Radiocarbon, Vol 63, Nr 4, 2021, p 1149–1163 DOI:10.1017/RDC.2021.50
Selected Papers from the 1st Latin American Radiocarbon Conference, Rio de Janeiro, 29 Jul.–2 Aug. 2019

BIOINDICATORS OF SEA-LEVEL FLUCTUATIONS IN SOUTHEASTERN BRAZIL: NEW DATA AND METHODOLOGICAL REVIEW

Julia Caon Araujo[1]* • Kita Chaves Damasio Macario[2] • Vinícius Nunes Moreira[2] • Anderson dos Santos Passos[3] • Perla Baptista de Jesus[3] • José Carlos Sícoli Seoane[1] • Fabio Ferreira Dias[3]

[1]Departamento de Geologia, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 274, Ilha do Fundão, Rio de Janeiro (RJ), Brazil
[2]Laboratório de Radiocarbono, Instituto de Física, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza s/n, 24210-346, Niterói, RJ, Brazil
[3]Instituto de Geociências, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza, Campus da Praia Vermelha, Boa Viagem, Niterói, RJ, Brazil

ABSTRACT. The vermetidae fossils of *Petaloconchus varians*, formed by calcium carbonate, associated with their radiocarbon ages, are the most accurate indicators of paleo sea level due to their restricted occupation in the intertidal zone in the rocky shore. However, the recrystallization of minerals can affect these age calculations and, consequently, the interpretation of the data. The aim of this study is to present new indicators of paleo sea-level changes in Southeast Brazil for the last 6000 years contributing to fill the data gap for the late Holocene. The influence of the recrystallization process was successfully resolved using the CarDS protocol, enabling the separation of the original aragonite fraction by density, prior to radiocarbon dating. This avoids the rejuvenation of ages and ensures greater efficiency for data interpretation. Paleo sea-level indicators were able to show a progressive increase in sea level up to the transgressive maximum of 4.15 m in 3700 BP years, followed by a regression to the current zero. This regression seems to have in addition, here we reinforce the reliability of the use of fossil vermetids as indicators of sea-level fluctuations.

KEYWORDS: biological indicators, CarDS, marine samples, paleo sea level, *Petaloconchus*, recrystallization, sea-level fluctuation.

INTRODUCTION

It has been the goal of multiple authors (e.g., Suguio et al. 1985; Angulo and Lessa 1997; Castro et al. 2014; Jesus et al. 2017) to reconstruct Late Holocene paleo sea-level fluctuations along the Brazilian coast, in order to correlate it to current climate changes, and thus anticipate and aid in the mitigation of future impact.

According to Suguio et al. (1985), evidence of relative sea-level variations can be grouped into three distinct sets: (1) prehistoric, which is evidenced by the constructions of ancient native peoples of the coastal zones—the shell midddens, called *sambaqui* in the native language; (2) geological, such as sandy terraces of marine origin and beach rocks; and (3) biological, defined by incrustations of vermetidae, oysters and hedgehog marks, located above the current life span of these animals.

Recent studies cover a strip of the Brazilian coast, which extends from the state of Rio Grande do Norte to Rio Grande do Sul, assessing the transformations of the last 7000 years. For the region of Southeast Brazil, several studies suggest a transgressive maximum at around 5600 cal BP followed by a regression with small oscillations to the current zero (Suguio et al. 1985; Martin et al. 2003; Castro et al. 2014; Jesus et al. 2017). So far, sea-level fluctuation indicators are scarce in the Angra dos Reis region. Delibras and Laborel (1969); Martin and Suguio (1978); Martin et al. (1979, 1980), Martin and Suguio (1989), and Suguio et al. (1985) have only established a sea-level variation curve for the last 2500 years. Souza et al.

*Corresponding author. Email: juliacaon@id.uff.br

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

(2015a, 2015b) present an alternative to the lack of data on the north coast of the State of São Paulo, old records of sea urchin—holes in the rocks—that integrate the fauna of the infralittoral and beachrocks as indicators of sea-level fluctuations during the Holocene.

Fossil worm groups—tubular shell-shaped gastropod mollusks that live embedded in a substrate—are commonly used as indicators of sea-level variation because they dominate the mid-tidal portion of the rocky shores, indicating more accurately the relative sea-level in a given region (Delibrias and Laborel 1969; Laborel 1986; Angulo et al. 1999; Angulo et al. 2006; Dias et al. 2011). Reconstructions of former relative sea-level positions are based on evidence defined in space and time. To define the position of this evidence in space it is necessary to know their current altitude in relation to the original, that is, to know their position in relation to sea-level at the time the evidence was formed. To define it in time, it is necessary to find out the period of its formation through dating methods, such as the ^{14}C method.

By establishing many former relative sea-level positions, it is possible to construct a sea-level fluctuation curve for a specific region covering a given time interval (Suguio et al. 1985). Currently, for the Angra dos Reis region, a relative sea-level variation curve exists, covering the last 3500 years BP, with special emphasis on the final 2500 years (Suguio et al. 1985).

Most articles about sea-level variation curves in Brazil do not address the protocol used for carbonate sample treatment prior to dating. The first researchers to show concern over this were Angulo et al. (1999, 2002) and Ribeiro et al. (2011). The former reported on the use of hydrochloric acid to remove calcite, and the latter, on the results of X-ray diffraction analyses to verify the presence of secondary minerals in the vermetid samples. In the present study, we use the methodology of Moreira et al. (2020). Treatment with hydrochloric acid proved to be not enough to allow the elimination of calcite. In the present work, the separation of aragonite and calcite by density proved to be more efficient, avoiding the influence of recrystallization of the newly formed mineral.

The new data provide information that contributes to the period of 2500 to 6000 years BP, partially filling the gap of Suguio et al. (1985) for the Ilha Grande Bay region. Samples of fossil vermetids were dated by ^{14}C from the original aragonite, which guarantees greater precision of the results. This article seeks to emphasize the importance of a detailed description of the pretreatment methods for dating by ^{14}C in carbonate incrustations due to their influence on the calculation of ages.

Thus, the development of this study sought to verify the relative sea-level variations in Angra dos Reis using biological samples (vermetidae) as indicators through literature reviews and analysis using new vermetid dating methodology.

STUDY AREA

Angra dos Reis is located on the southern coast of the state of Rio de Janeiro, Brazil, between latitudes 22°50'S, 44°00'W and 23°20'S, 44°45'W. Angra dos Reis is located in the Ilha Grande Bay (65,258 ha) and borders the municipalities of Paraty and Mangaratiba.

The Ilha Grande Bay has a tropical climate, hot and humid, with high temperatures and high rainfall. The continental portion of the Ilha Grande Bay has a very rugged, mountainous terrain, with undulating to steep terrain. In this configuration, the only flat areas are floodplains and

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

mangroves. Sandy strands are restricted, with a predominance of rocky coastline. Thus, it is characterized by a submergent coastline with several islands (Neves and Muehe 2008).

Bathymetry is characterized by extensive shallow areas with depths of up to 40 m, except for interior channels where the bathymetric elevation can reach 55 m. In natural harbor and bight areas the average depth is less than 10 m. During the summer, the sea surface temperature varies from 24.4ºC to 28.4ºC. During the winter, they register temperatures between 24ºC and 26ºC (Inea 2015).

The region suffers direct action from the waves in the south quadrant. In winter, the region is exposed to swells in the southern quadrants (SW–S–SE), wind speeds above 18 m/s and waves 5–6 m high in the open sea. In summer, it presents smaller waves, between 0.3 and 0.4 m (Cavalcante 2010). The tidal regime is of the semidiurnal type with diurnal inequality, keeping with the pattern of the southeastern coast of Brazil.

METHODOLOGY

Suguio et al. (1985) tried to outline the sea-level fluctuation curve for the sector located between Paraty and Angra dos Reis, making it possible to reconstruct 17 old positions of relative sea-level. These indicators only represent the last 2500 years and it is, therefore, not possible to draw a curve. Some researchers have shown concern about using fossil material for the purposes of dating. The presence of calcite occurring next to aragonite can change the apparent ages of the records. Ribeiro et al. (2011) analyzed the samples by X-ray diffraction to check their mineralogy. In his sample dating treatment methodology, Angulo et al. (2002) added a step whereupon shells were washed in HCL to eliminate calcite, avoiding interference in the ages. Dias et al. (2011), visiting islands in the Ilha Grande Bay, determined ages and heights at sea level of vermetidae fossil and calculated the altitudes of living gastropods.

The methodology consisted of developing safer techniques for obtaining space-time information on samples, their height on the rocky shore and dating by AMS ^{14}C.The CarDS protocol uses a heavy liquid (in our case sodium polytungstate, SPT) of known density to separate original aragonitic structures from secondary calcite ones, prior to AMS dating (Moreira et al. 2020). In addition, we sought to analyze the influence of the polynomial degree on the configuration of the sea-level fluctuation curve and its effects on data interpretation.

Vermetidae Fossils and the Definition of Current and Paleo Sea Levels

Occurrences of fossilized vermetid fouling were investigated in the rocky shores located in the Ilha Grande Bay. Altitudes were defined using Zenith GPS trackers as static GPS, with post-processed differential correction, in relative mode.

The search for fossils occurred on several islands (Figure 1), always in the more sheltered faces, especially in cracks parallel to the horizontal arrangement of the organisms that inhabit the rocky shores, such as barnacles, sea urchins, seaweed, and mussels, thus indicative of different positions of the water level. Preference was given to the vermetidae fossils that appear along lines formed by old barnacle and sea urchin holes. Urchin holes situated above the present-day tide level can no longer be occupied (Figure 2), becoming a type of

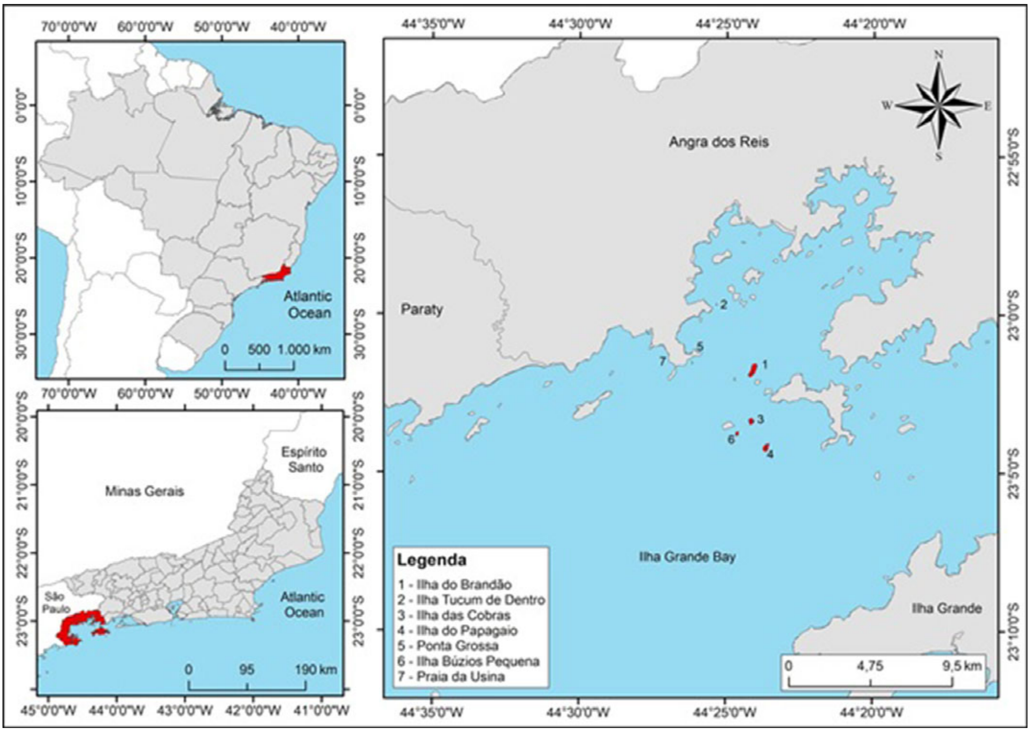

Figure 1 Map of the study area, Ilha Grande Bay, Rio de Janeiro, Brazil. Localization of vermetidae scale samples.

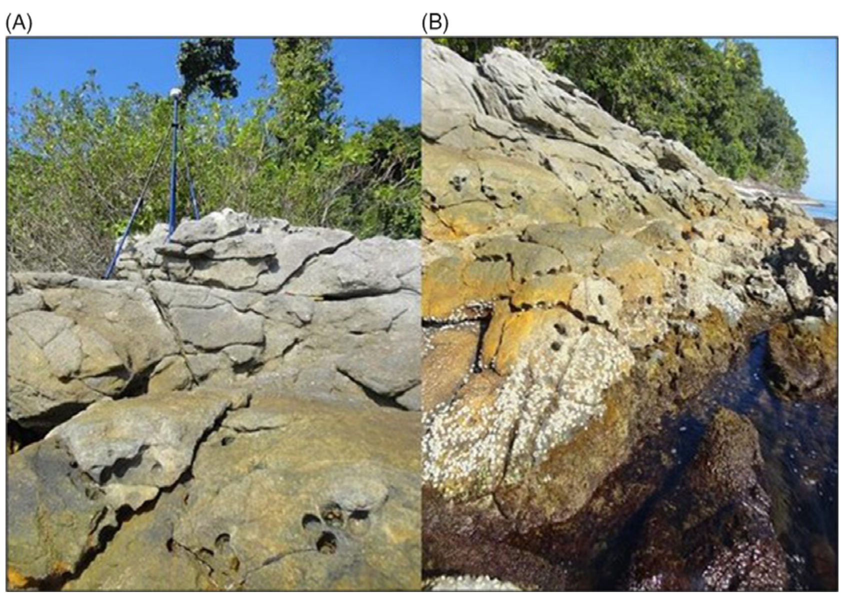

Figure 2 (A) vermetid fossil location; (B) rocky shore ecology.

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

iconofossil that could be used to infer below tide conditions and periods of sea-level stability (Angulo and Souza 2014).

The base station was set up on Reference Level (RN) number 93520 - Angra dos Reis, which has data is made available by the Brazilian Institute of Geography and Statistics - IBGE in its geodetic database for post processing.

The altitude determined by a GNSS receiver is not related to mean sea-level (geoid), but rather to a reference ellipsoid with specific dimensions. Thus, it was necessary to establish the difference between the geoid and ellipsoid surfaces, that is, the geoidal height (or undulation), in order to determine the altitude above mean sea-level, orthometric height.

The conversion of the ellipsoidal altitude (h) resulting from the field survey with GNSS receivers to orthometric altitude (H) is performed using the geoidal height value (N) provided by a geoidal undulation model, as follows: $H = h - N$.

The ellipsoidal heights were processed in the EzSurver subprogram to obtain geographic coordinates. The geoidal ripple calculation was performed using the software MAPGEO 2015.

Vermetidae samples were collected on rocky shores (attached to metamorphic rocks) in the islands and continental shores of the Ilha Grande Bay: Brandão Island and Tucum de Dentro Island; Parrot Island (2 collection points), Cobras Island, Ponta Grossa, Buzios Pequena Island, and Usina Beach (Figure 1).

Radiocarbon Dating

Vermetidae fossils of the species *Petaloconchus varians* are sessile gastropods, belonging to the Vermetidae Rafinesque family, 1815 (Mollusca, Prosobranchia, Caenogastropoda). They consist of dense assemblages with a gregarious way of life (living in groups) that grow fixed in the substrate and may form a dense carbonate reef structure (Soares et al. 2010). They are formed by tubular shells characterized by extremely irregular growth and are strictly associated with the lower limit of the mid-coastal region (Vescogni et al. 2008).

Ages were determined by radiocarbon method of accelerator mass spectrometry (^{14}C-AMS) at the Radiocarbon Laboratory of the Fluminense Federal University (LAC-UFF). Samples of vermetidae, mostly composed of calcium carbonate ($CaCO_3$) in the form of aragonite (2.93 g/cm^3), are likely to recrystallize and become calcite (2.71 g/cm^3), the most stable crystalline form of $CaCO_3$ (Schmalz 1967; Bathurst 1972) and thus may or may not capture exogenous carbon, which is not original to the sample, influencing the measured age. To obtain more reliable dating, a new density separation protocol was applied following Moreira et al. (2020), where the samples were grinded and subjected to a known density solution (2.84 g/cm^3) prepared with sodium polytungstate (SPT). This solution separates the calcite fraction, so that only the original carbon of the sample (from the aragonite shell) is measured. To check if the separation was done correctly, we performed an X-ray diffraction (XRD) analysis, with results are presented below (Table 1).

To ensure the correct interpretation of ages, the results were calibrated from the database produced by the radiocarbon scientific community. Calibration is necessary as it considers variations in ^{14}C production and distribution over time and, in samples from the marine environment, correct for the marine reservoir effect (Macario and Alves 2018).

Table 1 Results of XRD analysis before and after the CarDS protocol (Moreira et al. 2020).

Sample	Before		After	
	Aragonite (%)	Total calcite (%)	Aragonite (%)	Total calcite (%)
A03	47.30	50.97	100.00	0.00
A04	64.32	30.39	100.00	0.00
A05	73.27	21.47	100.00	0.00
A06	83.39	12.14	100.00	0.00
A07	34.47	62.93	93.94	6.06
A08	62.57	26.01	100.00	0.00
A09	76.74	13.22	100.00	0.00
A10	36.80	58.73	96.46	3.54

Table 2 Paleo sea levels inferred from vermetids (Angulo et al. 2014).

Source	Site	Height (m)	^{14}C age (BP)	Code
Martin and Suguio (1989)	Tarituba	0.7	550 ± 70	Bah-478
	Praia de Mambucaba	1.5	1370 ± 100	Bah-471
Martin et al. (1979–1980)	Praia do Meio	0.4	390 ± 100	Bah-488
Martin and Suguio (1978)	Mangaratiba	1.7	3040 ± 100	Bah-472
	Mangaratiba	0.8	1150 ± 80	Bah-499
	Frade	1.5	2380 ± 180	Bah-465
	Coroa Grande	1.6	2250 ± 180	Bah-473
	Ilha do Araújo	1.4	1880 ± 120	Bah-470
	Mosuaba	0.5	230 ± 60	Bah-483
	Parati-Mirim	1.0	1020 ± 100	Bah-482
Delibras and Laborel (1969)	Ilha Grande	3.0	3240 ± 110	Gif-1061
	Ilha Grande	1.5	1180 ± 100	Gif-1060
	Ilha Grande	0.5	390 ± 90	Gif-1059

Conventional ages were calibrated using Marine13 (Reimer et al. 2013) and $\Delta R = 32 \pm 44$ (Alves et al. 2015) calibration curve.

Relative Sea-Level Fluctuation Curve

Despite having few samples, two curves of relative sea-level variation to the south of the State of Rio de Janeiro were drawn using vertical altitude measurements (y) (altitude) and the age averages calibrated on the horizontal axis (x) to compare the effects of SPT treatment on the model. The fourth-degree polynomial was used to establish the best fit trendline based on the data set and the field evidence.

The first shows the calibrated ages of the samples which underwent HCl pretreatment only, while the second shows the variation in sea level in relation to the calibrated ages after pretreatment with SPT.

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

The ages obtained from vermetid samples after SPT treatment (Aragonite) were compared with samples from other Holocene sea-level fluctuations studies for the same region. Data from Delibras and Laborel (1969); Martin and Suguio (1978); Martin et al. (1979, 1980) and Martin and Suguio (1989) are presented in Table 2.

RESULTS

Bioindicator Heights and Radiocarbon Ages

The resulting orthometric heights of the fossil vermetidae range from –0.05 to 4.15 m above MSL, with corresponding geographic coordinates (SIRGAS 2000 datum) and ellipsoidal heights. The results of orthometric heights and radiocarbon ages are presented in Table 3.

There is observable difference in the age range after the CarDs treatment (dating of the original aragonite fraction, before the recrystallization process).

Preliminary Sea-Level Fluctuation Curve

The different protocols for radiocarbon dating in fossil vermetids can considerably impact the interpretation of sea-level behavior during the Holocene, as shown in Figure 3. Ages obtained after sample treatment with HCl are more recent, with differences of up to 2000 years. Despite few samples, the preliminary curve corroborates with other studies carried out in the region, such as Delibras and Laborel (1969), Martin and Suguio (1978), Martin et al. (1979, 1980), Suguio et al. (1985), Martin and Suguio (1989), Dias (2009), Castro et al (2014), and Jesus et al. (2017), showing a progressively increasing sea level up to the transgressive maximum of 4.15 ± 0.5 m to about 3792 ± 25 cal years BP, followed by regression with possible fluctuations to the current sea level.

The solid line shows a similar trend to the ones of the Brazilian coast and elsewhere in the Southern Hemisphere (Angulo and Lessa 1997; Ramsay and Cooper 2002; Milne et al. 2005; Sloss et al. 2007; Martinez and Rojas 2013). Sea-level behavior during the Holocene in the coast of Southeast Brazil is represented by a rise of the sea-level between 6000 and 4000 years BP, reaching a peak then (Suguio et al. 1985; Dias et al. 2011; Castro et al. 2014; Jesus et al. 2017), followed by a regression to the current zero.

DISCUSSION

Vermetidae are organisms that during their lives build reefs (biological carbonate concretions) forming complex structures that occupy the middle portion of the region between tides of rocky shores (Breves-Ramos et al 2010). They are currently considered by several authors as one of the most reliable indicators of sea level variation (Suguio et al. 1985; Angulo and Lessa 1997; Vescogni et al. 2008; Dias 2009; Spotorno-Oliveira et al. 2016; Jesus et al 2017; Areias et al. 2020). Their strict ecology on the coast means that the vermitids occupy the intertidal region and colonize rocky shores up to 1 m above the current sea level in regions of low tide and low wave exposure (Angulo et al. 2006).

Vermetidae are considered excellent indicators of sea level due to their wide distribution, abundance and narrow vertical range of occurrence, ensuring accuracies of ± 10 cm (Laborel 1986; Baker and Haworth 1997; Baker et al. 2001; Angulo and Souza 2014). However, inaccuracies may be related to (1) fossil formation processes and (2) the degree of exposure to waves. Such factors can be minimized by considering the recrystallization

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

Table 3 Altitude and chronology of the bioindicators.

Sample	Site	Geographic coordinates	Height (m)	Treatment	^{14}C age (BP)	UGA ID	LACUFF ID
A03	Brandão	−23°01'36.2865" −44°23'57.4554"	0.44	Bulk raw	1053 ± 32	—	180175
				Bulk HCl	1425 ± 73	—	180176
				Bulk H_2O_2	—	—	—
				Aragonite	1677 ± 36	—	180177
				Calcite	1321 ± 36	—	190193
A04	Tucum de Dentro	−22°59'40.6745" −44°25'21.3800"	−0.05	Bulk raw	786 ± 40	—	180178
				Bulk HCl	927 ± 52	—	180179
				Bulk H_2O_2	—	—	—
				Aragonite	877 ± 47	—	180180
				Calcite	509 ± 33	—	190194
A05	Cobras	−23°03'17.7455" −44°24'14.7884"	0.72	Bulk raw	1709 ± 32	—	180181
				Bulk HCl	1822 ± 38	—	180182
				Bulk H_2O_2	1450 ± 33	—	190196
				Aragonite	1702 ± 47	—	180183
				Calcite	1450 ± 31	—	190195
A06	Papagaio 1	−23°04'10.2313" −44°23'44.3402"	0.20	Bulk raw	873 ± 31	—	180184
				Bulk HCl	940 ± 50	—	180185
				Bulk H_2O_2	817 ± 27	—	190198
				Aragonite	917 ± 31	—	180186
				Calcite	785 ± 31	—	190197
A07	Papagaio 2	−23°04'10.2246" −44°23'43.9961"	2.71	Bulk raw	3527 ± 49	—	180187
				Bulk HCl	3587 ± 51	—	180188
				Bulk H_2O_2	—	—	—
				Aragonite	5819 ± 45	—	180189
				Calcite	5108 ± 37	—	190199

Table 3 (*Continued*)

Sample	Site	Geographic coordinates	Height (m)	Treatment	^{14}C age (BP)	UGA ID	LACUFF ID
A08	Ponta Grossa	−23°01'10.8537" –44°25'52.8693"	2.26	Bulk raw	1682 ± 36	—	180190
				Bulk HCl	2222 ± 41	—	180191
				Bulk H_2O_2	2451 ± 34	—	190201
				Aragonite	2814 ± 40	—	180192
				Calcite	2391 ± 33	—	190200
A09	Búzios Pequena	−23º03’44.2255” –44º24’39.4538”	0.36	Bulk raw	962 ± 41	—	180193
				Bulk HCl	1092 ± 60	—	180194
				Bulk H_2O_2	753 ± 31	—	190203
				Aragonite	743 ± 34	—	180195
				Calcite	774 ± 30	—	190202
A10	Usina Beach	−23°01'13.7571" –44°26'58.4568"	4.15	Bulk raw	3198 ± 24	30648	—
				Bulk HCl	3256 ± 24	30649	—
				Bulk H_2O_2	3600 ± 32	34702	—
				Aragonite	3792 ± 25	30650	—
				Calcite	3632 ± 26	30651	—

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

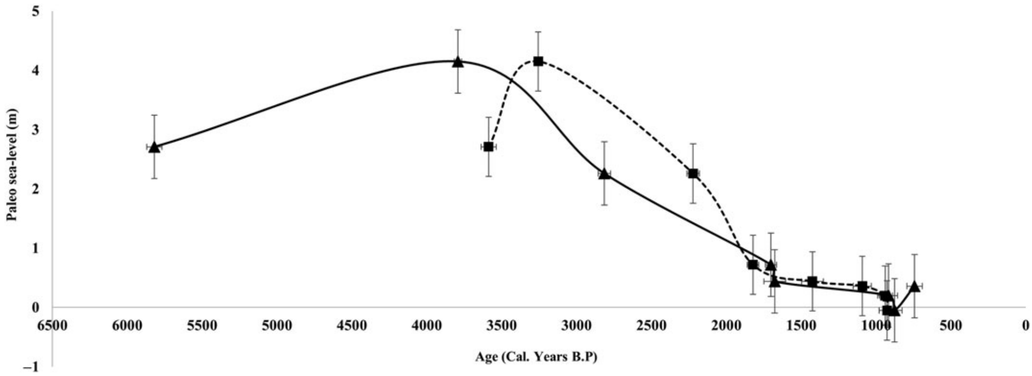

Figure 3 Effect of age difference on the sea-level variation curve with SPT treatment. Squares correspond to the ages obtained after treatment with HCl, while ages for samples dated from the original aragonite content are represented by triangles.

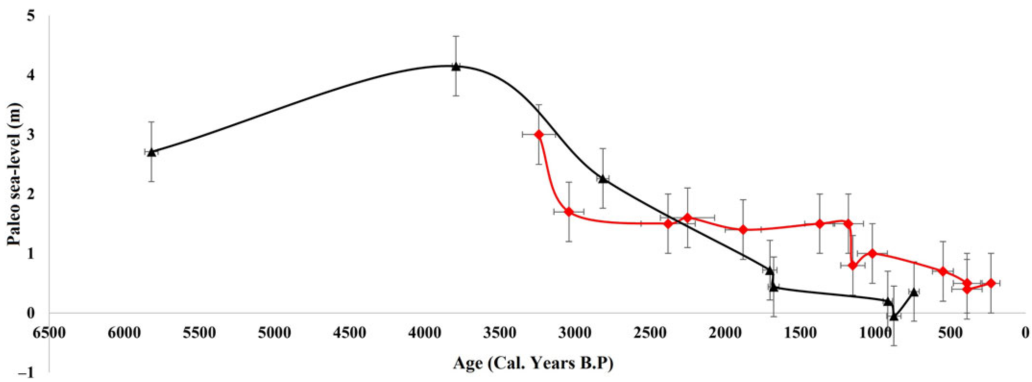

Figure 4 Sea-level curve form age-dated vermetids from the SPT treatment (aragonite—black line). Curve composed from data compiled for the Ilha Grande Bay region (red line). Data compiled from Delibras and Laborel (1969), Martin and Suguio (1978), Martin et al. (1979, 1980), Suguio et al. (1985), and Martin and Suguio (1989). (Please see electronic version for color figures.)

process at the time of dating, that is, the replacement of aragonite by calcite (Silenzi et al. 2004) and ± 0.50 m in sheltered shores and ± 1.0 m in exposed shores (Jesus et al. 2017).

Previously, sea-level data for the region covered only the last 3500 years BP, at a maximum sea level about 3 m above the current (Suguio et al. 1985). Dias et al 2011 reported the occurrence of fossil vermetids in the Bay of Ilha Grande at 2.5 m above sea level dated 2810 ± 95 years cal BP. Martin and Suguio (1978) dated two samples of oysters (5200 ± 200 years AP and 4800 ± 200 years BP) at about 4.8 m above current sea level. Despite signaling an altitude higher than that recorded in the present study, Angulo et al. (2006) reinforces that oysters can live in a wide range of altitude, being limited of limited use as paleo-indicators of the level of the sea.

Figure 4 shows the proposed sea-level curve (black line) compared to a curve obtained from old data from by Delibras and Laborel (1969), Martin and Suguio (1978), Martin et al. (1979, 1980), Suguio et al. (1985) and Martin and Suguio (1989) for the same region (red line). The comparison of the two trend lines highlights the differences between the dating

https://doi.org/10.1017/RDC.2021.50 Published online by Cambridge University Press

methods, as well as the compromises in the interpretation of the old data, and the need for and importance of collecting new data for the region.

The data obtained for sea-level fluctuation indicators for the Ilha Grande Bay, in Southeast Brazil, corroborates with the various curves already presented for the Brazilian east coast (Angulo and Lessa 1997; Jesus et al. 2017; Castro et al. 2018). It shows a transgressive maximum between 5000 and 3500 years BP, following a regressive movement, not without significant oscillations, to the current zero. In Suguio et al. (1985) several RSL curves are presented for the Brazilian coast, including the study for Angra dos Reis, which contemplates only the last 2500 years BP and presents some oscillations. However, the authors infer the existence of two transgressive maxima, the first just over 3 m between 3650 and 3450 years BP and the second of about 4.8 m at 5200 years BP. The present data can contribute to this discussion because it presents indicators with a height of 2.71 m in ca. 5819 cal years BP and 4.15 m at ca. 3792 cal years BP.

The new indicators cover the last 6000 years and only show subtle oscillations—within the margin of errors of the indicators, unlike the only other published curve for this region (Suguio et al. 1985), which has several sea-level oscillations for the last 2500 years BP. Such differences are explained by the use of different indicators, precision altitude reading and dating methodologies. However, oscillations can be masked by the construction of the curves, disguising subtler sea-level variations, often identified in the height range of the vermetid inlays. As more samples are used, these subtleties will tend to appear more.

Few studies related to sea-level variation in Brazil describe the pretreatment for radiocarbon dating of its biological indicators. The ages of fossil vermetids presented in previous curves did not consider the effect of aragonite recrystallization into calcite (Suguio et al. 1985; Dias 2009; Dias et al. 2011; Castro et al. 2014), which can increase the margin of uncertainty with the rejuvenation of ages. Angulo et al. (1999) point to the importance of pretreatment with rapid immersions in HCl (2%) to eliminate secondary carbonate in vermetid tubes. However, this is not enough to eliminate the secondary calcite fraction, as shown in the present study, for example, in the age difference before and after pretreatment with SPT, for sample A07 (Bulk HCl 3587 ± 51 yr; Aragonite 5819 ± 45). Ribeiro et al. 2011 recognize the considerable role of recrystallization in calculating ages by ^{14}C in fossil vermetid samples from the coast of Espírito Santo (southeastern Brazil). The authors carried out mineralogical analysis of fossil vermetids by XRD (X-ray diffraction) which showed a tendency of calcite and aragonite mixed at the upper levels (related to the oldest samples), and of purely aragonitic composition, in the lower ones (newer samples). The authors also observed, through SEM (scanning electron microscope), layers of secondary calcite covering aragonite tubes in greater proportions in the samples with upper levels. This trend is also noted here, as shown in Tables 1 and 3.

Disregarding the effects of the recrystallization process may lead to errors and interfere with sample age results, as well as problems related to calibration, thus compromising data interpretation. Age calibration aims to correct variations in atmospheric isotopic concentrations caused by several factors (Hajdas 2009; Queiroz-Alves et al. 2018). In addition to this, it is important to consider the reservoir effect whenever the medium presents a different isotopic concentration than the current atmosphere (Macario and Alves 2018), as in the case of vermetid shell samples. Previously published sea-level variation curves for sections of the Brazilian east coast were reconstructed after normalization and age calibration ^{14}C (Suguio et al.1985; Martin et al. 2003), thus emphasizing the need for age calibration to correct the interpretation of the data.

Other factors must be considered in relation to the precision of the fossil vermitid altitudes: (1) the amplitude of the occurrence of living vermitid in relation to fossil ones; (2) local hydrodynamics; (3) presence of shelter in the rocks (cracks and fractures) to protect against mechanical abrasion by waves and chemical weathering by meteoric water; (4) salinity and water temperature and luminosity; (5) neotectonic events (Angulo et al. 1999; Ribeiro et al. 2011; Angulo and Souza 2014). In the region of Angra dos Reis, living vermetids embedded in rocky shores occur at about –0.4 m (±0.05 m; Dias et al. 2011), typical amplitude of occurrence in bay regions.

It is possible that certain parts of the coast have been affected by a continental flexural mechanism, but this phenomenon seems to have an influence on a much larger scale of time than the Holocene (Martin and Suguio 1976). For some authors, the important role of neotectonics in the evolution of the Brazilian coast is almost unquestionable, with evidence of horizontal displacements of holocenic paleolines on the coast of the Brazilian coast as a consequence of vertical tectonic movements (Martin et al. 1984) and tectonic fractures appearing in the Barreiras Formation in the extreme north of Bahia (Lima 2010) as excellent examples. Suguio and Martin (1996), on the other hand, believe there is much speculation on the subject and a lack of scientific studies based on actual field and laboratory data, essential for getting a more reliable picture on the matter. Even in the marginal basins studied in the most detail, the majority of what is known about it is restricted to Cretaceous and Paleogene, and rarely have they been studied from a neotectonic point of view. It is therefore required and recommended that many more studies which encompass time and space scales are done for a better understanding of the true role played by neotectonics in the evolution of the Brazilian coast.

Thus, the importance of pretreatment of the samples by the CarDS method is observed in order to remove recent carbon contamination and avoid rejuvenation of measured ages (Douka et al. 2010; Moreira et al. 2020). In addition, for statistical analysis, it is necessary to consider the set of samples and the evidence from the field. Sea-level variation curves using multiproxy data may be the key to paleoenvironmental interpretations. For example, accumulations of shells in life may indicate transgressive highs and old beachrock shorelines lows (Ramsay 1996; Ramsay and Cooper 2002; Lewis et al. 2008; Dias 2009; Spotorno-Oliveira et al. 2016; Cunha et al. 2018; Ramsay and Cooper 2002; Malta and Castro 2018). Thus, the use of several types of indicators can provide information for a more complete paleoenvironmental reconstruction.

CONCLUSION

The separation of the original fraction of aragonite from secondary calcite by density (SPT) proved to be efficient for dating by ^{14}C. The new data presented contribute to the existing curves for the southeastern coast of Brazil and can fill the lack of data for the period of 6000 to 3500 years BP. According to the indicators, the sea level during the Holocene in the Angra dos Reis region behaved similarly to the rest of the Brazilian coast, although presenting a relatively higher transgressive maximum than most other published data for the State of Rio Janeiro. More surveys are needed to increase the accuracy of interpretation.

The new occurrences of fossil vermetidae and associated data expand the current knowledge of sea-level variations in southeastern Brazil. Through the process of recrystallization in vermetid fossils (transformation of aragonite to calcite in calcium carbonates) the ages of the samples can be rejuvenated, leading to misinterpretation. Over the years, research related to sea-level variations during the Holocene has warned us about changes in sample ages by recrystallization processes (Mendonça and Godoy 2004; Angulo et al. 2006; Ribeiro et al. 2011; Angulo and Souza 2014; Jesus et al. 2017). The CarDS protocol is used to overcome this problem.

Sea-level variation curve building needs to consider several factors regarding data collection: (1) types of marine paleo level indicators and their limitations, (2) precise methods for surveying the altitudes of the samples, and (3) pretreatment protocol for radiocarbon dating. Thus, we suggest continuing the surveying of indicators so that the behavior of sea level during the Holocene in the region becomes better understood, from samples dated after the SPT pretreatment. Improving the sea-level fluctuation curves contributes to more reliable paleoenvironmental reconstructions and to the determination of sea-level variation rates during the Holocene, which in turn subsidizes the simulations related to the sea-level rise foreseen for the current century. Such simulations identify areas most vulnerable to coastal flooding, coastal erosion, loss of habitats and many other impacts related to rising sea levels.

ACKNOWLEDGMENTS

The authors would like to thank Brazilian financial agencies CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, 307771/2017-2 and INCT-FNA, 464898/2014-5) and FAPERJ (Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, E-26/110.138/2014 and E26/203.019/2016) for financial support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and CLIMATE-PRINT-UFF (88887.310301/2018-00). We thank the editors and reviewers for comments and suggestions, which helped to improve the quality of the manuscript. This article is a tribute to Prof. Dr. Kenitiro Suguio, who contributed so much to studies related to sea level fluctuations during the Holocene in Brazil.

REFERENCES

Alves E, Macario K, Souza R, Pimenta A, Douka K, Oliveira F, Chanca I, Suguio K. 2015. Radiocarbon Reservoir corrections on the Brazilian coast from pre-bomb marine shells. Quaternary Geochronology 29:30–35. doi: 10.1016/j.quageo.2015.05.006.

Angulo RJ, Giannini PCF, Suguio K, Pessenda LCR. 1999. Relative seac level changes during the last 5500 years in the Laguna-Imbituba region (Santa Catarina, Brazil), based on vermetid radiocarbon ages. Marine Geology 159:323–339.

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

Angulo RJ, Lessa GC, Souza MC. 2006. A critical review of mid- to lateHolocene sea-level fluctuations on the eastern Brazilian coastline. Quaternary Science Review 25:486–506.

Angulo RJ, Pessenda LCR, de Souza MC. 2002. O significado das datações ao ^{14}C na reconstrução de paleoníveis marinhos e na evolução das barreiras quaternárias do litoral paraense. Revista Brasileira de Geociências 32:195–106.

Angulo RJ, Souza CM. 2014. Conceptual review of Quaternary coastal paleo-sea level indicators from Brazilian coast. Quaternary and Environments Geosciences 5(2):1–32.

Areias C, Spotorno-Oliveira P, Bassi D, Iryu Y, Nash M, Castro JWA, Tâmega FTS. 2020. Holocene sea-surface temperatures and related coastal upwelling regime recorded by vermetid assemblages, southeastern Brazil (Arraial do Cabo, RJ). Marine Geology 425 (2020): 106183. doi: 10.1016/j.margeo.2020.106183.

Baker RGV, Haworth RJ. 1997. Further evidence from relic shellcrust sequences for a late Holocene higher sea level for eastern Australia. Marine Geology 141:1–9.

Baker RGV, Haworth RJ, Flood PG. 2001. Warmer or cooler late Holocene marine palaeoenvironments? Interpreting southeast Australian and Brazilian sea-level changes using fixed biological indicators and their δ^{18}O composition. Palaeogeography, Palaeoclimatology, Palaeoecology 168:3–4: 249–272.

Bathurst RGC. 1972. Carbonate sediments and their diagenesis. Elsevier.

Breves-Ramos A, Junqueira AOR, Lavrado HP, Silva SHG, Ferreira-Silva MA. 2010. Population structure of the invasive bivalve isognomon bicolor on rocky shores of Rio de Janeiro State (Brazil). Journal of Marine Biological Association of United Kingdom 90(3):453–459.

Castro JWA, Suguio K, Seoane JCS, Cunha AM, Dias FF. 2014. Sea-level fluctuations and coastal evolution in the state of Rio de Janeiro, southeastern Brazil. Anais da Academia Brasileira de Ciências 86(2):671–683. doi: 10.1590/0001-3765201420140007.

Castro JWA, Seoane JCS, Cunha AM, Malta JV, Oliveira CA, Vaz SR, Suguio K. 2018. Comments to Angulo et al. 2016 on "Sea-level fluctuations and coastal evolution in the state of Rio de Janeiro, southeastern - Brazil" by Castro et al. 2014. Anais da Academia Brasileira de Ciências 90(2):1369–1375.

Cavalcante SLS. 2010. Estudo da influência da dinâmica da plataforma continental nas baías de Ilha Grande e Sepetiba via aninhamento de modelo numérico costeiro à modelo numérico oceânico. Rio de Janeiro, RJ: COPPE/UFRJ, Tese de Doutorado em Engenharia Oceânica. 127 p.

Cunha AM, Castro JWA, Carvalho MA. 2018. Holocene shell accumulations from the Cabo Frio coastal plain, southeastern Brazil: taxonomy, taphonomy, geochronology and paleoenvironmental implications. Ameghiniana 55:55–74.

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

Dias FF. 2009. Variations of Level Relative to the Sea in the Coastal Plain of Cabo Frio and Armação dos Búzios - RJ: Holocene Paleoambiental Reconstruction and Future Scenarios [PhD thesis]. Postgraduate Program in Geology, Federal University of Rio de Janeiro, Rio de Janeiro. 145 p.

Dias FF, Breves-Ramos A, Pimenta AD, Junqueira AOR, Seoane JCS, Castro JWA, Ramos RRC. 2011. Occurrence of aggregates of live vermin and fossils in rocky shores in the South Atlantic. XIII Congresso da Associação Brasileira de Estudos do Quaternário ABEQUA.

Douka K, Hedges REM, Higham TFG. 2010. Improved AMS ^{14}C dating of shell carbonates using high-precision X-ray diffraction and a novel density separation protocol (CarDS). Radiocarbon 52:735–775.

Hajdas I. 2008. Radiocarbon dating and its applications in Quaternary studies. Eiszeitalter und Gegenwart Quaternary Science Journal 57:1–24.

Inea – Instituto Estadual do Ambiente. 2015. Diagnóstico do Setor Costeiro da Baía da Ilha Grande. Subsídios a Elaboração do Zoneamento Ecológico-Econômico Costeiro. Volume I, Rio de Janeiro. p. 244.

Jesus PBJ, Dias FF, Muniz RA., Macário KDC., Seoane JCS, Quattrociocchi DSG, Cassab RTC, Aguilera O, Souza RCCL, Alvez EQ, Chanca IS, Carvalho CRA, Araujo JC. 2017. Holocene Paleo-sea level in southeastern Brazil: an approach based on vermetids shells. Sedimentary Environments 2(1):5–48.

Laborel J. 1986. Vermetid gastropods as sea-level indicators. In: Van de Plassche O, editor. Sea-level research: a manual for the collection and evaluation of Data. Norwich: Geo Books. p. 281–310.

Lewis SE, Wust RAJ, Webster JM, Shields GA. 2008. Mid-late Holocene sea-level variability in eastern Australia. Terra Nova 20(1):74–81.

Lima CCU. 2010. Evidências da ação tectônica nos sedimentos da Formação Barreiras presentes do litoral de Sergipe e ao norte da Bahia. Revista de Geografia. Recife:UFPE-DCG/NAPA, v. especial VIII SINAGEO,1. p. 140–151.

Macario K, Alves EQ. 2018. Efeito de reservatório marinho na costa do Brasil. Quaternary and Environmental Geosciences 9:11–17.

Malta JV, Castro JWA. 2018. Petrography, stable isotopes and geochronology of beachrocks from the coastline of Rio de Janeiro State, SE Brazil. Anuário do Instituto de Geociências, Federal University of Rio de Janeiro 41(1):232–244.

Martinez S, Rojas A. 2013. Relative sea level during the Holocene in Uruguay. Palaeogeography, Palaeoclimatology, Palaeoecology 374: 123–131. doi: 0.1016/j.palaeo.2013.01.010.

Martin L, Suguio K. 1976. Etude pr éliminaire du Quaternaire marin: Comparaison du littoral de São Paulo et de Salvador de Bahia (Brésil). Cah. O.R.S.T.O.M., Sér. Géol. VIII (1):33–47.

Martin L, Suguio K. 1978. Excursion route along the coastline between the town of Cananéia (state of São Paulo) and Guaratiba outlet (state of Rio de Janeiro). In: International Symposium on Coastal Evolution, Special Publication 2. p. 1–98.

Martin L, Suguio K, Flexor JM, Bittencourt ACSP, Vilas-Boas GS. 1979–1980. Le quaternaire

marin brésilien (littoral pauliste, sud fluminense et bahianais). Cahiers O.R.S.T.O.M., Série Géologie 11:95–124.
Martin L, Bittecourt ACSP, Flexor JM, Vilas-Boas GS. 1984. Evidencia de um tectonismo quaternário nas costas do Estado da Bahia. 33° Congresso Brasileiro de Geologia, Rio de Janeiro, SBG,1, 19-35.
Martin l, Suguio K. 1989. Excursion route along the Brazilian coast between Santos (SP) and Campos (RJ) (North of State of Rio de Janeiro). In: International Symposium on Global Changes in South America during the Quaternary, Special Publication 2:1–136.
Martin L, Dominguez JML, Bittencourt ACSP. 2003. Fluctuating Holocene sea levels in Eastern and Southeastern Brazil: Evidence from multiple fossil and geometric indicators. Journal of Coastal Research 19(1):101–124.
Mendonça MLTG, Godoy JM. 2004. Datação radiocarbônica de sítios arqueológicos do tipo sambaqui pela técnica de absorção de CO_2: uma alternativa à síntese benzênica. Química Nova 27(2):323–325.
Milne AG, Long JÁ, Bassett ES. 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. Quaternary Science Reviews 24:1183–1202.
Moreira VN, Macario KD, Guimarães RB, Dias FF, Araújo JC, Jesus P, Douka K. 2020. Aragonite fraction dating of vermetids in the context of paleo sea-level curves reconstruction. Radiocarbon 62(2): 335–348.
Neves CF, Muehe D. 2008. Vulnerabilidade, Impactos e Adaptações a Mudanças do Clima: a Zona Costeira. http://www.antaq.gov.br/portal/pdf/meioambiente/publicacoes/2008mudancasclimaticascgee2008v080301.pdf. Access date: 06/29/2017.
Queiroz-Alves E, Macario K, Ascough P, Ramsey CB. 2018. The worldwide marine radiocarbon reservoir effect: definitions, mechanisms and prospects. Reviews of Geophysics 56:1–28.
Ramsay PJ. 1996. 9000 years of sea-level change along the Southern African coastline. Quaternary International 31:71–75.
Ramsay P, Cooper J. 2002. Late Quaternary sea-level change in South Africa. Quaternary Research 57(1):82–90.
Ribeiro, PC, Giannini PCF, Nascimento Junior DR, Sayeg IJ. 2011. Vermetídeos fósseis em costões rochosos de Guarapari, ES: distribuição espacial, morfologia, mineralogia e $\delta^{18}O$. XIII Congresso da Associação Brasileira de Estudos do Quaternário – ABEQUA. Armação dos Búzios, RJ. 5 p.
Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck C, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887. doi: 10.2458/azu_js_rc.55.16947.
Schmalz RF. 1967. Kinetics and diagenesis of carbonate sediments. Journal of Sedimentary Petrology 37(1): 60–67.
Silenzi S, Antonioli F, Chemello R. 2004. A new marker for sea surface temperature trend during the last centuries in temperate areas: vermetid reef. Global and Planetary Change 40: 105–114.
Sloss CR, Murray-Wallace CV, Jones BG. 2007. Holocene sea-level change on the southeast coast of Australia: a review. The Holocene 17(7):999–1014.
Soares MO, Meirelles CAO, Lemos VB. 2010. Distribuição espacial de vermetídeos (Mollusca: Gastropoda) no Atol das Rocas, Atlântico Sul equatorial. Boletim do Museu Paraense Emílio Goeldi. Ciências Naturais 5(2):225–231.
Souza CRG, Vilano WF. 2015a. Utilização de Bandas de Paleolocas de Ouriços-do-Mar como Indicadores de Estabilização do Nível do Mar no Holoceno. XV Congresso da Associação Brasileira de Estudos do Quaternário – Abequa, Tramandaí/Imbé, Rio Grande do Sul, Brazil.
Souza CRG, Sobrinho JMA. 2015b. Beachrock De Ubatuba (Litoral Norte De São Paulo): Evidências De Oscilações Negativas E Positivas Do Nível Do Mar No Holoceno Médio A Superior. XV Congresso da Associação Brasileira de Estudos do Quaternário – Abequa, Tramandaí/Imbé, Rio Grande do Sul, Brazil.
Souza TCS, Carvalho MA, Dias FF, Barreto CF, Freitas AS, Castro JWA. 2016. Analysis of particulate organic matter in Holocene sediments of coastal plain from Pero Beach, Cabo Frio, Rio de Janeiro, Brazil. Journal of Sedimentary Environments 1(2):242–253.
Spotorno-Oliveira P, Tâmega FST, De Oliveira CA, Castro JWA, Coutinho R, Iryu Y, Bassi D. 2016. Effects of Holocene sea-level changes on subtidal palaeoecosystems, southeastern Brazil. Marine Geology 381:17–28.
Suguio K, Martin L. 1996. The role of neotectonics in the evolution of the Brazilian coast. Geonomos 4(2):45–53.
Suguio K, Martin L, Bittencourt ACSP, Dominguez JML, Flexor JM, Azevedo AEG. 1985. Relative sea level fluctuations during the Upper Quaternary along the Brazilian coast and its implications for coastal sedimentation. Brazilian Journal of Geosciences 15(4):273–286.
Vescogni A, Bosellini FR, Reuter M, Brachert TC. 2008. Vermetid reefs and their use as palaeobathymetric markers: new insights from the Late Miocene 175 of the Mediterranean (Southern Italy, Crete). Palaeogeography, Palaeoclimatology, Palaeoecology 267:89–101.