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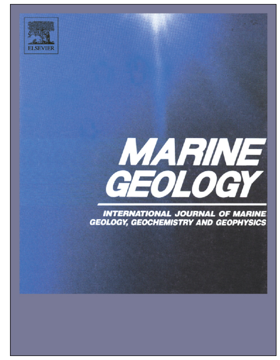

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Holocene sea-surface temperatures and related coastal upwelling regime recorded by vermetid assemblages, southeastern Brazil (Arraial do Cabo, RJ)

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ABSTRACT

In places where ocean currents cause upwelling, nearshore sea-surface temperatures (SST) are often cooler than nearby offshore waters. In the Arraial do Cabo Bay coast upper Holocene aragonitic vermetids are represented by monospecific clusters of overgrowing *Petaloconchus varians* occurring in supratidal/intertidal carbonate and mixed siliciclastic carbonate deposits. Based on stable isotope composition ($\delta^{13}C$, $\delta^{18}O$) of fossil vermetid shells, radiocarbon ages and altimetric survey, the upper Holocene upwelling system of the Cabo Frio area (southeastern Brazil, Rio de Janeiro) is assessed. In the studied region, at 3700 cal. years BP the maximum relative sea level (RSL) was + 4.0 m with a SST of 20.7 °C. Subsequently, vermetid-based SST decreased from ~ 22.8 to ~ 17 °C (at ~ 3300 cal. years BP), with the coldest temperatures recording a strong upwelling event at around 2000 cal. years BP when the RSL was at + 2 m. The intensification in upwelling water masses is identified by the ^{13}C enrichment, along with higher $\delta^{18}O$, in the vermetid shells. The decreasing SST trend assessed from ~ 3300 to ~ 2000 cal. years BP can be related to more frequent South Atlantic Coastal Water intrusions on the surface layer in the mid-shelf, increasing the nutrient concentration in the upper layer. From ~ 1900 to ~ 1300 cal. years BP, a higher SST up to ~ 21 °C occurred during the continuous sea-level fall.

Keywords: vermetids; stable isotopes; palaeotemperature; upwelling current; Holocene; Brazil

1. Introduction

Marine organisms thriving only in a narrow vertical range within the intertidal rocky shore are fixed biological indexes (FBI; Baker and Haworth, 2000), ideal for reconstruction of relative sea-level (RSL) and palaeoenvironmental changes (Lambeck et al., 2011).

In tropical and subtropical regions, FBI such as the vermetids form rigid bioconstructions in the intertidal/supratidal zone from depths of 0 to ~ –6 m on rocky shores (Keen, 1961; Laborel, 1986; Schiaparelli, 1995; Calvo et al., 1998; Spotorno-Oliveira et al., 2016; Breves-Ramos et al., 2017) and coral reefs (Hughes and Lewis, 1974; Kappner et al., 2000; Zuschin et al., 2001; González-Delgado et al., 2005; Spotorno-Oliveira et al., 2015; Webster et al., 2018).

Vermetids are reliable RSL indicators, with an altimetry precision varying between ±0.1 to ± 1.0 m, when occurring in tectonically stable coasts, in transitional regions between tropical and temperate ocean, and where the tidal range is less than the variation in the sea-level fall (e.g., Laborel, 1986; Baker et al., 2001).

Stable oxygen isotope composition ($\delta^{18}O$) obtained from the calcium carbonate of the FBI provides indications of sea surface temperature (SST; Baker et al., 2001; Silenzi et al., 2004). Using vermetid shells for palaeotemperature reconstructions is possible if the analysed shells are composed of aragonite and have not undergone diagenetic alteration (e.g., Laborel, 1986; Sisma-Ventura et al., 2009). This shell composition may fall within the range of values of calcite precipitated in carbon and oxygen isotope equilibrium with ambient seawater (e.g., Silenzi et al., 2004; Sisma-Ventura et al., 2009; Chemello and Silenzi, 2011; Shemesh et al., 2017). Oxygen isotopes of *Dendropoma cristatum* (Biondi, 1859) (i,e., *Dendropoma petraeum* (Monterosato, 1884)) vermetid reefs from the western Mediterranean have been used as climate proxies of the past 500 years, recording SST changes with high resolution during the Little Ice Age (Antonioli et al., 1999; Silenzi et al., 2004; Sisma-Ventura et al., 2009). Consequently, Holocene vermetid assemblages are potentially a very good proxy to understand the RSL and SST changes (e.g., Rovere et al., 2015; Vacchi et al., 2016).

The oxygen and carbon isotope composition of vermetid aragonitic skeletons ($\delta^{18}O_{ver}$ and $\delta^{13}C_{ver}$, respectively) have been used to track the SST warming of Mediterranean surface waters during the Late Holocene to modern times (Sisma-Ventura et al., 2009). The $\delta^{13}C$ may reflect the metabolic activity of the vermetids and the carbon isotope composition of their food, as well as the values of dissolved inorganic carbon (DIC) from ambient seawater. Assuming that the vermetid diet remains constant, $\delta^{13}C$ can be used as a proxy for palaeo-productivity in marine surface waters (Sisma-Ventura et al., 2009, 2014) and trophic sources and food web structures (e.g., Vizzini et al., 2012).

In south-eastern Brazil in summer and spring periods the wind blows across the ocean surface and pushes away the Brazilian Current (BC), carrying surface Tropical Waters (TW) far from the coast producing coastal upwelling events. The subsurface South Atlantic Central Water (SACW), formed in the confluence zone Brazil-Malvinas, emerges (e.g., Belem et al., 2013).

This sector of the Atlantic Ocean represents a key area to investigate widespread and well-preserved Holocene and modern intertidal/supratidal benthic communities as far as relative sea-level, SST and upwelling input changes are concerned. Regional trends of biotic responses to climate change from nearshore settings can help to delineate potential future impacts of SST and circulation changes (e.g., Gruber, 2015). This can be done if the SST are appropriately dated for predicting upwelling-induced variability (Tapia et al., 2009). Local dynamics of coastal marine populations and entire communities may be profoundly affected by spatial and temporal variability in regimes of coastal upwelling.

In this study, by analysing fossil and modern *Petaloconchus varians* (d'Orbigny, 1839) vermetid assemblages using $\delta^{18}O_{ver}$ and $\delta^{13}C_{ver}$, we present a new SST record and related evidence of upwelling currents from upper Holocene intertidal/supratidal settings from the Arraial do Cabo area, state of Rio de Janeiro, south-eastern Brazil.

This study has direct implications for how coastal benthic populations are likely to respond to ongoing alterations to global patterns of SST and upwelling intensity.

2. Regional setting

2.1. Field survey

This study was carried out at the Arraial do Cabo Bay, Rio de Janeiro State, Brazil (23° S, 42° W; Spotorno-Oliveira et al., 2016; Fig. 1). In this area the bedrock is represented by orthogneiss and nepheline syenite rocks. Holocene deposits are constituted of beach sands, climbing dunes and beachrocks characterizing the Holocene embayment caused by the sea-level fall (e.g., Castro et al., 2014). The inner continental shelf bottom is characterized by medium- to fine-grained sand and a narrow muddy belt extending down to 25 m water depth (Castro et al., 2018). The micro-tidal regime is asymmetrical and semi-diurnal, with a highest tide of 1.0 m and low tides between 0.06 and 0.025 m (Brazilian Navy; Castro et al., 2018). An atmospheric center of semi-permanent high pressure over the South Atlantic Ocean produces northeastern trade winds, which in turn generate coastal upwelling nearby Cabo Frio (Cabo Frio upwelling system, CFUS), thereby producing cold and nutrient rich waters (Valentin, 1984).

Field campaigns were carried out along the coasts of Arraial do Cabo and in the Cabo Frio Island in order to (1) geologically survey the rocky shores, (2) sample living and fossil vermetid assemblages, (3) measure the tidal water-depth range and the topographic altimetry.

Living vermetid assemblages were sampled along the intertidal/supratidal zones at the Praia dos Anjos rocky shore (RAJ-2905, RHA-1505, RHA-1007; Fig. 1, Table 1). Fossil vermetid assemblages were sampled in the supratidal zone from five sites (Fig. 1, Table 1): Prainhas do Pontal (PR-0370, PR-0371, PR-0372, PR-6639), Praia dos Anjos (AJ-9280), western coast of Porcos Island (PO-2509), western coast of the Cabo Frio Island, Praia do Farol (IL-3620, IL-3621, IL-3622, IL-3623) and Anequim (AN-2507).

The studied outcrops were georeferenced by high precision altitude GPS (Pro Mark II tracker), adjusted by Brazilian Geodetic System benchmarks (RRNN), maintained by the Brazilian Institute of Geography and Statistic (IBGE; see Spotorno-Oliveira et al., 2016). The nominal accuracies of the horizontal and vertical displacements are ± 0.02 m + 1 ppm and ± 0.04 m + 2 ppm respectively with a confidence level of 95%. The altimetric data were processed using the GNSS Solutions 2010 Ashtech.

TABLE 1 HERE

FIGURE 1 HERE

The upper Holocene RSL was calculated according to the indicative range of the relative palaeo-sea level and the associated uncertainties of the FBI (Rovere et al., 2016), with some adaptations for our study area (Table 2). Although previous studies suggested applying 0.5 or 1.0 m as a vertical error margin to vermetid location depending on exposition to wave action (Laborel, 1986; Angulo et al., 1999), to calculate these values we applied the error margin associated to the Rovere et al.'s (2016) formulas that consider the GPS vertical error and the indicative range of living vermetids.

The upper and lower bathymetric range of the living vermetid *P. varians* was based on the tide values extracted from the Banco Nacional de Dados Oceanográficos (BNDO), Diretoria de Hidrografia e Navegação (DHN), Marinha do Brasil (Brazilian Navy) associated with the corresponding amplitude along the intertidal/supratidal zones of the Praia dos Anjos rocky shores. The upper and lower ranges of living vermetids considered were + 1.30 m and –1.0 m respectively.

TABLE 2 HERE

The studied samples were deposited in the sedimentological collection of the Museu Nacional/Universidade Federal do Rio de Janeiro (MN/UFRJ), Brazil, under the deposit numbers MN-923ES to MN-932ES, and in the Instituto de Estudos do Mar Almirante Paulo Moreira, (IEAPM), Brazil, under the deposit numbers IEAPM00332 to IEAPM00336, IEAPM00510 to IEAPM00520.

3. Materials and methods

3.1. Laboratory analyses

Vermetid assemblages were studied based on macroscopic observations, in order to describe their size, shape, inner structure and preservation. Vermetid shells were removed from the outcrops using hammer and chisel. Some parts of the shell (such as the internal columellar lamellae) were exposed after crushing the last whorls of the shells, with a small lathe. For detailed examination, some entire shells and shell fragments were ultrasonic cleaned and air-dried, mounted on stubs with double-sided carbon tape, coated with a gold/ gold-palladium alloy and observed under Scanning Electron Microscope in the in the MN/UFRJ (Jeol, JSM-6390LV) and in the Centro de Microscopia Eletrônica do Sul, CEME-SUL, Universidade Federal do Rio Grande, FURG (Jeol, JSM - 6610LV). Petrographic thin sections were analyzed by a stereomicroscope (Spotorno-Oliveira et al., 2016).

The taxonomy of vermetids, identified on the base of shell morphology, follows Keen (1961), Morton (1965) and Spotorno-Oliveira (2009). The studied vermetid specimens were compared with voucher material deposited at the MORG (Museu Oceanográfico Prof. Eliézer de Carvalho Rios, Universidade Federal do Rio Grande, FURG, Brazil) malacological collection..

3.2. Radiocarbon dating

Seven vermetids bulk samples from different altimetric levels were analyzed for radiocarbon dating (^{14}C) at the Beta Analytic Laboratory Radiocarbon Dating, Miami, Florida (USA) (Table 1). To eliminate the secondary carbon components, samples were submitted to a pre-treatment, with hydrochloric acid HCl (conditioning acid). All the radiocarbon data were converted to calibrated years before present (cal. years BP) using the CALIB Radiocarbon Calibration software version 7.1 (Stuiver et al., 2019), the Marine13 curve (Reimer et al., 2013) and a reservoir effect (ΔR) of 96 ± 48 obtained for the local offset from the average global marine reservoir (Alves et al., 2015). Ages were interpolated using the Clam software (Blaauw, 2010) to create the age model and updated from Spotorno-Oliveira et al. (2016) with new ΔR value (Alves et al., 2015) and the isotopic concentration of ^{13}C and ^{18}O.

3.3. X-ray diffraction analyses

All studied vermetid samples were checked for the preservation state and homogeneity of the aragonite structure of the shells. X-ray diffraction analysis was used to check for the absence of secondary carbonates precipitation. According to the dos Santos et al.'s (2017) method, approximately 3 g of powdered bulk samples was submitted for X-ray diffraction analyses (XRD) to two laboratories: CEME-SUL and the Setor de Caracterização Tecnológica (SCT) of the Centro de Tecnologia Mineral (CETEM), Brazil.

XRD patterns were generated in D8 Advance Eco equipment (Brucker AXS, Karlsruhe, Germany) under the following operation conditions: Cu Kα sealed tube (= 0.154056 nm) operated at 40 kV and 25 mA, measured from 4° to 105° 2θ at 0.01° step with LynxEye XE energy-discriminant position sensitive detector. The identification of all minerals was performed with Bruker-AXS's Diffrac. EVA 4.0 or 4.1 software and PDF04+ database. Full Rietveld method refinement was accomplished with DIFFRAC.TOPAS v.4.2 or 5.0 (Brucker AXS, Karlsruhe, Germany) software (see dos Santos et al., 2017).

3.4. Stable isotope analysis

The $\delta^{13}C$ and $\delta^{18}O$ values of the fossil and modern aragonitic vermetid shells were measured on a Kiel IV Carbonate Device coupled to a Delta V Plus - IRMS (Thermo Scientific) system in the Chemostratigraphic and Organic Geochemistry Laboratory of the Universidade do Estado do Rio de Janeiro, Brazil and at the Department of Earth and Planetary Sciences, Weizmann Institute of Science, Israel. The fossil shells were separated from the encasing calcite cement using a small dental drill, then cracked and homogenized using an agate mortar and pestle to produce the fine-grained bulk samples. The modern shells were run four times and averages of all results were taken into consideration. The samples (~ 20 mg) were reacted with 100% phosphoric acid at ~ 70 °C. The isotope ratios $\delta^{13}C$ and $\delta^{18}O$ were expressed in conventional notation (δ‰) and calibrated to the IAEA–CO-1–Marble, international standard, relative to Vienna Pee Dee Belemnite (VPDB). The value of 1.01025 was used for the oxygen isotope fractionation factor during phosphoric acid digestion (Sharma and Clayton, 1965), with analytical precision of 0.07 for both $\delta^{18}O$ and $\delta^{13}C$.

Past SST were estimated based on the aragonite versus temperature fractionation equation we used [$T = 20.6 - 4.34 \times (\delta^{18}O_{aragonite} - \delta^{18}O_{seawater})$] (Grossman and Ku, 1986) and modern $\delta^{18}O$ values of seawater for the three different water masses SACW, SSW and

TW obtained from Venancio et al. (2014; + 0.4‰, 0.0‰ and + 1.35‰, respectively; – see Table 1 for referred water mass).

4. Results

4.1. The living vermetid assemblages

Living vermetid *P. varians* is found from the intertidal to the supratidal zones along the Praia dos Anjos rocky shores (Area 1, samples RAJ-2905, RHA-1505, RHA-1007; Fig. 2A–C). The *P. varians* shell exhibits considerable morphological plasticity. The studied vermetid specimens present a teleoconch of medium size, with the mean length 13.0 ± 0.44 mm (ranging from 3.8 to 34.24 mm, n = 154), composed of 8 to 14 rounded piled up whorls, irregularly extending laterally on the substrate (Fig. 2A). The aperture is circular with a mean diameter of 3.1 ± 0.05 mm (ranging from 1.3 to 5.0 mm, n = 154), generally projecting above its own teleoconch and sometimes slightly erect. The emergent tube (i.e., feeding tube) is up to 19.0 mm long showing feeding tube scars. Often abraded and not evident in the last whorl the shell sculpture shows the typical reticulated pattern. The early post-larval teleoconch is sometimes not preserved. The presence of paired internal and a low central columellar lamellae, as a diagnostic feature of the genus *Petaloconchus,* marks the columellar muscle attachment. The external shell color ranges from violet to dark brown, sometimes pale brown in abraded specimens (Fig. 2A).

At the Praia dos Anjos upper-intertidal rocky shores, living vermetids occur as solitary or small clusters attached on the rock surface, frequently associated to living cirripeds, oysters and limpets (Fig. 2A). Along the intertidal zone, the mean population density of *P. varians* was estimated as to 4 individuals per 100 cm^2, being 10.4 individuals per 100 cm^2 in the supratidal zone (Fig. 2B–C). Associated organisms include *Tetraclita stalactifera* (Lamarck, 1818), *Crassostrea brasiliana* (Lamarck, 1819), the invasive bivalve

Isognomon bicolor (Adams, 1845), small patches of encrusting coralline red algae, and *Lottia subrugosa* (d'Orbigny, 1846) (Fig. 2A–C). In the supratidal zone (~ 1 m water depth), small colonies of living short erect vermetid tubes are encrusted by coralline algae *Lithophyllum pustulatum* (Lamouroux) Foslie, *Spongites fruticulosus* Kützing, *Spongites yendoi* (Foslie) Chamberlain, *Mesophyllum engelharti* (Foslie) Adey (Tâmega et al., 2016). Subordinate fauna consists of the non-indigenous bivalve *Myoforceps aristatus* (Dillwyn), the non-native vermetid *Eualetes tulipa* (Rousseau in Chenu, 1843) (Spotorno-Oliveira et al., 2018) and *Fissurella* sp., the sea anemone *Bunodosoma caissarum* Corrêa in Belém, the mussel *Perna perna* (Linnaeus) and the macroalgae *Amphiroa* sp., Ceramiales, *Codium intertextum* Collins and Hervey, *Codium taylorii* Silva, *Colpomenia sinuosa* (Mertens ex Roth) Derbès and Solier, *Jania* sp. and Peyssonelliaceae (Fig. 2A–C).

FIGURE 2 HERE

4.2. The Holocene vermetid assemblages

The studied fossil outcrops are located in the innermost (shallowest) part of the Arraial do Cabo Bay (Fig. 1). Dense fossil vermetid assemblages occur in upper Holocene carbonate and mixed siliciclastic-carbonate coralline algal deposits in the supratidal rocky coast in PR, AJ, PO, IL, and AN (Figs. 1, 2D–H).

The rare entire shells present a teleoconch of medium size, with the length varying between 15 and 20 mm, with about 7 irregularly piled up whorls or extending laterally on the substrate (Fig. 3A). The circular aperture is about 2 mm in diameter. The feeding tube is smooth, without ornamentation, emerging for more than 10 mm in length, adhered to other specimens, parallel or perpendicular to the substrate (Fig. 3A). The studied specimens show the internal columellar lamellae which is a diagnostic feature of *Petaloconchus* (Figs. 3B–C). The inner-tube dimensions are about 0.64 mm in diameter and 0.11 mm thick.

The fossil *P. varians* shells show, as their living counterparts, a considerable morphological plasticity. The dense continuous assemblages are characterized by younger specimens located at the top of the encrusting succession (Fig. 3A). Abundant superimposed vermetids grew irregularly, curving perpendicular or parallel to the substrate with the tubes frequently cemented each other forming rigid structures (Figs. 3B–C). Some aggregates consist of tightly attached individuals, locally encrusted by thin corallines (Fig. 2H), sometimes sharing a mutual shell wall (Fig. 3B). The empty spaces between the tubes are filled by spatic cement. The shell sculpture of reticulated ornamentation is typically poorly preserved (Fig. 3A). The external shell color ranges from white, beige to brown and bright beige in the inner side.

At PR, AJ and PO sites (Area 1), the fossil *P. varians* lies on the metamorphic rock basement. In PR site, the fossil vermetid assemblages extend almost along the entire rocky coast. Some of these assemblages occurs parallel to the beach line, at the same altimetric level (+ 1.49 m), forming a sub-horizontal hard *P. varians* pavement at the intertidal zone (PR-6639; Fig. 2G). Other fossil vermetid assemblages occur on the wall of rocky caves in the supratidal zone protected from wave action (PR-0370, 0371, 0372; Figs. 2E–F, H). Encrusting coralline red algae are abundant (PR-6639; Figs. 2G, 3D). The AJ vermetid assemblages form discrete patches lying directly on the supratidal rock basement (AJ-9280) and under basement boulders at PO (i.e., PO-2509). These assemblages range from 4 to 56 cm in thickness, from 6 to 135 cm in length, and 15 to 63 cm in width.

In the Cabo Frio Island (IL, AN, Area 2; Fig. 1) the upper Holocene vermetid assemblages occur in the sheltered supratidal zone. The thickness of the studied assemblages ranges from 11 to 14 cm, the length from 16 to 32 cm and the width from 10 to 32 cm.

Taphonomic signatures of the vermetid assemblages are encrustation, bioerosion and fragmentation. Encrustation is mainly performed by vermetids and coralline algae, subordinately by the foraminifer *Homotrema rubrum* and cirripeds. Bioerosion is represented by the ichnotaxa *Gastrochaenolites* (made by boring bivalves) and subordinately by *Entobia* (by hatching sponges) and rare *Trypanites* (by polychaete worms). Shell debris consists of small fragmented bryozoans, bivalves and echinoderms.

FIGURE 3 HERE

4.3. Altimetric and geochronological data

In Area 1 the altimetry of the studied samples ranges from + 1.04 m to + 1.97 m above the current mean sea-level. The lowest sample was not dated and the highest one was dated 3400 cal. years BP, calibrated at (2σ) with an altimetry error of ± 1.15 m. In Area 2, the lowest sample is located at around + 1.3 m and the highest at around + 4.0 m, with ages ranging from 1300 cal. years BP to 3700 cal. years BP calibrated at 2σ with an error of ± 1.15 m (Table 1).

4.4. X-ray diffraction analyses

The X-ray diffraction data analyses of the studied fossil vermetids assemblages show different mineralogical compositions (Table 3). In the Area 1, the samples are made of high-Mg calcite (~ 14 mol%, up to 86% by volume of the total rock) with low proportions of aragonite (< 15%). In the Area 2 the samples show a higher proportion of aragonite (up to ~ 62% by volume of the total rock) with subordinate high-Mg calcite (< 35%; Fig. 4A). The occurrence of aragonite along with high-Mg calcite indicates that the studied fossil vermetid shells are in a good state of preservation with shells exhibiting same mineralogical composition as the modern counterparts (Laborel, 1986). The SEM analysis shows well-defined individual aragonite crystals with distinct boundaries and the absence of crystal fusion, with no traces of dissolution and recrystallization (Fig. 4B).

FIGURE 4 HERE

TABLE 3 HERE

4.5. Stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope composition

In the Area 1 the $\delta^{18}O$ values of the fossil aragonitic vermetid shells ranges from 0.57 ± 0.03 to 1.27 ± 0.02, while in the Area 2 from 0.40 ± 0.03 to 0.60 ± 0.03. In both areas the $\delta^{13}C$ values varies from 2.00 ± 0.07 to 3.10 ± 0.05 and from 1.74 ± 0.02 to 2.83 ± 0.04 respectively (Table 1).

The living vermetids show average values of $\delta^{18}O$ as to 0.09 ± 0.32 (RAJ-2905), 0.45 ± 0.09 (RHA-1505) and 0.26 ± 0.13 (RHA-1007). The $\delta^{13}C$ average values are 0.29 ± 0.27, 0.23 ± 0.04, 0.67 ± 0.23. Positive correlations were observed between $\delta^{13}C$ and $\delta^{18}O$ of fossil (r^2 = 0.56) and no correlation for living vermetids (r^2= – 0.08).

5. Discussion

5.1. The upper Holocene RSL changes

The studied vermetids assemblages, occurring subsequently to the PSLM whose eustatic maximum was + 4.7 m (at around 5200 cal. years BP; Martin et al., 1997), recorded a smooth RSL fall (Fig. 5). Geochronological and altimetric data allow the studied samples to be placed in the last regression marine phase between 3700 and 1300 cal. years BP. These data show that in the southeastern Brazilian coast the RSL passed from ~ + 4 m at around 3700 cal. years BP to ~ + 1.30 m at 1300 cal. years BP (e.g., Spotorno-Oliveira et al., 2016).

FIGURE 5 HERE

The upper and lower bathymetric limits of the studied living *P. varians* range were based on specimen locations (e.g., along the intertidal/supratidal zones of the Praia dos Anjos rocky shore and Forno Harbor). The upper bathymetric limit corresponds to the upper intertidal zone (+ 1.30 m) and their lower bathymetric limit (– 1.0 m) corresponds to the subtidal zone.

Along the Brazilian coast, local assessed RSL curves have been mitigated for possible influences of sedimentological factors and tide gauge by using a 4th degree polynomial curve (Angulo and Lessa, 1997). For Arraial do Cabo region the RSL curve shows a positive correlation (r = 0.83) between the interpolated ages and the altitude of the samples. Because a quintic statistic model (Baker et al., 2001) provides equivalent results (r = 0.84) as to the 4th degree curve, we used this latter curve as correlation to previously curves produced for the studied area (Fig. 6A).

FIGURE 6 HERE

5.2. The upper Holocene SST palaeotemperature

In the two studied areas the fossil vermetid assemblages show high-Mg calcite and aragonite contents (Fig. 4A). Although both areas have high-Mg calcite (~ 14 mol% $MgCO_3$), in Area 1 the amount of > ~ 25 (weight %) found in the fossil samples is likely due to the occurrence of abundant coralline algae associated with the vermetids. In fact present-day crustose corallines consist predominantly of high-Mg calcite (> 8 mol %; Nash et al., 2019) and the microfacies analysis confirms the occurrence of corallines (Spotorno-Oliveira et al., 2016). In Area 2 the fossil vermetids are very well preserved showing high percentages of Mg calcite and aragonite. The local occurrence of dolomite may be related to the minor occurrence of dolomite within cell walls and/or cell spaces of the corallines (Nash et al., 2019) and to echinoderm fragments (e.g., Dickson, 2004).

Because no significant relationship was observed between mineralogical compositions of the studied fossil vermetid assemblages and age or altimetry, the studied shells are thought to have retained their primary chemical compositions and original shell aragonitic microstructures.

Considering that the precipitation of the original aragonite in the vermetid shell is in isotopic equilibrium with the seawater (Silenzi et al., 2004; Sisma-Ventura et al., 2009), the obtained $\delta^{18}O$ values allow estimates of palaeo-SST (Chemello and Silenzi, 2011; Sisma-Ventura et al., 2014). The reconstructed palaeo-SST for the last ~ 4000 years BP ranges between ~ 17 °C and 21.2 °C (Fig. 6B).

The analyses performed on the modern vermetids show average $\delta^{18}O$ and $\delta^{13}C$ values between + 0.35–0.47 ‰ and + 0.15–0.46 ‰, respectively. Our $\delta^{18}O$ data agree with the estimated vermetid modern base values (+ 0.3 ‰) for the last ~ 500 years in the Brazilian coast (Baker et al., 2001). The estimated modern temperature range (~ 20 °C – ~ 24 °C; Table 2) derived from the vermetids $\delta^{18}O$ is comparable to the annual SST average of ~ 21 °C, measured in 2017 (unpublished data from the Brazilian Navy Department), and the temperature range of 21.5–23.6 °C found in the in-shore area of CFUS (Cordeiro et al., 2014).

Living *P. varians* are found in the Arraial do Cabo region where the SST can reach 13.5 °C during the SACW upwelling events (Lima and Coutinho, 2016) and 22 °C at the inner shelf when SSW is active (Venancio et al., 2014). These temperature ranges are comparable to those of *Dendropoma mejiloensis* Pacheco & Laudien, 2008 vermetid reefs which grow when the winter temperature is between 14 °C (Mediterranean Sea; Chemello and Silenzi, 2011) and 19 °C (Bermuda islands; Safriel, 1975). In Abrolhos Archipelago reefs (approximately 70 km off north-eastern Brazil), *Dendropoma irregulare* (d'Orbigny,

1841) colonizes and grows together with corallines at summer water temperature of 27 °C (Spotorno et al., 2012; 2015).

For the last 9000 years BP, five oceanographic phases of the CFUS have been distinguished by mean of planktonic foraminiferal assemblages (I–V in Lessa et al., 2016). Phase I (9000–7000 cal. years BP) is characterized by RSL variations, ranging from – 45 to 0 m, with influence of shelf waters and coastal upwelling plume indicated by cold water foraminiferal assemblages. Phase II (7200–5000 cal. years BP), at the beginning of the middle Holocene, was marked by high SST (~ 26 °C) in contrast with the frequent subsurface upwelling events, and migration of the Brazilian Current (BC) towards the outer shelf. The studied vermetid samples are localized in phases III–V (Fig. 6B): one sample (IL-3620) in phase III, two samples (IL-3622, PR-0371) in phase IV and four samples (PR-0370, PR-0372, IL-3623, IL-3621) in phase V. In the phase III (5000–3500 cal. years BP) the SST of studied coastal area was about ~ 20 °C. This phase is characterized by the offshore displacement of the strong BC and a greater stratification of the water masses isolating the cold waters on the subsurface (Lessa et al., 2016). This phase represents the Holocene Cabo Frio Transgression, whose maximum was + 4.0 m above current RSL (Castro et al., 2014; Fig. 6A).

In the studied area the highest temperatures occurred during phase IV (3500–2500 cal. years BP; Fig. 6B), when a weakening in the SACW upwelling was registered by a decrease in organic carbon input and an increase in very fine sand and mud (Nagai et al., 2009; Lazzari et al., 2019) with SST between 25 °C and 27 °C (maximum temperature ~ 22 °C recorded by the studied vermetids). A coeval drop in the relative abundances of planktonic foraminiferal species occurred (Lessa et al., 2016).

Although upper Holocene vermetids have been identified along the Rio de Janeiro coasts (Angulo et al., 1999, 2006; Castro et al., 2014; Jesus et al., 2017; Fig. 7), in the period of ~ 3200–2000 cal. years BP no vermetids have been recorded in the studied area (Fig. 6B, Table 1).

At around 2800 cal. years BP, a decrease in continental input is followed by increased productivity (Lazzari et al. 2019). From this time slice to the present the upwelling events are more frequent as well as the continental input (Lessa et al., 2016; Lazzari et al., 2019).

Nearly coeval to the absence of vermetids in the studied area, a hiatus in reef flat accretion has been recognized in the southwestern Atlantic and interpreted as due to increased precipitation and higher sediment flux (~ 3700–2500 years BP; Dechnik et al., 2019). The absence of vermetids at the studied sites can be likely related to the increase in sediment input and turbidity which negatively impacted on vermetids especially along the coasts most exposed to the SACW, as was the studied area (Laborel, 1986; Laborel and Laborel-Deguen, 1996; Breves-Ramos et al., 2017). Alternatively, vermetids were present but the their outcrops ~ 3000–2100 years in age did not preserve.

During the phase V (2500–800 years BP) the water temperature decreased (at ~ 16.8 – ~ 20.5 °C; Fig. 6B), with the lowest values at around 2000 years BP. This drop in temperatures, still lower than the SST recorded by planktonic foraminifera (~ 24 °C; Lessa et al., 2016), corresponds to the peak in $\delta^{18}O$ (Fig. 6B). In this phase the CFUS oceanographic current configuration set up (Lessa et al., 2016). The assessed SST curve obtained by the vermetid $\delta^{18}O$ analyses shows colder inner-shelf settings than the mid-shelf settings, where the mixture of upwelling water masses occurred (Lessa et al., 2014, 2016; Venancio et al., 2014). The SACW upwelling brings relatively low $\delta^{18}O$ seawater (+ 0.4‰). This value is ~1‰ lower than that of TW (+ 1.35‰), which would generate past SST ~4.3°C higher than the former one.

FIGURE 7 HERE

5.3. The upper Holocene upwelling climatic events

For the period ~ 3500–1000 cal. years BP, a number of environmental changes influencing the southeastern Brazilian benthic communities have been identified: increase in the primary productivity index and in the organic carbon content in the sediments from the inner shelf of Cabo Frio (Nagai et al., 2009), gradual increase of cold and nutrient-rich waters (Lessa et al., 2016), and abrupt switch from organic-carbonate to carbonate deposits in the coastal lagoons (Sylvestre et al., 2005; Laslandes et al., 2006; Nascimento et al., 2019). All of these are related to the intensification of the upwelling process which was mainly controlled by the combined action of NE winds, increasing of the BC meandering pattern and coastline morphology (Nagai et al., 2009; Reddin et al., 2015). Coastal upwelling driven by coastline topography brought about the cooling of the coastal SST as recorded by compositional changes in subtidal communities (Spotorno-Oliveira et al., 2016) and by the studied vermetids (Fig. 6B). The discrepancy between the colder SST in shallowest setting (intertidal/supratidal) and the warmer SST offshore (as recorded by coeval planktonic foraminifera) is related to upwelling system.

The drop in temperature recorded by the studied aragonitic vermetids from ~ 22 °C at ~ 3300 cal. years BP to ~ 17 °C at ~ 1900 cal. years BP corresponds to the coldest period detected by planktonic foraminifera (~ 23 °C at ~ 2000 cal. years BP; Lessa et al., 2016; Fig. 6B). Since no correlation between the seawater δ^{18}O and salinity in the CFUS has been observed (Venancio et al., 2014), the salinity is ruled out as important factor mediating the δ^{18}O of the studied vermetid shells. Discrepancies between oxygen isotope thermometers can also be explained by the vital effect (biological controls) on oxygen isotope equilibrium carbonate in the shell growth (Boersma, 1998; Sisma-Ventura et al., 2009; Takayanagi et al., 2015). The difference between the vermetid-related and planktonic-related palaeo-SST is ~ 6 °C. Different upper Holocene SST estimations have been made for the studied area using diverse proxies (Table 4). These estimations show a range of ~ 7 °C which is within our assessed palaeo-SST estimation.

Our palaeo-SSTs based on aragonitic vermetids shells distinguish three temperature gradients as already indicated by the planktonic foraminiferal analysis (Fig. 7B). After 3700 years BP (phase III of Lessa et al., 2016), the low SST (~ 20 °C) corresponds to the decreasing amplitude of the seasonal ITCZ (Intertropical Convergence Zone) migration resulting in a decreasing of both TW and intense upwelling events between 4000 and 3500 cal. years BP (Lessa et al., 2014). The time interval of 3500–2000 years BP is marked by large local temperature variations in the CFUS associated with atmospheric component (Laslandes et al., 2006; Nagai et al., 2009) and by changes in the strength of the Brazilian Current (BC) which transports TW and SACW (Chiessi et al., 2014). At around 2000 years BP lower vermetid-based SST (~ 17 °C; Fig. 6B) is related to an intensification of the upwelling events at the Southeast Brazilian coast. In the studied area this event is recorded by a change in the microfacies from vermetid-coralline packstone to vermetid packstone (Spotorno-Oliveira et al., 2016; Fig. 6B). After ~ 1300 cal. years BP, the SST is higher than before (~ 20.5 °C) and has a similar magnitude as the modern SST at active upwelling system of CUFUS (Venancio et al., 2014).

Angulo et al. (1999) found δ^{18}O values from vermetid shells ranging between + 0.91 ‰ and –0.66 ‰ for samples dated between 5691 ± 80 and 100 ± 65 cal. years BP, with higher values related to younger samples. The studied fossil vermetid samples do not show any relationship between calibrated ages and δ^{18}O values ($r^2 = 0.03$). The changes in the δ^{18}O values could be, therefore, related to the SST. The weak positive correlation of fossil vermetids (Fig. 8) is due to by two outliers with high δ^{18}O values caused by cold upwelling inputs at around 2000 cal. years BP (see Fig. 6).

The δ^{13}C data of the studied fossil aragonitic vermetid shells vary between 1.94 ± 0.05 to 3.1 ± 0.05 ‰, showing higher values than those found in present-day vermetids from the Laguna–Imbituba region (Brazil; i.e., 1.55–2.96 ‰ in Angulo et al., 1999) and from the southeastern Australian coast (i.e., 0.2–2.4 ‰ in Baker et al., 2001; Fig. 8). The $\delta^{13}C$ of P. varians, reflecting the metabolic activity of the individuals, is the result of $\delta^{13}C$ from dissolved inorganic carbon and the primary production activity (Sisma-Ventura et al., 2009). The kinetic isotope fractionation effect during the shell precipitation is not recognized in the data from modern vermetid samples (Fig. 8).

Vermetid shells are depleted in ^{13}C relative to the equilibrium calcite for the studied area (3.15–6.20 ‰). The average $\delta^{13}C$ of living vermetids showed an offset of 1.30 ‰ from the annual average $\delta^{13}C_{DIC}$ at 10 m-water depth in the studied area (Venancio et al., 2014). Similar offset observed in Mediterranean vermetids (Sisma-Ventura et al., 2014) reflects the combined kinetic and metabolic isotope fractionation effects of 10–37 % in most gastropods (McConnaughey and Gillikin, 2008).

The $\delta^{13}C_{DIC}$ can be, therefore, achieved adding a constant offset (1.27 ‰) to the $\delta^{13}C$ value of vermetid shells (Sisma-Ventura et al., 2014). The reconstructed $\delta^{13}C_{DIC}$ record from living vermetids reflects the average values of the upper layer mixing water $\delta^{13}C_{DIC}$ (Venancio et al., 2014), where in the inner and middle shelf the enriched $\delta^{13}C_{DIC}$ is associated with upward movement of SACW promoting higher primary productivity in modern environment from CUFUS region (Venancio et al., 2014;, Lessa et al., 2016).

The reflected higher $\delta^{13}C_{vermetid}$ is likely due to the incorporation of ^{12}C by phytoplankton and consequently inorganic carbon dissolved in the surface water becomes enriched in $\delta^{13}C$ (Meyers, 2003). The enriched $\delta^{13}C$ of the studied fossil vermetids is related to the elevated upper Holocene primary production in the Arraial do Cabo Bay area (Lessa et al., 2016; Nagai et al., 2009).

FIGURE 8 HERE

In the studied upper Holocene vermetids the observed $\delta^{13}C$ along with $\delta^{18}O$ derived temperatures confirm the upwelling intensification during ~ 2000 years BP bringing about lower SST in intertidal/supratidal settings than offshore. The decreasing SST trend assessed from ~ 3300 to ~ 2000 cal. years BP can be related to (a) more frequent South Atlantic Coastal Water intrusions on the surface water layer in the mid-shelf and onshore, (b) an increasing of the surficial nutrient concentration and (c) the possible constrained reef-flat growth on the Brazilian platform (Fig. 9).

FIGURE 9 HERE

6. Concluding remarks

During the last ~ 3700 cal. years *Petaloconchus varians* assemblages associated with coralline red algae and barnacles thrived along the Arraial do Cabo Bay intertidal/supratidal coastal settings, Rio de Janeiro. After identifying the RSL changes in the studied time span, stable isotopes from present-day and upper Holocene well preserved aragonitic vermetids allowed the coastal SST and upwelling current trend to be assessed.

At 3700 cal. years BP the RSL was localized at around + 4 m above the present sea level, representing the Holocene eustatic maximum for the Rio de Janeiro coast. Estimated SST obtained from the stable isotopes of the aragonitic vermetids was ~ 20 °C.

At ~ 3300 cal. years BP during the RSL fall the SST reached its upper-Holocene maximum temperature of ~ 22 °C. At ~ 2000 cal. years BP, the RSL was + 2 m and an intensification of the upwelling events brought about lower SST (~ 17 °C) in the intertidal/supratidal settings than offshore. This intensification, confirmed by the observed $\delta^{13}C$ enrichment in the vermetid shells, can be related to more frequent South Atlantic

Coastal Water intrusions on the surface layer in the mid-shelf. The following period (from ~ 1900 to ~ 1300 cal. years BP), characterized by a continuous sea-level fall, recorded a SST of ~ 20.5 °C, higher than before.

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Figures and Tables with Captions

Fig. 1. Geographic maps of the studied area with the locations of the modern (yellow circle/dots) and fossil (red squares/circles) studied samples at Forno Harbour (RHA) Prainhas do Pontal (PR), Praia dos Anjos (RAJ, AJ), Ilha dos Porcos (PO), Praia do Farol (IL) and Anequim (AN). Modified from Spotorno-Oliveira et al. (2016).

Fig. 2. A, living vermetids from the Anjos Beach, intertidal, site RAJ (RAJ-2905); Pv, *Petaloconchus varians*; Cb, *Crassostrea brasiliana*; Ts, *Tetraclita stalactifera*. B, living vermetids from the Anjos Beach, subtidal, site RAJ (RAJ-2905), showing actual bioconstruction. C, living vermetids from the Anjos Beach, site RAJ (RAJ-2905), detail showing specimens of *P. varians* associated with coralline algae. D, studied fossil vermetid outcrops (arrows), site AJ (AJ-9280). E, locations of the studied samples of fossil vermetids (arrows), site PR (PR-0371, PR-0372). F, fossil, site PR (PR-0370), basal sample. G, studied fossil vermetids from the intertidal setting, site PR (PR-6639). H, fossil, site PR (PR-0372) showing the vermetid shells (white arrows) and encrusting coralline red algae (black arrows). Scale bars represent 2 cm (G, H), 4 cm (A, C), 10 cm (F), 20 cm (B), 50 cm (E).

Fig. 3. Studied fossil vermetids. A, SEM, terminal portion of vermetid tube (feeding tube) with no ornamentation (arrow) (IL-3623). B, Thin section, vermetids sharing mutual shell wall (IL3620). C, SEM, columellar lamellae (arrows) (IL-3623). D, SEM, shell sculpture with longitudinal ribs crossed by well-marked transverse growth lines (arrow) (PR-6639). Scale bars represent 1 mm (A, D), 0.5 mm (B), 0.1 mm (C).

Fig. 4. A, mineralogical composition of the studied fossil vermetid assemblages from Arraial do Cabo Bay. In both studied areas the fossil samples mainly consist of high Mg-calcite and aragonite. Area 1 is characterized by abundant coralline algae made up of high Mg-calcite. B, SEM photo illustrating the well preserved aragonite crystals in the studied fossil vermetid assemblages (IL-3623). Scale bar represents 50 μm (B).

Fig. 5. Dated studied fossil samples plotted with Holocene sea-level curves of Angulo et al. (2006), Suguio et al. (2013) and Castro et al. (2014). Red circles represent samples collected in the Area 1 and blue squares represent those collected in the Area 2. See Fig. 1 for the geographic locations. PSLM, post-glacial sea-level maximum (5100–5700 cal. years BP; Angulo et al., 2006). Modified from Spotorno-Oliveira et al. (2016).

Fig. 6. A, upper Holocene RSL curve for the Arraial do Cabo area assessed by the studied fossil vermetid assemblages. The gray area represents the 2σ age uncertainty maximum and minimum ages. Green and red lines represent respectively the 4^{th} and 5^{th} degree polynomial curves based on the studied samples; vertical error margin assessed by the Rovere et al.'s (2016) formula (Table 1) equivalent to 1.15 m. Dashed lines represent the time period (3400–2000 cal. years BP) barren in vermetids. See Fig. 1 for the geographic locations of the studied samples. B, estimated SST (°C) based on $\delta^{18}O$ content of the studied fossil vermetid assemblages (red line) compared with the Mg/Ca SST (°C) based on planktonic foraminifera (black line; Lessa et al., 2016). The three phases (III, IV, V) represent the oceanographic phases of the Cabo Frio upwelling system (Lessa et al., 2016). The orange-colored bar highlights the upwelling intensification event at around 2000 years BP which is

recorded at the microfacies transition (VCP–VP, i.e., vermetid-coralline packstone–vermetid packstone; microfacies descriptions in Spotorno-Oliveira et al., 2016).

Fig. 7. RSL curve (4th, black line) assessed by fossil vermetid assemblages from the Rio de Janeiro coast (see text for details). Blue area marks the time interval barren in vermetids.

Fig. 8. Cross plot of $\delta^{13}C$ and $\delta^{18}O$ for fossil (dots) and modern (triangles) vermetid assemblages in three areas: this study (red), Laguna-Imbituba region (blue; Angulo et al., 1999) and southeast Australian coast (green; Baker et al., 2001; green). The $\delta^{13}C$ data of the studied fossil aragonitic vermetid shells (from 1.94 ± 0.05 to 3.1 ± 0.05 ‰) show positive values as those found in present-day vermetids from the Laguna–Imbituba region (Brazil; Angulo et al., 1999) and from the southeastern Australian coast (Baker et al., 2001). The $\delta^{13}C$ of *P. varians* reflecting the metabolic activity of the individuals, is the result of $\delta^{13}C$ from dissolved inorganic carbon and the primary production activity. The positive correlation of fossil vermetids are due to two outliers with high $\delta^{18}O$ values caused by the input of cold water during the upwelling at ~2 ka (Fig. 6).

Fig. 9. In the Arraial do Cabo area at ~2000 cal. years BP, the RSL was +2 m and an intensification of the upwelling events brought about lower SST (~17 °C) in the intertidal/supratidal settings than offshore. The SST recorded by the studied vermetids corresponds to the coldest period detected by planktonic foraminifera (~23 °C; Lessa et al., 2016; compare with Fig. 6B). The difference between the vermetid-related and planktonic-related palaeo-SST can be due to the regional evaporation/precipitation effect and by the vital effect (biological controls) on oxygen isotope equilibrium and carbonate precipitation (Takayanagi et al., 2015). MSL, mean sea level.

Table 1. Data of the studied samples from Arraial do Cabo: coordinates, analytical data for radiocarbon calibrated ages, current setting, depth range (m), and $\delta^{13}C$ and $\delta^{18}O$ content. For details on age dating see text. See Fig. 1 for sample locations. All dated samples: Delta R = 96 ± 48 (Alves et al., 2015). Average of stable isotopic composition ($\delta^{13}C$ and $\delta^{18}O$) and standard deviation of living samples (‰ PDB). Microfacies from Spotorno-Oliveira et al. (2016).

Sample	Coordinates (latitude, longitude)	Conventional age	Water mass *	Age (cal. years BP)	Probably age	Current setting	Depth range	Error of relative palaeo-sea level (m)	$\delta^{13}C$ (‰)	Std dev.	$\delta^{18}O$ (‰)	Std dev	T Derived (°C)	Microfacies
RAJ-2905	22°58'44.41" S, 42°0'55.30" W	Modern	-	-	-	Subtidal	-1	1.15	0.286	0.268	0.093	0.322	22	-
RHA-1505	22°58'21.45" S, 42°0'49.68" W	Modern	-	-	-	Upper intertidal	-0.5	1.15	0.227	0.043	0.447	0.090	20.5	-
RHA-100	22°58'20.57" S, 42°0'49.	Modern	-	-	-	Upper intertidal	-0.5	1.15	0.674	0.231	0.257	0.127	21.3	

7	83" W													
AN-2507	22°59'06.8" S, 41°59'26.3" W	No dating	-	-	-	Supratidal	+4.0	1.15	1.885	0.120	0.524	0.136	21.2	VP
IL-3620	22°59'52.5"S, 42°00'10.9"W	3.860 ± 30 BP	SACW	3.552-3.854	3.701	Supratidal	+4.03	1.15	2.770	0.043	0.592	0.032	19.8	VP/CAB
PR-0371	22°59'25.9"S, 42°00'47.1"W	3.620 ± 30 BP	TW	3.264-3.556	3.412	Supratidal	+1.97	1.15	3.028	0.012	0.570	0.025	21.7	CAB
IL-3622	22°52’51,5”S 42°00’10,4”W	3.470 ± 30 BP	TW	3.070-3.372	3.237	Supratidal	+3.22	1.15	2.828	0.039	0.512	0.025	21.9	-
PR-0370	22°59'26.5"S, 42°00'46.7"W	2.530 ± 30 BP	SACW	1.928-2.264	2.076	Supratidal	+1.84	1.15	3.078	0.036	1.106	0.013	17.6	VCP
PR-0372	22°59'25.9"S, 42°00'47.1"W	2.400 ± 30 BP	SACW	1.781-2.081	1.920	Supratidal	+1.80	1.15	3.106	0.049	1.268	0.023	16.9	VCP
IL-3623	22°52’51,6”S 42°00’11,0”W	2.160 ± 30 BP	SACW	1.510-1.795	1.638	Supratidal	+1.78	1.15	2.240	0.035	0.403	0.029	20.6	-
IL-3621	22°59'51.5"S, 42°00'10.4"W	1.880 ± 30 BP	SACW	1.231-1.477	1.333	Supratidal	+1.30	1.15	1.945	0.051	0.459	0.009	20.4	VP
AJ-9280	22°58'41.1"S, 42°00'48.2"W	No dating	-	-	-	Supratidal	+1.04	1.15	2.003	0.069	0.604	0.117	19.8	VP
PO-2509	22°57'57.9"S, 41°59'37.3"W	No dating	-	-	-	Supratidal	+2.0							VP
PR-6639	22°59'17.6"S, 42°00'46.8"W	No dating				Intertidal								

T Derived (°C) = mean temperature for the modern vermetids and fossil outcrops derived from the equation [$T = 20.6 – 4.34 \times (\delta^{18}O_{aragonite} – \delta^{18}O_{seawater})$] (Grossman and Ku, 1986). cal., calibrated; *= SACW (South Atlantic Coastal Water); TW (Tropical water); -, no entry.

Table 2. Equations used to calculate the palaeo-RSL and the error margin (m) applied to this study.

		Equation
Eq. 1	Reference water level	RWL = $\frac{U_l+L_l}{2}$
Eq. 2	Indicative range	IR = upper limit – lower limit
Eq. 3	Relative palaeo-sea level	Palaeo RSL = dGPS measurement – RWL
Eq. 4	Error of relative palaeo-sea level	Palaeo RSL error = $\sqrt{\left(\frac{IR}{2}\right)^2 + \left(\frac{dGPS_P}{2}\right)^2}$

*Ul = upper limit; Ll = lower limit; RWL = relative water level; dGPSp = error in elevation measurement

Table 3. Mineralogical composition and $MgCO_3$ content (mol%) of the studied fossil vermetid assemblages in the two analyzed areas (for details on sample location see Fig. 1).

-, no entry.

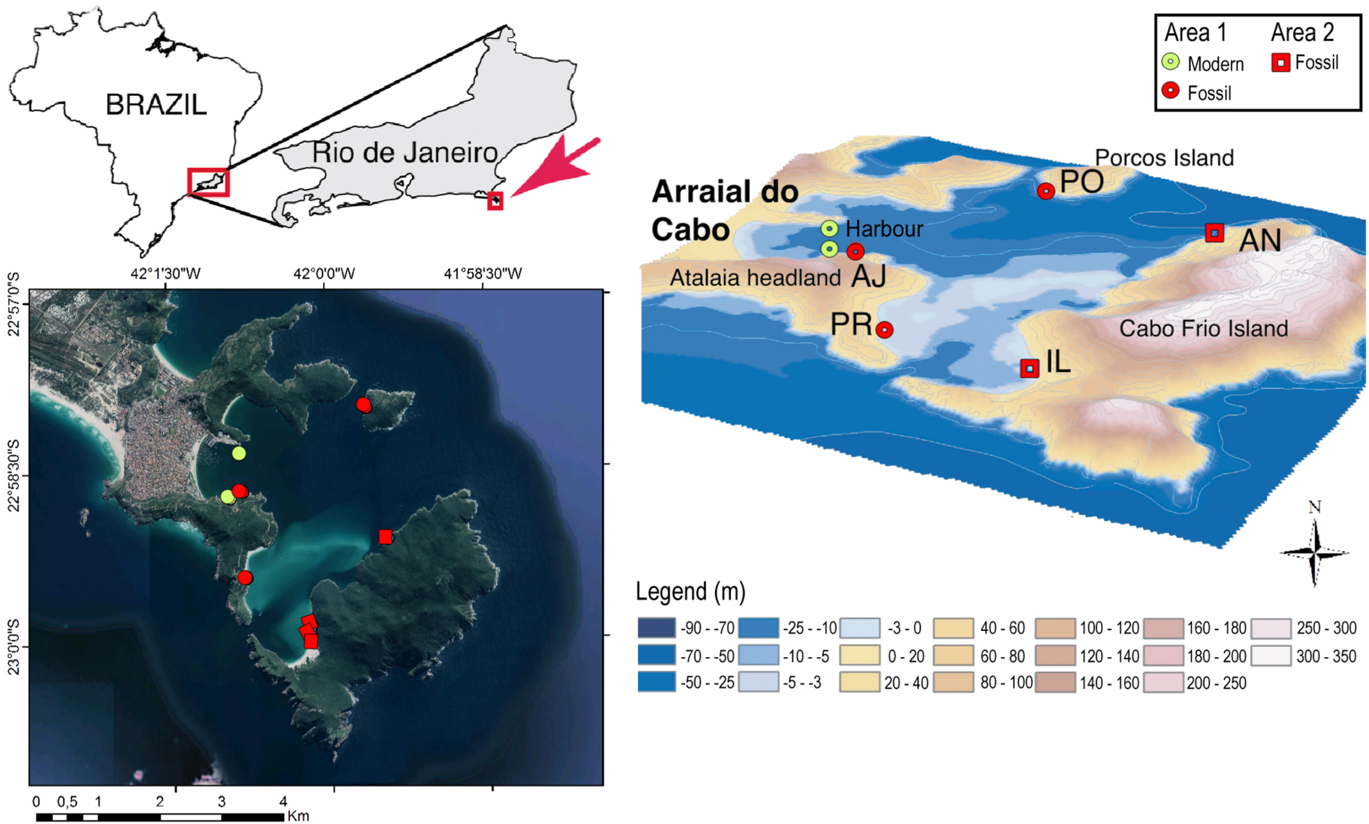
	AREA 1			AREA 2			
Mineral	**PR0370**	**PR0371**	**PR0372**	**IL3623**	**IL3620**	**IL3621**	**IL3622**
Calcite	4.1	-	4.8	2.7	3.4	4.8	36.8
Calcite-Mg	76.9	86.3	72.4	26.7	31.4	35.9	23.6
Aragonite	13.8	8.7	14.8	61.8	62.1	54.1	36.5
Quartz	5.3	5	7.9	6.9	1.8	0.9	3
Gypsum	-	-	-	-	1.2	0.4	-
Flourapatite	-	-	-	0.3	-	-	-
Dolomite II	-	-	-	-	-	3.1	-
Kaolinite	-	-	-	1,6	-	0.9	-
% mol $MgCO_3$	15	14	14	13	14	14	7

Table 4. Estimations of the upper-Holocene SST ranges for the studied area inferred from different fossil records.

Reference	Palaeotemp. range	Group	Proxy
Aguilera et al., 2016	18.1–24.1 °C	mollusk shells	$\delta^{18}O$
Lessa et al., 2016	21.9–28.9 °C	planktonic foraminifera	Mg/Ca
Bertucci et al., 2018	15–25 °C	otoliths	$\delta^{18}O$
Nascimento et al., 2018	21.6–28.9 °C	alkenone concentrations	$U^{k'}_{37}$
This study	16.8–22 °C	vermetids	$\delta^{18}O$

Highlights

- Stable isotope analysis on aragonitic fossil vermetids shells track changes in Sea Surface Temperatures and upwelling trends.
- Vermetids assemblages recorded the maximum sea level (+ 4.7m) at 3700 cal. years BP and a smooth sea level fall.
- During the sea level fall, at ~2000 cal. years BP, an intensification of the upwelling events was recorded by the vermetids with temperatures ~ 17°C at the inner shelf.
- The studied fossil vermetids recorded colder SST than the coeval planktonic foraminifera.



BRAZIL
Rio de Janeiro
42°1'30"W
42°0'0"W
41°58'30"W
22°57'0"S
22°58'30"S
23°0'0"S
0 0,5 1 2 3 4
Km
Area 1
Modern
Fossil
Area 2
Fossil
Arraial do Cabo
Porcos Island
PO
Harbour
AN
Atalaia headland AJ
PR
Cabo Frio Island
IL
N
Legend (m)
-90 - -70
-70 - -50
-50 - -25
-25 - -10
-10 - -5
-5 - -3
-3 - 0
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 - 180
180 - 200
200 - 250
250 - 300
300 - 350

Figure 1

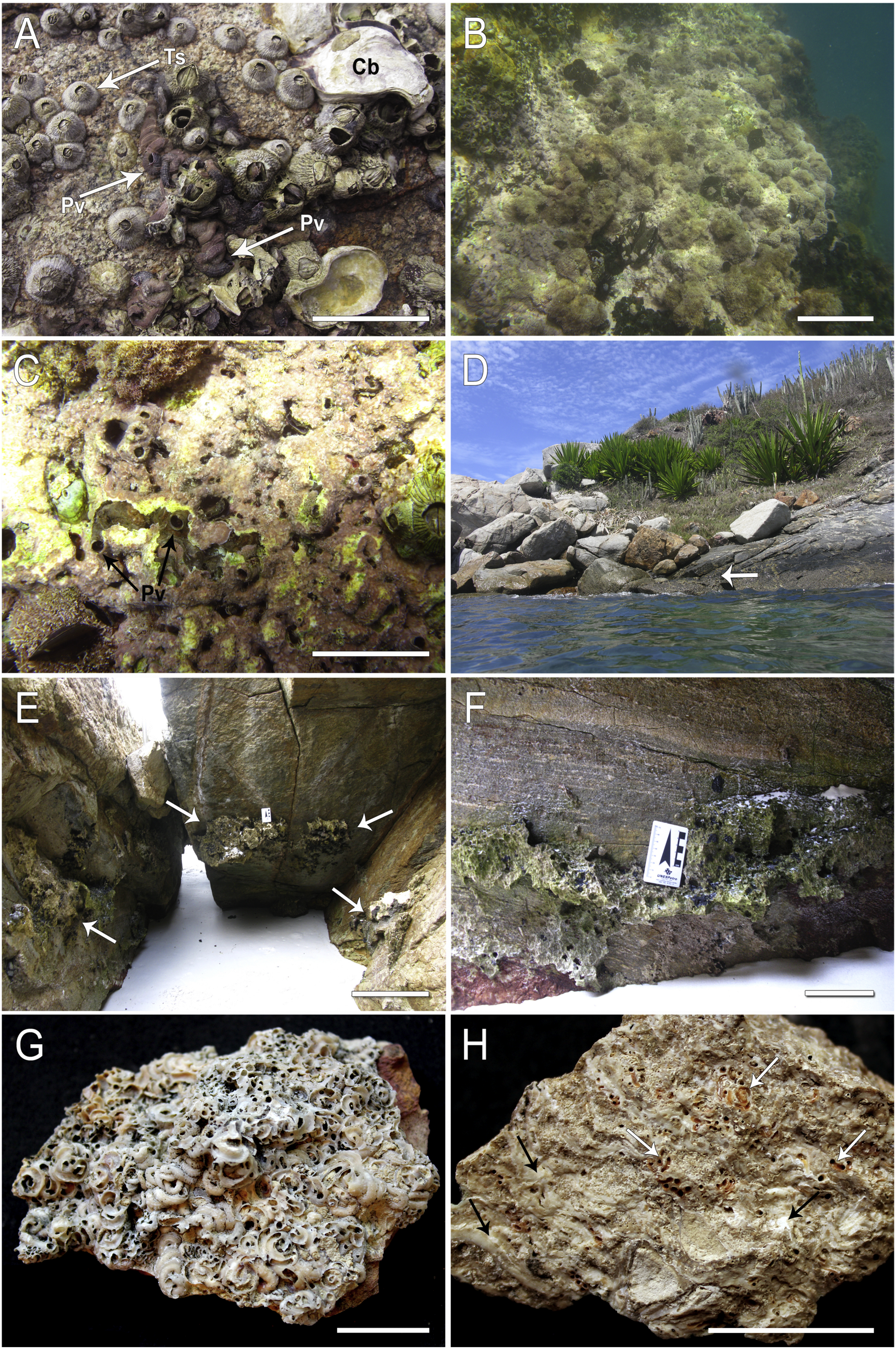


Figure 2

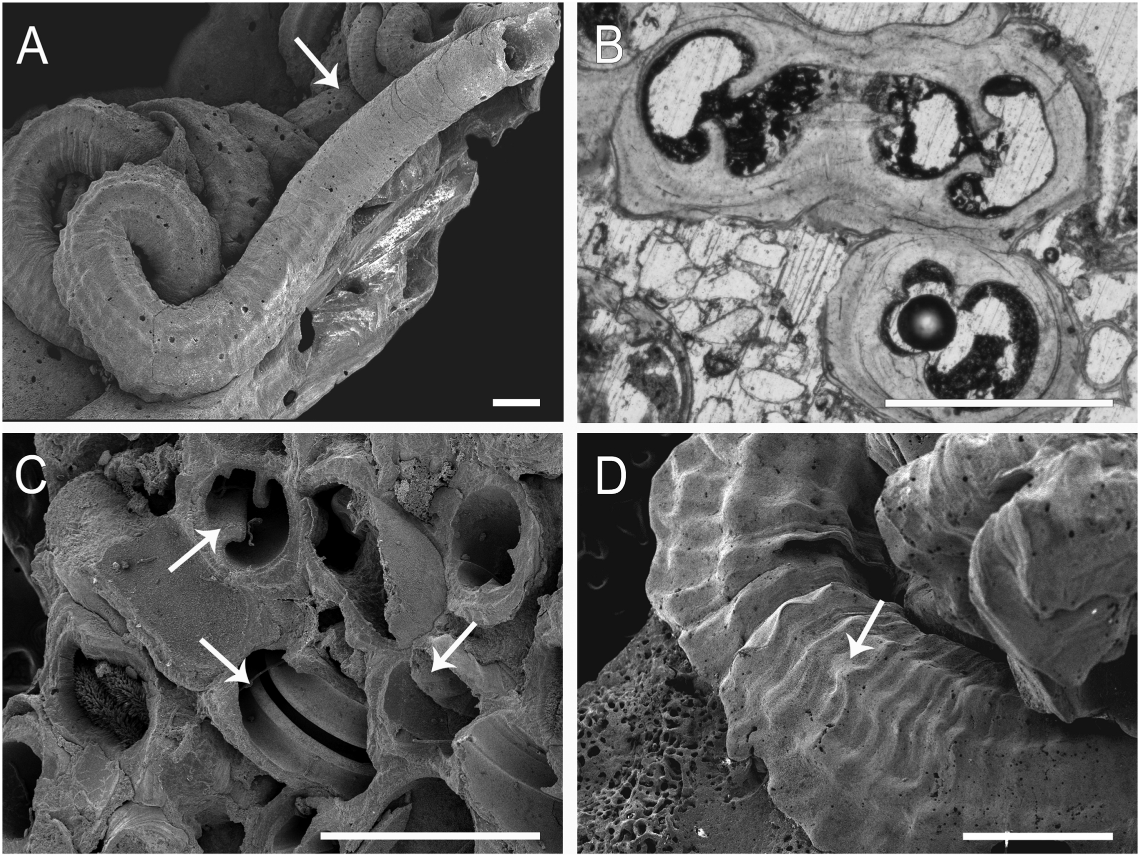


Figure 3

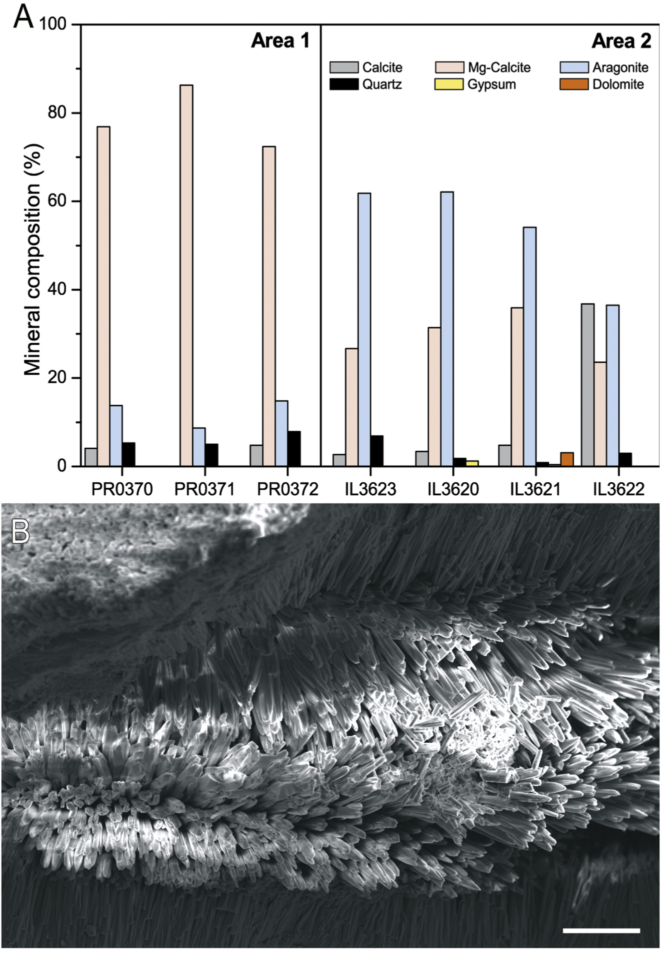
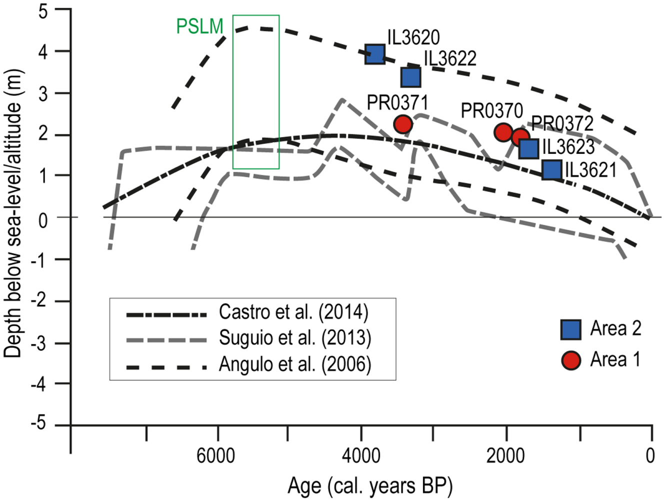

A
B
Area 1
Area 2
Calcite
Mg-Calcite
Aragonite
Quartz
Gypsum
Dolomite
Mineral composition (%)
0
20
40
60
80
100
PR0370
PR0371
PR0372
IL3623
IL3620
IL3621
IL3622

Figure 4



PSLM
IL3620
IL3622
PR0371
PR0370
PR0372
IL3623
IL3621
Depth below sea-level/altitude (m)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Castro et al. (2014)
Suguio et al. (2013)
Angulo et al. (2006)
Area 2
Area 1
6000
4000
2000
0
Age (cal. years BP)

Figure 5

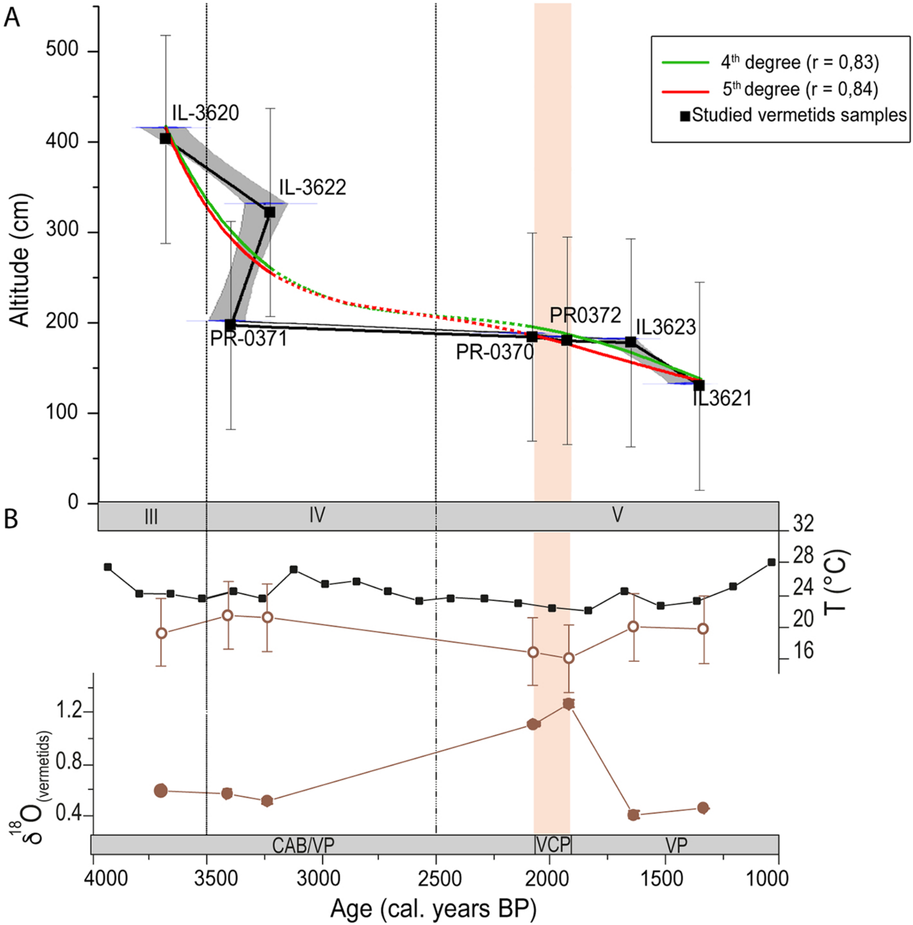
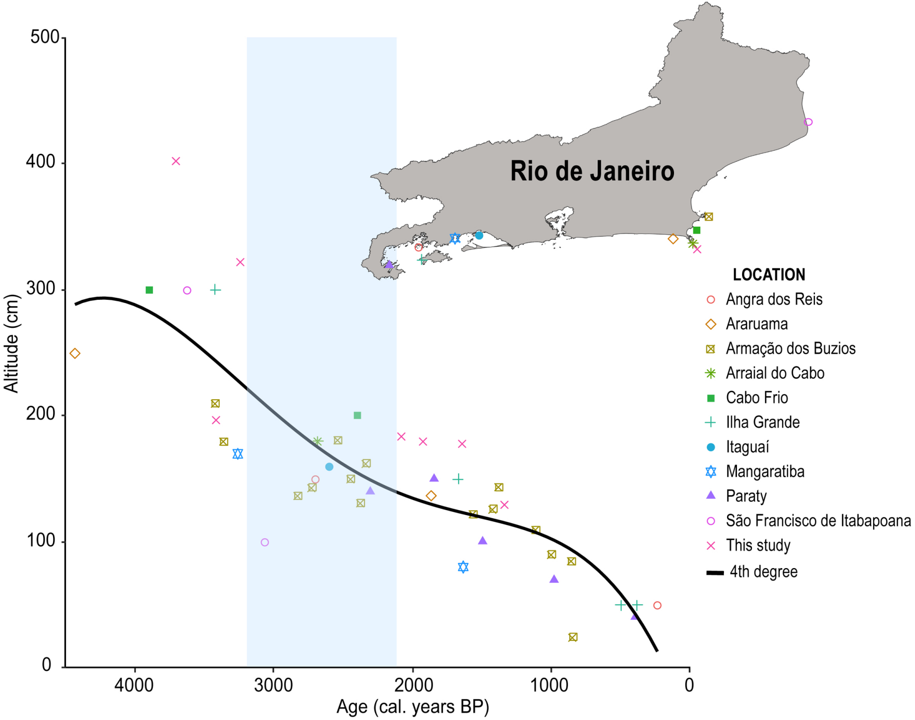

A
B
4th degree (r = 0,83)
5th degree (r = 0,84)
Studied vermetids samples
IL-3620
IL-3622
PR-0371
PR-0370
PR0372
IL3623
IL3621
Altitude (cm)
500
400
300
200
100
0
III
IV
V
T (°C)
32
28
24
20
16
δ18O(vermetids)
1.2
0.8
0.4
CAB/VP
VCP
VP
4000
3500
3000
2500
2000
1500
1000
Age (cal. years BP)

Figure 6



Rio de Janeiro
LOCATION
Angra dos Reis
Araruama
Armação dos Buzios
Arraial do Cabo
Cabo Frio
Ilha Grande
Itaguaí
Mangaratiba
Paraty
São Francisco de Itabapoana
This study
4th degree
Altitude (cm)
Age (cal. years BP)
500
400
300
200
100
0
4000
3000
2000
1000
0

Figure 7

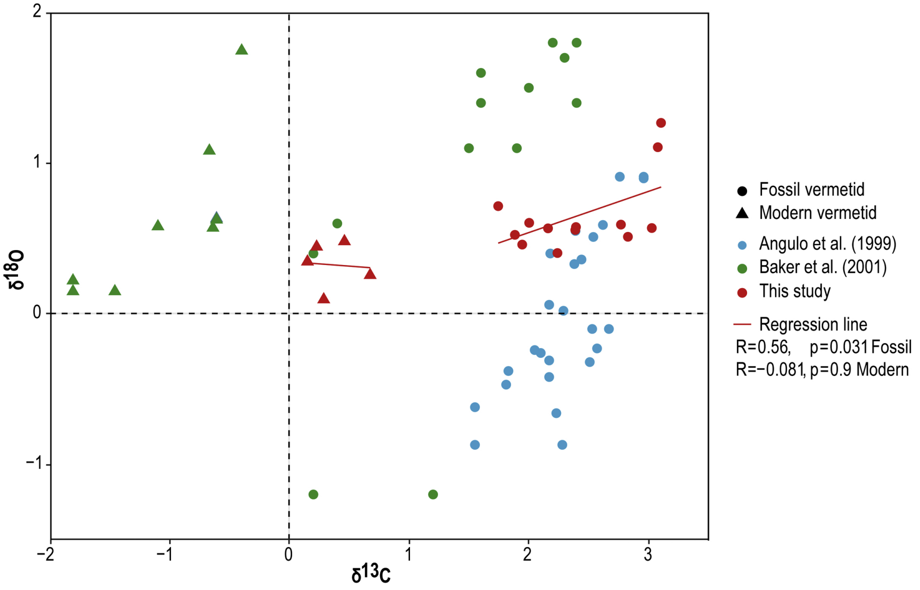

2
1
0
−1
−2
−1
0
1
2
3
δ18O
δ13C
Fossil vermetid
Modern vermetid
Angulo et al. (1999)
Baker et al. (2001)
This study
Regression line
R=0.56, p=0.031 Fossil
R=−0.081, p=0.9 Modern

Figure 8

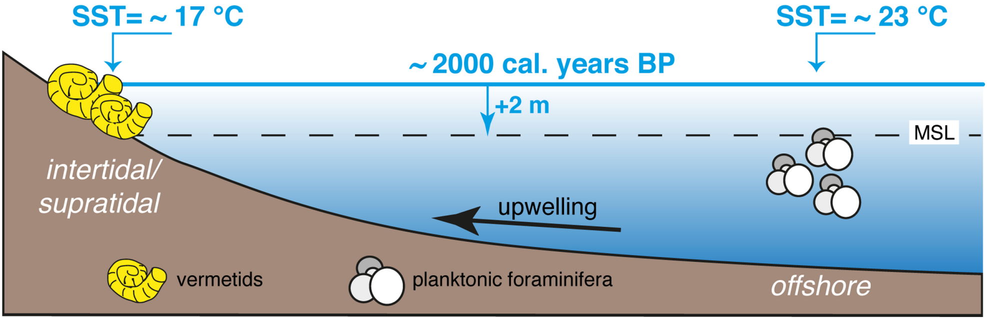

SST= ~ 17 °C
SST= ~ 23 °C
~ 2000 cal. years BP
+2 m
MSL
intertidal/
supratidal
upwelling
vermetids
planktonic foraminifera
offshore

Figure 9