present reference level for vermetids. In addition, it was observed that in the north of Santa Catarina State,

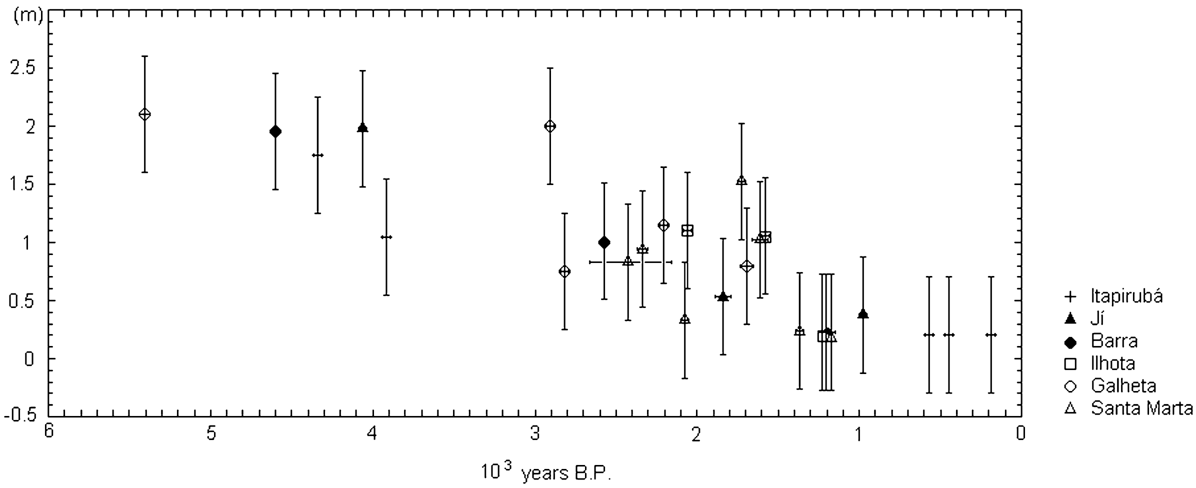


Fig. 10. Spatial and temporal reconstructions of paleosea levels in the region of Laguna–Imbituba (SC), on the basis of radiocarbon-dated vermetid tubes. The adopted error for the paleosea levels was ±0.5 m.

the upper limit of *Phragmatopoma* is situated around 0.30 m above the lower limit of *Tetraclita* (Fig. 11c).

5.1.2. Changes in the hydrodynamic characteristics of the coast since the lifetime of the vermetids

Variations of the RSL of more than 2 m (as indicated by the dated vermetids in the study region) or above 3.5 m (as indicated by paleosea level studies in the State of Paraná; Angulo and Lessa, 1997), could induce significant changes in the geomorphology and hydrodynamic characteristics of the coast. For example, a deeper shoreface fronting a rocky coast could induce less wave dampening and consequently, larger wave breaking heights, thus superelevating the spread of the biological zones.

Changes in the configuration of the coast and wave shoaling due to coastal progradation could alter

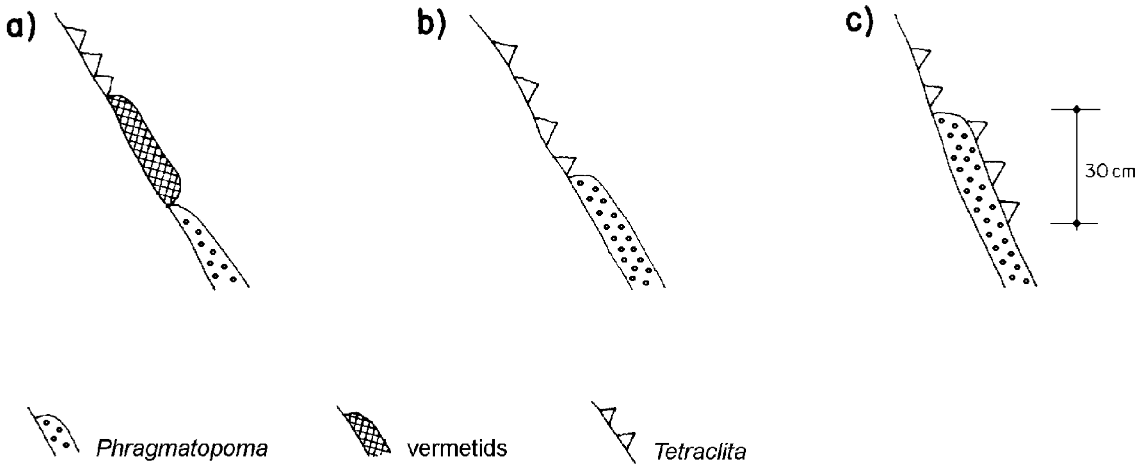


Fig. 11. Outlines of the upper limit of *Phragmatopoma* in relation to the lower limit of *Tetraclita* for: (a) the Brazilian coast (Laborel, 1979); (b) the region of Laguna–Imbituba—SC (this work) and (c) Itapoá—SC (this paper).

wave refraction patterns and change the mean water level close to the shore. The errors due to these hydrodynamic changes would tend to be smaller in younger samples, due to paleogeographical conditions more similar to the present ones.

5.2. Comparison with previous RSL curves

The existing RSL curves for southern Brazil (States of Paraná, Santa Catarina and Rio Grande do Sul) present two distinct patterns for the last 2000 years. The first one, proposed by Suguio et al. (1985) and Martin et al. (1988) for the Santa Catarina State (SC) (Figs. 1 and 12a), was based on very few data (especially in relation to the last 2000 years) and its general trend has been mostly inferred in analogy to better defined curves from the north of the country (Suguio et al., 1985). The second curve, proposed by Tomazelli and Villwock in Tomazelli (1990), suggests an RSL rise in the last 1000 years in Rio Grande do Sul State (RS) (Figs. 1 and 12b). Although in this case the RSL curve was also drawn in analogy to pre-existing curves, the differing trend in the last millennia was outlined based on two dated peat sample and on observations of widespread coastal erosion along the State's coastline.

The comparison of the paleosea level data from the Laguna–Imbituba region (this paper) with other published shows the following.

A. The overall elevation of the dated samples are lower than in other studied sectors of the Brazilian coast (Suguio and Martin, 1978; Martin et al., 1979a; Angulo, 1989; Dominguez et al., 1990; Angulo and Lessa, 1997). The highest level of ± 2.10 m at 5410 years B.P. seems to be at least 1 m lower than those observed in the States of São Paulo, Paraná and north of Santa Catarina.

Regarding the whole data set, it is observed that: (a) four ages in the 4600 to 3900 years B.P. interval exhibited paleosea levels between 1.05 m and 2.00 m (mean of 1.69 m), in contrast with 1.90 m and 3.05 m (mean of 2.74 m) for four ages of the same interval from the states of Rio de Janeiro, São Paulo, and Santa Catarina (Delibrias and Laborel, 1969; Suguio and Martin, 1978; Angulo, 1989); (b) 12 ages in the 2900 to 1600 years B.P. interval presented paleosea levels between 2.00 m and 0.35 m (mean of 1.03 m), in contrast with 22 samples, distributed between the states of Pernambuco and São Paulo, with paleosea levels between 4.83 m and 0.80 m (mean of 1.78 m) (van Andel and Laborel, 1964; Delibrias and Laborel, 1969; Martin and Suguio,

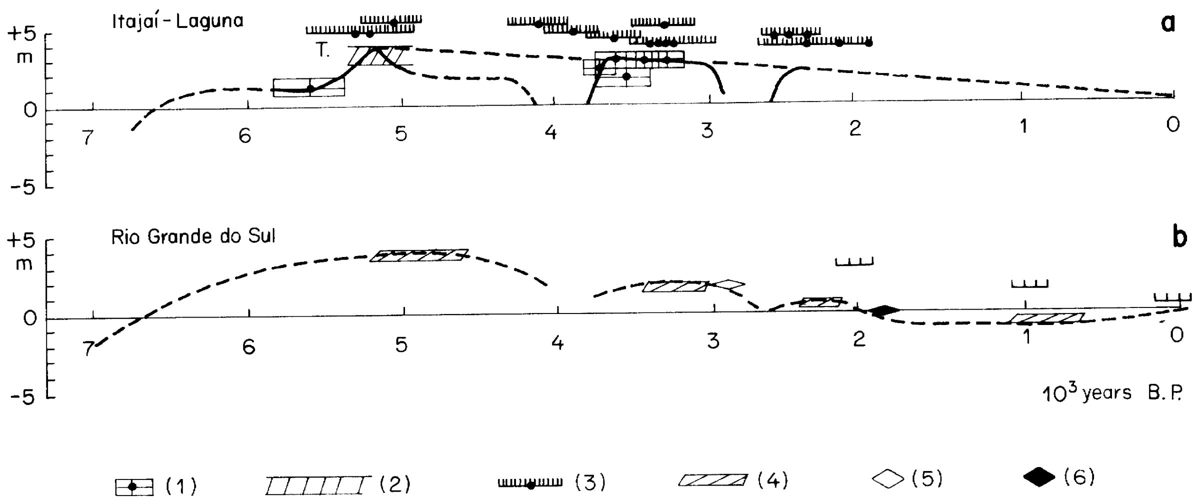


Fig. 12. Holocene RSL curves for the southern Brazil: (a) Santa Catarina (Suguio et al., 1985; Martin et al., 1988); (b) Rio Grande do Sul (Tomazelli and Villwock, 1989 in Tomazelli, 1990). (1) Reconstruction of paleosea levels; (2) marine terraces; (3) ages of shell middens; (4) lagoonal terraces; (5) Pontal das Desertas peat (2995 $\pm$ 125 years B.P.); (6) Conceição lignite (1975 $\pm$ 150 years B.P.).

1978; Suguio and Martin, 1978; Martin et al., 1979b; Dominguez et al., 1990); and (c) eight ages in the 1400 to 200 years B.P. interval, showed paleosea levels between 0.40 m and 0.20 m (mean of 0.23 m), in contrast with 21 samples between Pernambuco and Paraná, with paleosea levels between 2.55 m and 0.20 m (mean of 0.95 m) (van Andel and Laborel, 1964; Delibrias and Laborel, 1969; Martin and Suguio, 1978; Suguio and Martin, 1978; Martin et al., 1979a,b; Angulo, 1989, 1992).

B. The data presented here do not contradict the existence of a maximum around 5100 years B.P., as suggested by four dated samples in the states of Bahia (vermetids), Rio de Janeiro (oyster shells) and São Paulo (vermetids and wood detritus) (Suguio and Martin, 1978; Martin and Suguio, 1978; Martin et al., 1979a; Suguio et al., 1980, 1985)

C. During the intervals of the proposed negative sea-level oscillations (Suguio et al., 1985), four samples indicated paleosea levels between +0.70 m and +2.00 m above the present one.

D. The absence of vermetid tubes with ages between 5300 and 4700 years B.P. and between 3800 and 3000 years B.P., indicating higher-than-present paleosea levels in the study region, seems to be fortuitous. There are four datings corresponding to the first period and nine to the second (van Andel and Laborel, 1964; Delibrias and Laborel, 1969; Suguio and Martin, 1978; Martin et al., 1979a; Martin and Suguio, 1989; Angulo, 1992), distributed between the State of Pernambuco and the State of Paraná, indicating paleosea levels above the present one.

E. The paleosea levels inferred from the vermetid tubes in the study region indicate RSL higher than the present one during the last 2000 years, at least until 190 ± 65 years B.P. This pattern is in contrast with that outlined by Tomazelli and Villwock in Tomazelli (1990) for the adjoining area of Rio Grande do Sul, and is compatible with the trend suggested by the sea-level curve of Suguio et al. (1985). This strengthens the suggestion made by Angulo and Giannini (1996) that the field observations used by Tomazelli and Villwock in Tomazelli (1990) are not sufficiently sound as evidence of millennial and ongoing RSL rise.

However, if the hypothesis of a recent RSL rise in Rio Grande do Sul is admitted, a possible explanation for the contrasting RSL behavior between Santa Catarina and Rio Grande do Sul coasts could be a differential neotectonism of their respective structural sectors, adjacent to the paleostructural high of Florianópolis and Pelotas Basin, respectively.

5.3. Relationships between δ^{18}O and the age of vermetid tubes

An inverse relationship, in the millennial time scale, between the paleosea surface temperatures and δ^{18}O from organic carbonate remains from the seabed has been assumed (Emiliani, 1954, 1955; Shackleton, 1967; Bowen, 1978; Lowe and Walker, 1984). Extending this relationship for the vermetid tubes, the general trend for increasing δ^{18}O with a reduction in age in the studied samples would indicate a gradual reduction of water temperature in the region during the last 5000 years. If true, this could explain the disappearance of vermetids to the south of Cabo Frio (22° south). Analogously, discrepant values of δ^{18}O recorded in samples comprised in a short time span (1180 to 1210 ± 70 years B.P.) and related to a constant sea level, could indicate a phase of intense paleoclimatic fluctuations, possibly with a regional character.

Acknowledgements

We would like to thank Guilherme Lessa for his comments and revision of this work, and Jacques L. Laborel for the suggestions that greatly improved the quality of the manuscript. We are thankful to the Laboratory of Environmental Isotopes of the University of Waterloo, Canada, for the determinations of δ^{18}O. Financial support for this work was provided by FAPESP (Proc. 95/2939-2), CNPq (Proc. 306327/88-0 and 522079/95-4) and the Geological and Mineralization Evolution Project-3, FINEP/PADCT-UFPR (no. 65.91.03.03.00).

References

Angulo, R.J., 1989. Fossil Vermetidae between latitudes 25°34′S and 27°09′S, State of Paraná and State of Santa Catarina, Brazil. Int. Symp. on Global Changes in South America during Quaternary, São Paulo, no. 1., Special Publ. São Paulo, Abequa/Inqua, pp. 263–268.

Angulo, R.J., 1992. Geologia da Planície Costeira do Estado do Paraná, PhD Thesis (unpublished). São Paulo, Instituto de Geociências, Universidade de São Paulo, 332 p.

Angulo, R.J., 1993. Indicadores biológicos de paleoníveis marinhos quaternários na costa paranaense. Bol. Paranaense de Geoc. 41, 1–34.

Angulo, R.J., 1994. Datações ao C14 do litoral paranaense e sua utilização na reconstrução de paleoníveis marinhos quaternários. Congresso Brasileiro de Geologia, 38, Balneario Camboriú. Resumos Expandidos, Vol. 1. Florianópolis, SBG, pp. 400–401.

Angulo, R.J., Giannini, P.C.F., 1996. Variação do nível relativo do mar nos últimos dois mil anos na Região Sul do Brasil: uma discussão. Bol. Paranaense de Geoc. 44, 67–75.

Angulo, R.J., Lessa, G., 1997. The Brazilian sea level curves: a critical review with emphasis on the curves from Paranaguá and Cananéia regions. Marine Geology 140, 141–166.

Bowen, D.Q., 1978. Quaternary Geology. Pergamon Intern. Oxford, Library, 237 p.

Castro, V.H.S., Castro, E.C., 1969. Geologia da Quadrícula de Laguna, SC, Internal report (unpublished). Porto Alegre, DMPM-1°, Distrito, 38 p.

Delibrias, C., Laborel, J., 1969. Recent variations of the sea level along the Brazilian coast. Quaternaria 14, 45–49.

DHN (Diretoria de Hidrografia e Navegação), 1989. Porto de Imbituba, DHN, Tábua de Marés. Rio de Janeiro, Ministério da Marinha, pp. 173–176.

Dominguez, J.M.L., Bittencourt, A.C.S.P., Leão, Z.M.A.N., Azevedo, A.E.G., 1990. Geologia do Quaternário costeiro do Estado de Pernambuco. Revista Brasileira de Geociências 20 (1–4), 208–215.

Emiliani, C., 1954. Depth habitats of some species of pelagic foraminifera as indicated by oxygen isotope ratios. Am. J. Sci. 252, 149.

Emiliani, C., 1955. Pleistocene temperatures. J. Geol. 63, 538–578.

Giannini, P.C.F., 1993. Sistemas Deposicionais no Quaternário Costeiro entre Jaguaruna e Imbituba, SC, PhD Thesis (unpublished). São Paulo, Instituto de Geociências, Universidade de São Paulo, 2v, two maps, 439 p.

Giannini, P.C.F., Santos, E.R., 1994. Padrões de variação espacial e temporal na morfologia de dunas de orla costeira no centro-sul catarinense. Bol. Paranaense de Geoc. 42, 73–95.

Giannini, P.C.F., Suguio, K., 1994. Diferenciação entre gerações de depósitos eólicos quaternários da costa centro-sul de Santa Catarina. Congr. Bras. Geol., 38, Balneário Camboriú. Bol. Resumos Expandidos, Vol. 1. Florianópolis, SBG, pp. 402–403.

Horbach, R., Marimon, R.G., 1980. Esboço da evolução tectônica e seu significado na gênese dos depósitos de fluorita do sudeste catarinense. Congr. Bras. Geol., Balneário Camboriú, Anais, Vol. 3. Florianópolis, SBG, pp. 1540–1551.

Laborel, J., 1979. Fixed marine organisms as biological indicator for the study of recent sea level and climatic variations along the Brazilian tropical coast. Proc. Int. Symp. on Coastal Evolution in the Quaternary, São Paulo, 1978. Proceedings, São Paulo, IGCP/Project 61, Instituto de Geociências, Universidade de São Paulo, pp. 193–211.

Laborel, J., 1986. Vermetid gastropods as sea-level indicators. In: van de Plassche, D. (Ed.), Sea-level Research: A Manual for the Collection and Evaluation of Data. Norwich, Geo Books, pp. 281–310.

Lister, G.S., Etheridge, M.A., Symonds, P.A., 1986. Detachment faulting and the evolution of passive continental margins. Geology 14 (3), 246–250.

Lowe, I.J., Walker, M.J.C., 1984. Reconstructing Quaternary Environments. London, 389 p.

Martin, L, Flexor, J.M., Boas, G.S.V., Bittencourt, A.C.S.P., Guimarães, M.M.M., 1979a. Courbe de variation du niveau relatif de la mer au cours des 7000 derniéres années sur un secteur homogène du littoral brésilien (nord de Salvador-Bahia). Int. Symp. on Coastal Evolution in the Quaternary, São Paulo, 1978. Proceedings, São Paulo, IGCP/Project 61, Instituto de Geociências, Universidade de São Paulo, pp. 296–331.

Martin, L., Suguio, K., Flexor, J.M., 1979b. Le Quaternaire marin du littoral brésilien entre Cananéia (SP) et Barra de Guaratiba (RJ). Int. Symp. on Coastal Evolution in the Quaternary, São Paulo, 1978. Proceedings, São Paulo, IGCP/Project 61, Instituto de Geociências, Universidade de São Paulo, pp. 296–331.

Martin, L., Suguio, K., 1978. Excursion rout along the coastline between the town of Cananéia (state of São Paulo) and Guaratiba outlet (state of Rio de Janeiro). Int. Symp. on Coastal Evolution, São Paulo, 1978. Spec. Publ. no. 2, São Paulo, IG, USP, SBG, 98 p.

Martin, L., Suguio, K., 1989. Excursion Route along the Brazilian Coast Between Santos (SP) and Campos (RJ) (North of State of Rio de Janeiro). Int. Symp. on Global Changes in South America during the Quaternary, São Paulo. Special Publ. No. 2, São Paulo, Abequa, Inqua, 136 p.

Martin, L., Suguio, K., Flexor, J.M., Azevedo, A.E.G., 1988. Mapa Geológico do Quaternário Costeiro dos Estados do Paraná e Santa Catarina. Brasília, DNPM, 2 mapas (Série Geologia 28), 40 p.

Morgental, A., Kirchner, C.A., 1983. Síntese do mapa previsional do distrito de fluorita de Santa Catarina. Simpósio Sul-brasileiro De Geologia, 1, Porto Alegre. Atas, Porto Alegre, SBG/RS-SC, pp. 294–306.

Pereira, M.J., Macedo, J.M., 1990. A bacia de Santos: perspectivas de uma nova província petrolífera na plataforma continental sudeste brasileira. Bol. Geoc. Petrobrás 4 (1), 3–11.

Pessenda, L.C.R., Camargo, P.B., 1991. Datação radiocarbônica de amostras de interesse arqueológico e geológico por espectrometria de cintilação líquida de baixo nível de radiação de fundo. Química Nova 14 (2), 98–103.

Porto de Imbituba, 1997. http://200.135.0.104/caracteristica.html.

Shackleton, N.J., 1967. Oxygen isotope analyses and Pleistocene temperatures reassessed. Nature 215, 15–17.

Suguio, K., Martin, L., 1978. Formações quaternária marinhas do litoral paulista e sul fluminense. Int. Symp. on Coastal Evolution in the Quaternary, São Paulo, 1978. Spec. Publ., no. 1. São Paulo, IGCP, Project 61, Instituto de Geociências, Universidade de São Paulo, 55 p.

Suguio, K., Martin, L., Flexor, J.M., 1980. Sea level fluctuations during the past 6000 years along the coast of the state of São Paulo, Brazil. In: Mörner, N.A. (Ed.), Earth reology, isostasy and eustasy. Chichester, Wiley, pp. 471–486.

Suguio, K., Martin, L., Bittencourt, A.C.S.P., Dominguez, J.M.L., Flexor, J.M., Azevedo, A.E.G., 1985. Flutuações do nível relativo do mar durante o Quaternário superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira. Rev. Bras. Geoc. 15 (4), 273–286.

Tomazelli, L.J., 1990. Contribuição ao Estudo dos Sistemas Deposicionais Holocênicos do Nordeste da Província Costeira do Rio Grande do Sul, com Ênfase no Sistema Eólico, PhD Thesis (unpublished). Porto Alegre, Universidade Federal do Rio Grande do Sul, 270 p.

Trainini, D.R., Dias, A.A., Krebes, J., Souza, E.C., Capeletti, I., Toniolo, J.A., Silva, M.A.S., 1978. Projeto Vidal Ramos-Biguaçu, Relatório Final, Internal report (unpublished). Porto Alegre, DNPM/CPRM, 5v., maps.

van Andel, T.H., Laborel, J., 1964. Recent high relative sea level stand near Recife, Brazil. Science 145, 571–580.

Zembruscki, S.G., 1979. Brasil, Margem Continental, Mapa Fisiográfico (Área Sul). Rio de Janeiro, Petrobras/Cenpes/Dintep (Projeto Remac Series).