Effects of Holocene sea level changes on subtidal palaeoecosystems, southeastern Brazil

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Southeastern Brazilian marine coastal deposits provide an excellent opportunity to investigate environmental changes such as sea level and trophic variability during the Holocene period. In this study, we present a sediment record from Arraial do Cabo Bay, Rio de Janeiro State. In order to improve the understanding of the upper subtidal palaeoecosystem evolutionary dynamics of this Bay, we provide a microfacies analysis of Holocene carbonate and mixed siliciclastic-carbonate deposits cropping out today from the supratidal to the subtidal zones. The age-depth model is based on ^{14}C dating and revealed a basal age of ~ 7000 cal. years BP. In the six distinguished microfacies, the biogenic components are dominated by vermetids and coralline algae. A number of subordinate components are also present, including the microfacies determining thin-shelled bivalves. Fossil vermetids are represented by monospecific clusters of overgrowing Petaloconchus varians. Coralline red algae are represented by Lithophyllum pustulatum, Spongites fruticulosus, Spongites yendoi, Mesophyllum engelharti, and unidentified ge-niculate corallines. The microfacies analysis revealed that the substrate of the benthic community in the upper subtidal ecosystem of the Bay changed according to the relative sea level: (1) during the rapid sea transgressive trend it was coarse soft substrate, (2) after the postglacial sea level maximum succeeding a slow decline to pres-ent sea level it changed into fine soft substrate. At ~7000 years ago the coarse soft substrate was characterised by fruticose corallines and composed of quartz grains from continental run off input. After the postglacial sea level maximum the highstand elevation along with the established upwelling system brought about a predominantly carbonate deposition. Vermetids and corallines, along with thin-shelled bivalves, thrived in a low sedimentation rate setting and high nutrient level environment.

1. Introduction

Estimation of the overlying depth of water is crucial for the recon-struction of past sea levels from geological deposits. This approach has succeeded in producing archives of Holocene sea level from a variety of Brazilian locations (e.g., Angulo and Suguio, 1995; Angulo and Lessa, 1997; Angulo et al., 1999, 2006; Castro et al., 2009; Dias et al., 2009; Castro et al., 2012, 2014; Suguio et al., 2013; Shennan et al., 2015; Tâmega et al., 2016; Bastos et al., in press).
In this study, we present microfacies and palaeoecological analyses of new data regarding Holocene subtidal sedimentary deposits and in-vestigate the effects of sea level changes on the related benthic communities in the Arraial do Cabo area, off the northern coast of the state of Rio de Janeiro, southeastern Brazil.

Arraial do Cabo has unique features related to its marine environ-ment, being a Marine Extractive Reserve (RESEX-MAR Arraial do Cabo). Within the framework of an ecological survey project carried out in the Arraial do Cabo Bay, several Holocene outcrops of beachrocks, now-a-day cropping out from the supratidal to the subtidal zones, characterised by vermetids and coralline algae were found. Here, we document these deposits to assess the evolutionary dynamics of the upper subtidal palaeoecosystem of the Bay during the last ~ 7000 years BP. After performing a microfacies analysis of carbonate and mixed siliciclastic-carbonate deposits, the sea level chang-es were assessed coupling palaeoecological interpretations and esti-mated ages. This study provides an integrated palaeoecological model highlighting the role of subtidal benthic communities in re-cording sea level changes

Since Delibrias and Laborel (1971), several typologies of biological proxies have been used as sea level indicators. Many palaeoshorelines are characterised by upper subtidal marine fauna/flora, constituting hard-cemented deposits which mark the altitude of formation relative to the sea level. Among these proxies, the colonial vermetid gastropods form dense bioconstructions together with coralline red algae in inter-tidal and shallow-subtidal water, from depths of 0 to ~ 6 m (e.g., Chemello and Silenzi, 2011; Aguirre et al., 2014; Spotorno-Oliveira et al., 2015).

Vermetids, whose geographic distribution is restricted to winter temperatures higher than 14 °C (e.g., Chemello and Silenzi, 2011), are characterised by a high phenotypic adaptation that makes them excel-lent organisms to withstand high hydraulic energy in shallow-water sedimentary deposits. They form bioconstructions referred to as vermetid reefs, trottoires or corniche from tropical to warm-temperate sea waters (e.g., Bosence, 1985a). These formations are highly diversi-fied being a refuge for many invertebrates (Morse, 1992; Hall-Spencer, 1998; Milazzo et al., 2014).

As a result of the vermetid wide geographical distribution, their con-tinuous growth, the possibility of dating the fossil specimens using ac-celerator mass spectrometry (AMS) ^{14}C, and their bathymetrical distribution generally restricted to a very narrow belt, vermetids are of great importance in palaeoenvironmental reconstructions, being uti-lized as fossil biological sea level indicators as well as to estimate tecton-ic uplift of land (Laborel, 1986; Laborel and Laborel-Deguen, 1996; Antonioli et al., 1999; Silenzi et al., 2004; Chemello and Silenzi, 2011).

The taxonomic coralline assemblage, as well as differences in coral-line algal thallus morphology, reflects changes in environmental param-eters such as water temperature and bathymetry, which constrain coralline algal growth (e.g., Foster et al., 1997; Foster, 2001; Bassi et al., 2010; Aguirre et al., in press). These variations in taxonomic compo-sition as well as differences in coralline morphology can be used to as-sess the palaeoecological settings (e.g., Braga and Aguirre, 2001; Nebelsick et al., 2005; Checconi et al., 2010; Bassi et al., 2012a; Aguirre et al., in press).

Concretioned vermetid-coralline assemblages can be observed in several places along the Brazilian coast, between São Roque Cape (Rio Grande do Norte State) and Rio de Janeiro State (Laborel and Kempf, 1965; Spotorno-Oliveira et al., 2012). These assemblages are located at the lower intertidal/upper subtidal zone (in the lower limit of the midlittoral zone, sensu Stephenson and Stephenson, 1949), as described in Bermuda and the Mediterranean (Laborel and Kempf, 1965).

2. Regional setting

2.1. Geographical, oceanographical and geomorphological settings

This work was carried out at Arraial do Cabo Bay, Rio de Janeiro State (23° S, 42° W; Fig. 1). Study sites included the continental part of Arraial do Cabo, Praia dos Anjos (AJ, 22°58′41.1″ S, 42°00′48.2″ W), Prainhas do Pontal (PR, 22°59′18.4″ S, 42°00′46.8″ W), and two islands, Porcos Is-land (PO, 22°57′57.9″ S, 41°59′37.3″ W), and Cabo Frio Island (Praia do Farol; A0, A1, B, C, IL, 22°01′41″ S, 42°01′41″ W; Maramutá, MA, 22°59′49.1″ S, 41°59′79.5″ W; Anequin, AN, 22°59′06.8″ S, 41°59′26.3″ W; Fig. 1). The Recent marine environment of Arraial do Cabo sustains highly diversified reef faunas and floras (Castro et al., 1995; Guimaraens and Coutinho, 1996; Ferreira et al., 1998) that flourish in embayment conditions upon a rocky reef formation. This is covered with a diverse epilithic algal community (Guimaraens and Coutinho, 1996), patches of Palythoa caribaeorum, colonies of Millepora alcicornis, and hermatypic corals (Castro et al., 1995).

The whole region is influenced by a coastal upwelling event associ-ated with the local wind regime and bathymetry in summer and spring periods (Castelao, 2012; Belem et al., 2013). This occurs when the wind blows across the ocean surface and pushes away the Brazilian Current (BC), carrying surface Tropical Waters (TW) far from the coast and as a result the South Atlantic Central Water (SACW) subsurface water, formed in the confluence zone Brazil-Malvinas emerges. The SACW is generally colder, richer in nutrients and biologically more productive than the TW (Castelao, 2012; Belem et al., 2013). The upwelling in the region is strictly related to the coast topography (changes in the cost line orientation), wind directions (predominantly NE) and the conver-gence of forces generated by the Brazilian Current and the Coriolis Effect (Valentin, 1984).

The upwelling in the region is intermittent, occurring as short epi-sodic events all year-round, but particularly enhanced during austral spring/summer under prevailing NE winds on the inner shelf (Castro et al., 1987; Campos et al., 2000). In contrast, cold front S-SW winds dur-ing fall and winter inhibit the surface upwelling of SACW (Valentin et

Fig. 1. Geographic maps of the studied area (red arrow) with the locations of the analysed samples. Area 1 (on metamorphic basement) represents the continental part of Arraial do Cabo, and the western coast of Porcos Island, whilst Area 2 (on nepheline syenite basement) comprehends the western coast of the Cabo Frio Island. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article

al., 1987). Along the Southeastern coast the TW are characterised by temperatures above 20 °C and salinities above 36 (Silveira et al., 2000).

The tidal regime is asymmetrical and semi-diurnal, with a high tide of 1.0 m and low tides between 0.06 and 0.025 m, referencing the tide reduction (0.67 m) by the Brazilian Navy (Silva, 2009).

The study site is located in the southeastern Brazilian coast and its geological setting belongs to the Cabo Frio Tectonic Domain. The Cabo Frio Tectonic Domain is mainly formed by a Palaeoproterozoic base-ment affected by a Cambrian thermo-tectonic event, interleaved with high-grade metavolcanic and metasedimentary rocks (Schmitt et al., 2008).

The Cabo Frio Island is located at the eastern end of the Poços de Caldas-Cabo Frio alkaline rock alignment, Cretaceous to early Cenozoic in age (Motoki et al., 2013).

In the Arraial do Cabo area, the Prainhas do Pontal is characterised by a metamorphic basement (orthogneiss), whilst the basement along the coast near the Arraial do Cabo Bay's mouth is composed of nepheline sy-enite (Motoki et al., 2013; Fig. 1). Quaternary deposits, lying on the rock basement, represent deltas, estuaries, beaches, marches, dunes, lakes, lagoons, swamps and beachrocks (Castro et al., 2009).

3. Materials and methods

3.1. Studied outcrops

Seventeen outcrops, above (supratidal zone) and below (subtidal zone) the present-day sea level (intertidal zone), were surveyed, sam-pled and described. The outcrops occurred in two areas: (Area 1) along the coast of the peninsula (samples Prainhas do Pontal, PR, and Praia dos Anjos, AJ), and at the western coast of the Porcos Island (PO); and (Area 2) along the western coast of the Cabo Frio Island (Praia do Farol, A, B, C, IL; Maramutá, MA; Anequin, AN; Fig. 1). In Area 1 the studied outcrops, represented by ten samples (PR, AJ, PO; Table 1), were localized as spots lying directly on the rock basement or as bioencrustations on basement boulders in the intertidal (PR3002) and in the supratidal (PO2508, 2509; AJ9280, 6942; PR0369, 0370, 0371, 0372, 0373) zones (Fig. 2A–B; Table 1). In Area 2 two sam-ples were collected from submerged outcrops (subtidal, A0, A1), one sample across to the present sea level (intertidal, B) and four samples from outcrops above the present sea level (supratidal, C, IL3620, 3621; MA2506; AN2507) (Fig. 2C–D; Table 1). The thickness of each studied outcrop, occurring within the beach sands (A0, A1, B and C), was not able to be evaluated because the contact with the rock basement was covered by thick beach sandy deposits (Fig. 2C–D). The studied outcrops do not show bedding.

The outcrops occurring below the present-day sea level (A0, − 3.0 m; A1, − 4.5 m; Figs. 1–3, Table 1) do not show bedding. Represen-tative samples for each studied outcrop and their altitudes were collect-ed by SCUBA diving using a hammer and a chisel (Fig. 3). The water depth of the sample location was measured by a diving computer.

Since the beachrock formation zone ranges from slightly subtidal to supratidal (Vousdoukas et al., 2007) and considering that the studied area is a Bay with a tidal range of ~1.2 m (data from Instituto de Estudos do Mar Almirante Paulo Moreira, IEAPM), we adopted a conservative in-dicative range of +1 m to −1 m mean sea level (compare with Vacchi et al., 2016). This range largely encompasses the beachrock formation zone amplitude for the microtidal coasts of the Arraial do Cabo. The tidal error (Vacchi et al., 2016) was not introduced because the tidal in-formation is based on a single tidal station. In the studied area the tidal error does not eventually exceed ±0.3 m due to the microtidal setting of the Bay (IEAPM data).

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

3.2. Topographic survey

To define the position of the outcrops in relation to the present-day sea level, the topographic data and coordinates (x, y) were obtained using the Pro Mark II GPS tracker using the static method. The nominal accuracies of the horizontal and vertical displacements are ±5 mm + 1 ppm and ±10 mm

+ 2 ppm, respectively. Two fixed re-ceivers were used: one located in the geo-refenciated landmark from IBGE (Instituto Brasileiro de Geografia e Estatística), located at the IEAPM (Instituto de Estudo do Mar. Almirante Paulo Moreira), geodetic station "2987S", corrected by the geodetic station "3088S", and the one positioned above each studied outcrop. The topographic data were processed by the GNSS (Global Navigation Satellite System) Solutions software. The information from the geodetic stations 2987S and 3088S were obtained from the IBGE website (IBGE, 2015). To convert the geo-metrical or ellipsoidal elevation (h), obtained through the GNSS in orthometric height (H), the mathematical expression H = h − N was applied, where N is the geoid undulation, provided by the MAPGEO2010 software (IBGE, 2015).

Fig. 2. Four representative photos of the outcrops. A–B, Holocene vermetid-coralline bioconstruction lying on the metamorphic basement rock; area 1 (A, samples PR0371, CAB microfacies; B, samples AJ9280, VP microfacies). C–D, Holocene coralline debris grainstone deposits spotted from the beaches or lying on the magmatic basement rock; area 2 (C, samples B, CQG microfacies; D, samples AN2507, VP microfacies). Compare with Fig. 6

3.3. Biogenic components and microfacies analysis

For each studied outcrop one sample was collected from which one to three thin sections were prepared. Forty-nine petrographic thin sec-tions of carbonate and mixed siliciclastic-carbonate rocks were made using a geological saw and successively polished in order to prepare petrographic sections (e.g., Woelkerling et al., 2012). Thin-sections were analysed using optical microscopy equipped with an eyepiece ret-icule to perform micrometer measurements of the biogenic compo-nents and digital images were captured using the same system. This analysis aimed to carry out a detailed assessment of vermetids and cor-alline algal distribution to perform microfacies analysis. Microfacies analysis of the studied material was based on field observations and on thin sections (~ 6 × 3 cm) through petrographic microscopy. The modified Dunham (1962) textural classification of Embry and Klovan (1972) was used allowing for a general component and matrix descrip-tion. Semiquantitative data on the component distribution of thin sections were collected using the comparison charts depicted in Flügel (2004).

Vermetids were studied based on macroscopic observations, in order to describe their size, shape, inner structure and preservation. Taxonomic identification followed Keen (1961); Spotorno-Oliveira (2009) and Spotorno-Oliveira et al. (2012).
The coralline algal identification followed Tâmega et al. (2016); coral-line algal growth-form terminology followed Woelkerling et al. (1993).

3.4. Radiocarbon dating

Radiocarbon dating was performed on nine samples representing the distinguished microfacies, collected at the deposit–rock basement interface. The radiocarbon measurements were carried out by the stan-dard method, at the Beta Analytic Radiocarbon Dating Miami, Florida (USA). Acid etch (hydrochloric acid, HCl) was applied as pre-treatment. The value of 205 ± 27 (Delta R) was obtained for the local offset from the average global marine reservoir (Eastoe et al., 2002).

4. Results

Biogenic components are dominated by vermetids and coralline algae (Fig. 4). These represent a single assemblage concurring in the vermetid-coralline microfacies. Vermetid shell tubes and coralline algal debris were recognised within the other distinguished microfacies. A number of subordinate components also occur including the microfacies determining thin-shelled bivalves

Fig. 3. Schematic diagram of the field and laboratory methods performed in reconstructing the RSL changes for the studied Holocene deposits, Area 2. Red arrows point to the reference water-level of the analysed samples located above and below the present-day sea level. m, meter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Photomicrographs showing representative Holocene biogenic components in the Arraial do Cabo Bay. See Fig. 1 for the sample locations. A, vermetids showing mutual shell wall (rectangle) and columellar lamellae (arrows); sample AJ6942. B, superimposed coralline algal thalli; sample IL3620. C, articulated thin-shelled bivalve; sample PR3002. D, barnacle shell; sample IL3620. bar, barnacle; co, corallines; geo, geopetal structure; q, quartz; ver, vermetid; m, micrite

4.1. Vermetids

Vermetid gastropods occur in the carbonate and mixed siliciclastic-carbonate deposits as intergrowth of Petaloconchus varians (d'Orbigny, 1841), cemented by coralline algae. The vermetid taxon is represented by monospecific colonies of P. varians. The presence of three internal columellar lamellae (paired lamellae, with a low central in the area of attachment of the columellar muscle) is a diagnostic feature of the genus Petaloconchus (Fig. 4A, arrows). The in situ vermetid colony is formed by tightly uncoiled shells, mostly preserved in growth position, and in contact with one another, sometimes sharing a mutual shell wall (Fig. 4A, rectangle). The continuous overgrowing of shells (exhibiting a massive growth form) builds up large colonies (with the juvenile spec-imens on the top) encrusting on basement boulders. The shells are 0.64 mm in mean inner diameter and 0.11 mm in mean thickness. The shells typically have a weak or unpreserved exterior ornamentation due to erosional processes, though the internal structures of the shell tubes are well preserved.

The vermetid colonies are commonly affected by bioerosion and en-crustation. Boring traces can be referred to Gastrochaenolites, Entobia and, subordinately, polychaete annelid traces. Vermetid shells often preserved geopetal structures.

4.2. Coralline red algae

Coralline algae are frequent to dominant components of the studied carbonate and mixed siliciclastic-carbonate deposits (Fig. 4B) and are represented by different growth forms and species. Coralline algal growth-forms are mainly encrusting and lumpy. The term "debris" re-fers to small (b 1 mm in diameter) and abraded fragments of fruticose corallines or where the growth forms cannot be identified (Table 2). Four species representing the subfamilies Lithophylloideae, Neogoniolithoideae and Melobesioideae (Corallinales, Hapalidiales, Rhodophyta) were identified, and undetermined geniculate corallines are also present (Tâmega et al., 2016). Lithophylloids are represented by Lithophyllum pustulatum (Lamouroux) Foslie. Spongites

fruticulosus Kützing and Spongites yendoi (Foslie) Chamberlain are the members of the subfamily Neogoniolithoideae (Rösler et al., 2016). Melobesioideae are present with Mesophyllum engelharti (Foslie) Adey.

The identified coralline algal species show growth-forms that result in different types of detrital thalli (Table 2). All the species grow as encrusting thalli. S. fruticulosus and S. yendoi show lumpy morphologies. The algal debris is made of fragments derived from fruticose thalli, how-ever, do not show enough diagnostic characters for the genus and spe-cies identification. Lithophyllum pustulatum and M. engelharti only reveal encrusting growth-forms.

4.3. Other biogenics

Subordinate components are thin-shelled bivalves (Fig. 4C), barna-cles (Fig. 4D), bryozoans, encrusting arborescent foraminifera (Homotrema cf. rubrum), small benthic foraminifera (textulariids and rotaliids), small gastropods, polychaete worm tubes, brachiopods, and echinoderms. Thin-shelled bivalves commonly occur as articulated specimens with no taphonomic signature. Smaller articulated bivalves can occur within a larger bivalve specimen (Fig. 4C).

4.4. Microfacies

Six microfacies were distinguished on the base of component distri-bution and fabric analysis: vermetid packstone (VP), vermetid-coralline packstone (VCP), vermetid-bivalve packstone (VBP), coralline algal bindstone (CAB), coralline algal debris grainstone (CDG) and coral-line-quartz grainstone (CQG; Figs. 5A, 6A−F, Table 3).

4.4.1. Vermetid packstone (VP)

This microfacies is characterised by vermetids which are filled in by peloidal packstone within a packstone matrix (Fig. 6A). The vermetid P. varians is the dominant component (Table 3). Subordinate components are represented by articulated thin-shelled bivalves with geopetal fea-tures, serpulids, barnacles, and quartz grains. Corallines are rare with very thin thalli of M. engelharti and S. yendoi. Geniculate corallines are also present. Entobia isp. occurs in the vermetid shells.

4.4.2. Vermetid-coralline packstone (VCP)

This microfacies consists of packstone with quartz grains and silty matrix (Fig. 6B). It occurs as bioconstructions, up to 0.56 m in thickness, on the metamorphic basement rock at ~2.0 m above the present day sea level. The largest coralline-vermetid bioconstruction had a vertical range of 1.35 m and thicknesses of 0.56 m. Biogenic components are dominated by vermetids and corallines (Table 3). Thin-shelled bivalves, barnacles, bryozoans, serpulids, and peloids are common.

Three coralline algal species are recognised: M. engelharti, L. pustulatum and S. yendoi. All these species are common and show encrusting growth forms. Fragments of undetermined encrusting coral-line thalli are present in the matrix. Fragments of undetermined genic-ulate corallines are also present.

Within the P. varians shells common geopetal structures are pre-served (Fig. 6B). The skeletal surfaces of the bioclasts show encrusta-tions by corallines and barnacles. No abrasion and rounded edges were found.

4.4.3. Vermetid-bivalve packstone (VBP)

The dominant biogenic components are vermetids and thin-shelled bivalves (Fig. 6C, Table 3). Subordinate components are barnacles, gastropods, brachiopods, serpulids, and corallines. Benthic foraminifera consist of textularids and miliolids. Peloids are abundant and occur within the vermetid and barnacle shells. Within these shells geopetal structures are also preserved.

Coralline algae are represented by M. engelharti and S. yendoi as encrusting growth-forms. Some shells are perforated by etching sponges forming the ichnotaxon Entobia isp.

4.4.4. Coralline algal bindstone (CAB)

Coralline algae are the dominant components making up a coralline bindstone with packstone matrix and superimposed thin encrusting thalli of M. engelharti, L. pustulatum and S. fruticulosus (Fig. 6D, Table 3). Subordinate components are represented by serpulids and barna-cles. Quartz grains are also present.

4.4.5. Coralline algal debris grainstone (CDG)

This microfacies is characterised by the highest amount of fruticose coralline algae and their debris within a grainstone matrix (Fig. 6E, Table 3). The fruticose corallines occur as small abraded fragments ᵇ0.8 mm in size. The absence of well-preserved coralline specimens did not allow for species identification. Corallines are bordered by thin isopachous fibrous marine cement up to 50 µm thick. Subordinate com-ponents are fragmented and abraded bivalves, and small benthic fora-minifera. Rare quartz grains ᵇ0.35 mm in size are also present. Some coralline fragments are characterised by Entobia isp.

4.4.6. Coralline-quartz grainstone (CQG)

Coralline fragments and poorly sorted quartz grains are the domi-nant components of this microfacies (Fig. 6F, Table 3). Subordinate com-ponents are represented by bivalve fragments. Echinoderms, barnacles, small benthic foraminifera, and geniculate corallines are also present. Corallines occur as rounded fragments, highly abraded, ᵇ0.5 mm in size. No reproductive features were preserved. Sub-angular quartz grains are ᵇ0.35 mm in size. Grains are bordered by thin isopachous mi-crocrystalline calcite up to 50 µm thick.

4.5. Radiocarbon dating

The ^{14}C dated samples occurred near the mouth of Arraial do Cabo Bay (Fig. 1). Nine samples were dated: three from Area 1 and six from Area 2 (Table 1). Along the coast of the peninsula (PR, Area 1) the measured records range from 3370 to 1695 cal. years BP (2σ), while in the western coast of the Cabo Frio Island (Area 2) the measured records extended from 13,130 to 3300 cal. years BP (2σ) (Fig. 5B; Table 1).

The oldest sample (C; CDG microfacies) occurred in Area 2 and the youngest (PR0372; VCP microfacies) occur in Area 1 (Fig. 5B). The dated samples from Area 1 are younger than those of Area 2.

5. Discussion

In the Arraial do Cabo Bay Holocene carbonate and mixed siliciclastic-carbonate deposits, characterised by a various suite of vermetid-coralline, vermetid-bivalve and coralline debris microfacies, demonstrate that the substrate of the benthic community in the upper subtidal ecosystem changed according to the RSL: (1) it was coarse soft substrate just before overtaking the present-day sea level (~ 7000 cal. years BP), and (2) it changed into fine soft substrate after the postglacial sea level maximum (PSLM; 5100–5700 cal. years BP, Angulo et al., 2006; Fig. 7).

Therefore, our microfacies data provides a reliable palaeoecological assessment for the Arraial do Cabo Bay over the past 7000 years. In the following discussion we address details of the benthic faunal and coralline algal assemblage dynamics to examine the response of the shallow-water benthic communities to the sea level changes.

The interpretation of the benthic assemblage dynamics to RSL is based on the dated microfacies and on the palaeoecological demands of identified faunal and floral assemblages. Other factors such as siliciclastic terrigenous input (i.e., quartz) and the amount of hydrody-namic energy are also discussed. The RSL change was also assessed by the constraining parameters such as (a) location, (b) age, and (c) sam-pling elevation (e.g., Mauz et al., 2015).

5.1. ^{14}C dating and microfacies evidence: assessing the RSL trend

Among the dated samples, the grainstone microfacies age ranged from 13,130 to 11,149 cal. years BP (Table 1). In the eastern Brazilian coastline complex indicators (including changes of the geoidal surface) point to that the sea level had already overtaken present mean sea level (MSL) by 6900–7700 cal. years BP (Angulo et al., 2006). The altitude of the studied grainstone (from −4.5 to +1.5 m) confirms that these sam-ples formed in a high hydrodynamic energy setting that cannot be relat-ed to the sea level at that age (Fig. 7). In fact, at ~13,000 cal. years BP the sea level had a depth of ~−60 m (Deschamps et al., 2012). It ensures that the radiocarbon dating of the grainstone deposits may have been effected by a number of processes and uncertainties, including incorpo-ration of "dead" carbon into the dated samples (a) from basement rock and soil (from weathering of the basement rocks), and (b) from boring bivalves prior to final deposition and cementation in the grainstone.

Incorporation of "dead" carbon fraction within radiocarbon dated grainstone may result in an overestimate of the age of palaeoshoreline (e.g., Wiener, 2012). "Dead" carbon fraction may accumulate in the shells of marine organisms through ingestion of pre-existing carbon in their food source. For the grainstone samples it was not possible to dis-criminate shell materials derived from boring bivalves. Hence, the stud-ied samples could include "dead" carbon. Determining the influence of "dead" carbon on the age of grainstone samples is difficult given that neither the proportion of boring bivalves nor the proportion of cement is known for each sample. In the absence of compositional data for each sample, we have assessed the potential influence of "old" carbon by plotting the altitude of each dated sample versus calibrated radiocar-bon age for each of the nine dated samples (Fig. 7). For the plot in Fig. 7, considering that the grainstone formed in a very shallow-water setting, we shifted to the right (younger age) the sample positions in the dia-gram until crossing the sea level curves. As a result we can speculate that the grainstone samples are tentatively ascribed to the interval

~7300–6800 cal. years BP. The samples B and C with an elevation of 0–1.5 m (Table 1) plot within the Suguio et al.'s (2013) sea level curve, showing that the sea level reached those elevations at ~ - 7400 cal. years BP, when the studied grainstone microfacies were deposited.

5.2. Holocene upper subtidal ecosystem dynamics

The microfacies CDG and CQG were deposited from ~ 7300 to 6800 cal. years BP in the most proximal part of the Arraial do Cabo Bay (Area 2, Figs. 1, 5). The fragments of fruticose corallines are indica-tive of shallow, high-energy settings (e.g., Nebelsick et al., 2005; Peña et al., 2015). The fragmented and abraded bivalves along with barnacles confirm this interpretation. The sub-angular quartz grains occurring in these microfacies are likely to be produced from the magmatic base-ment. The isopachous microcrystalline calcite rimming the grains is in-dicative of intertidal/upper subtidal marine phreatic zone (Mauz et al., 2015; Fig. 6E–F). As a consequence, these microfacies are interpreted to have been deposited in a high water energy environment (swash and backswash area) colonized by scattered fruticose corallines and bi-valves on coarse soft mobile substrate (Fig. 8).

From the inner part of the Arraial do Cabo Bay (i.e., Prainhas do Pontal, PR) towards the Porcos Island, the microfacies pass from CDG and CQG to VP, VCP, VBP, and CAB. The VP, VCP, VBP and CAB were de-posited from 3370 to 1695 cal. years BP in Area 1 and the Porcos Island (Fig. 5). This change in microfacies is characterised by an increase in micrite content (from grainstone to packstone), and a higher biogenic diversity: the dominance of vermetids and coralline algae, and the oc-currence of articulated thin-shelled bivalves.

The identified Petaloconchus bioconstructions (VP and VCP microfacies), occurring as dominant, suggest a palaeobathymetric range of −1.184 to 4.075 m, corresponding to the lowermost intertid-al/upper subtidal zone during ancient times, as indicated by various ob-servations in many parts of the world (Laborel and Kempf, 1965; Safriel, 1966; Rovere et al., 2015; Vacchi et al., 2016).

The morphological plasticity of the building vermetids reflects di-verse environmental conditions and sea level positions during their growth (Schiaparelli et al., 2006). In some studied outcrops (PR, IL, AJ) a ridge cap of young vermetids developed at the top of the outcrop points out the maximum RSL position at + 4.075 m above the pres-ent-day sea level (Fig. 8).

Under stressed conditions vermetids can produce temporary calcar-eous tubes (i.e., feeding tubes) which, once lost, leave characteristic scars on the shell (Keen, 1961). These feeding tube scars were common-ly observed in the studied specimens indicating an increase in sedimen-tation rate (Schiaparelli and Cattaneo-Vietti, 1999).

P. varians is widely distributed along the Brazilian coast, from north-east (Ceará to Bahia states), through southeast (Espírito Santo to São Paulo states), to the south (Paraná and Santa Catarina states; Spotorno-Oliveira et al., 2012). The southernmost record of living spe-cies remains unclear. Present-day Petaloconchus bioconstructions are commonly found in the Arraial do Cabo Bay from the lowermost inter-tidal zone of rocky shores (Spotorno-Oliveira,

pers. obs.). There are some records of living populations of P. varians on the southeastern Bra-zilian coast in earlier studies. According to Breves-Ramos et al. (2010), in Ilha Grande Bay, south of Rio de Janeiro state, P. varians can be found forming a complex structure that dominates the middle portion of the intertidal zone of rocky shores. Besides this record, living individuals had been registered in several locations along the southeast-ern coast, at Paraty, Mangaratiba, Maricá, Angra dos Reis, Ilha Grande, and Cabo Frio (Spotorno-Oliveira et al., 2012).

The identified coralline algal species occur in present-day coralline assemblages in Brazil (Amado-Filho et al., 2010; Figueiredo et al., 2012; Henriques et al., 2012, 2014; Costa et al., 2014a, 2014b; Tâmega et al., 2014, 2016). The majority of the identified species grow as encrusting thalli on other corallines and/or on hard substrates (vermetids, barnacles; Table 2). Only S. fruticulosus has a fruticose and lumpy growth form. Corallines encrust the vermetid shells strengthen-ing and stabilizing the bioconstruction (e.g., Laborel and Laborel-Deguen, 1996; Fig. 6B). This palaeoecological role along with the species bathymetric distribution point to an upper subtidal depositional setting for the analysed deposits. The identified fossil coralline assemblage (i.e., M. engelharti, L. pustulatum, S. fruticulosus, S. yendoi), identified in the fossil samples localized within the altitudinal range of + 1.2– 4.0 m (MA, AN, AJ, PO; Table 1), has been never found from Brazilian shal-low-water coasts (Tâmega et al., 2016). However, modern records of the single species are reported from the subtidal zone. M. engelharti oc-curs to a depth of 15 m of the Pacific and Atlantic areas (Guiry and Guiry, 2015). L. pustulatum occurs in similar depths in the Mediterranean area (e.g. Bassi et al., 2009; Braga et al., 2009; Bracchi et al., 2016) and has been found at 55–65 m water depth in Brazil (Henriques et al., 2014). In Brazil S. yendoi thrives at 9–25 m water depth (Costa et al., 2014b) and has been also collected at a depth of 50 m, whilst S. fruticulosus is a deeper form (Henriques et al., 2014). However, in the Mediterranean Sea S. fruticulosus thrives on mobile substrates shallower than 30 m water depth (e.g., Braga et al., 2009). In coastal to deep-subtidal settings encrusting corallines form rigid bioconstructions named algal ridges, algal frameworks, coralligènes, trottoirs, and corniches (e.g., Pérès and Picard, 1964; Blanc, 1968; Bosence, 1985b; Freiwald and Henrich, 1994; Freiwald, 1998; Macintyre et al., 2001; Ballesteros, 2006; Georgiadis et al., 2009). None of these bioconstructions were identified in the studied area, rather the microfacies VCP and CAB represent fine soft substrates consisting in a quartz-silty packstone with thin-shelled bivalves and peloids. The vertical growth of the vermetid–coralline algal framework may have trapped the fine-grained sediment. Furthermore, low hydrodynamic energy allowed the formation of a stable substrate for the effective attachment of gastropod larvae and algal propagules as well as the subsequent development of the framework.

In Area 2 the presence of articulated thin-shelled bivalves along with encrusting coralline thalli on a soft substrate suggests that these sedi-ments were deposited in protected areas with low hydrodynamic ener-gy. Barnacles, vermetids, and coralline algae have the ability to make up complex encrusting sequences. The occurrence of barnacles within the superimposed coralline thalli localizes an upper subtidal depositional setting (e.g., Stotz et al., 2016; Fig. 8).

5.3. Evolution of the Holocene upper subtidal palaeoecosystem in Arraial do Cabo Bay

During the Holocene the upper subtidal benthic communities in the Arraial do Cabo Bay underwent changes according to sea level oscilla-tions. From ~9900 cal. years BP, an onset of deposition of the muddy, or-ganic-carbon-rich bank formation in the Cabo Frio mid-shelf area has been reported (Albuquerque et al., 2016). The nature of this formation records the establishment of the upwelling system that, in Cabo Frio, be-came positioned at its present location at ~9000 years BP (Albuquerque et al., 2016).

At ~7300 years ago the intertidal setting was characterised by coarse soft substrate colonized by fruticose corallines and scattered with quartz grains (i.e., microfacies CDG, CQG; Figs. 7–8), possibly originating from the magmatic and metamorphic basement and continental runoff input. These deposits represent the high-energy nearshore depositional setting during the progressive rapid sea level rise (Angulo et al., 2006; Castro et al., 2012; Suguio et al., 2013; Fig. 7).

After the PSLM the benthic community's substrate in the intertidal ecosystem of the Bay changed. The existence of the high-frequency sea level oscillations in Brazil after the PSLM has long been debated (Angulo and Lessa, 1997; Martin et al., 1998, 2003; Angulo et al., 2006; Suguio et al., 2013). It is hypothesized that these fluctuations had amplitudes of 3–4 m, and occurred between 4200–3700 and 2700–2100 cal. years BP. Our samples confirm this amplitude (Fig. 7). In fact, as mentioned above, the identified vermetids assemblage occur-ring in the VP–VCP microfacies marks a maximum reference water-level position at +4.075 m (Table 1). The identified fossil coralline species in-habit the present-day upper subtidal zone, whose upper limit is at ~5 m water depth (Candella, 2009).

This change in substrate may well reflect a transition to a less turbu-lent depositional setting in the studied area that allowed accumulation of finer sediments with predominantly carbonate deposition (i.e., VP, VCP, VBP, CAB microfacies). Low sedimentation rate is argued by the oc-currence of boreholes within the vermetids and coralline thalli (i.e., Gastrochaenolites, Entobia; Bassi et al., 2012b).

In Arraial do Cabo, after the PSLM, the appearance of coralline bindstones, vermetids, and thin-shelled bivalves (~3400 cal. years BP; Fig. 8) points to a change in the trophic system. During the sea level highstand, these benthic components thrived in a high-nutrient level setting (e.g., Reijmer et al., 2012; Colombo et al., 2013). This setting was promoted by the present-day combination of classic coastal up-welling, mid-shelf wind curl, and shelf-margin meanders of the Brazil Current, favouring high rates of marine productivity (Belem et al., 2013; Albuquerque et al., 2014).

Confirming and improving such conclusions of the inferred upper subtidal ecosystem evolutionary dynamics, and gaining a deeper under-standing of the climate dynamics underlying the Holocene climate in-tervals in southeastern Brazil represent a major advance in our efforts to build upon the current data assimilation framework.

6. Concluding remarks

Holocene carbonate and mixed siliciclastic-carbonate deposits occur as spotted outcrops along the coasts of the Arraial do Cabo Bay, south-eastern Brazil. These deposits recorded the upper subtidal palaeoecosystem evolutionary dynamics of the Bay over the last 7000 years. Benthic biogenic associations and related microfacies are in-dicative of water-energy changes, sediment supply, and nutrient input as a function of the variation of the sea level over the time.

At ~ 7000 cal. years BP the sea level in the bay was approximately 4 m below the present sea level and the upper subtidal benthic commu-nity was characterised by fruticose corallines on coarse soft substrate, composed mainly of quartz grains from continental runoff input. The transgressing sea rapidly rose until reaching the ~ + 4 m highstand level around 5000 years BP.

The sea level highstand is accompanied by: (1) an increase in the amount of micrite, (2) a shift from coarser to finer sediments, (3) the presence of encrusting corallines, and (4) an increase in abundance of vermetids and articulated thin-shelled bivalves. These communities thrived on fine soft substrate, under a low sedimentation rate and high nutrient levels.

Acknowledgements

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