



THE INFLUENCE OF SEDIMENT GRAIN SIZE AND COMPOSITION ON THE MORPHODYNAMIC STATE OF MIXED SILICICLASTIC AND BIOCLASTIC SAND BEACHES IN ESPIRITO SANTO STATE, BRAZIL

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Abstract

The beaches in front of the Barreiras Formation active sea cliffs are composed of mixed sands, which composition makes it more difficult to interpret the processes of their sedimentation. The most important source of bioclastic particles is calcium carbonate secreting marine organisms, which cover the inner continental shelf bottom abrasion terrace and are eroded by waves. The particles are mostly composed of coralline algae and mollusk shell fragments. The wave energy is dissipated by the presence of abrasion terraces on the inner continental shelf and in the adjacent foreshore zone. Consequently, the beaches acquire dissipative and intermediate stages according to WRIGHT *et al.* (1979) classification. The observed and predicted beach states sometimes showed lack of agreement, the disagreement being due to the geological control in geomorphology and the supply of sediment, i.e. the arrangements of the foreshore terraces and the diversity of mixed sand grain sizes on the beaches, which diversity is produced by very peculiar hydrodynamic processes in which tidal levels and the grain size and composition of sand are fundamental.

Keywords: Mixed sand beach; beach morphodynamic state; bioclastic composition; geological control.

Resumo

As praias arenosas adjacentes às falésias da Formação Barreiras são compostas por areias mistas, cuja diversidade composicional torna complexa a interpretação dos processos de sedimentação. A principal fonte dos sedimentos bioclásticos são as carapaças de organismos carbonáticos marinhos que recobrem os terraços de abrasão marinha presentes na plataforma continental interna. As partículas são compostas predominantemente por fragmentos de moluscos e algas coralinas. As ondas são dissipadas pelos terraços de abrasão e conseqüentemente as praias apresentam tipologia dissipativa e intermediária, segundo a classificação de WRIGHT *et al.* (1979). Os estados morfodinâmicos observado e estimado não são coincidentes, o que é explicado pelo controle geológico e pelo suprimento de sedimentos, i.e., a distribuição dos terraços de abrasão e a diversidade granulométrica e composicional das areias mistas, que produzem processos hidrodinâmicos peculiares nos quais as oscilações de maré e a sedimentologia das areias são fundamentais.

Palavras-chave: Praia de areia mista; estado morfodinâmico praias; composição bioclástica; controle geológico.

Introduction

Biological calcium carbonate incrustations are very common in tropical marine shallow waters, where there is an adequate rocky bottom. Frequently, they are subject to wave and tidal current hydrodynamics, which are particularly active within the surf zone. Together with bioerosion, these mechanical processes cause intensive fragmentation, which results in bioclastic particles being deposited on adjacent beaches.

Usually, the composition of bioclastic fragments is more changeable than that of the associated terrigenous sediments. CHAVE (1964) concluded that their resistance to processes of abrasion controls the composition of the skeletal remains within a sedimentary deposit. Porous algae, echinoderm and bryozoans fragments are more readily worn by abrasion than massive mollusk shells. In contrast, MAIKLEM (1968) stated that the frequency of calcium carbonate fragments is due to their abundance, in addition to their production and disintegration. However, irrespective of abundance, it remains true that hydrodynamic effects are responsible for the final composition of a sedimentary deposit, in accordance with the physical properties of the grains, such as shape, size, density and angularity. In general, the mean grain sizes of biotrital particles are coarser and more poorly sorted than associated quartz and heavy mineral grains (FOLK and ROBLES, 1964; GILES and PILKEY, 1965; PILKEY *et al.*, 1967) due to the great diversity of shapes and sizes of organisms. Finally, TANNER (1995) observed that bioclastic fragments tend to become finer when they are associated with hard quartz grains, as a consequence of the enhanced abrasion of bioclastic fragments.

An adequate interpretation of hydrodynamic processes in mixed sand beaches is rendered problematic by their variable physical properties, which difficulty increases as the proximity of a carbonate sediment source area increases (SWINCHATT, 1965; PILKEY, MORTON and LUTERNAUER (1967). OEHMIG and MICHELS (1993) wrote that a coarser grain size suggests that the source area is nearby, because when the source area and sand deposit are in close proximity, there is no opportunity for the fragments to disintegrate completely. Considering the influence of the source area, FOLK and ROBLES (1964) suggested that bioclastic, as well as nonbioclastic grain-size distributions indicate conditions in sedimentary environments. According to CARTER (1982), when grain-size compositions of siliciclastic and bioclastic fragments in a single mixed-sand beach are comparable, the fragments must behave differently, because the energy levels required to overcome the inertial state and begin their transportation are different.

The model of beach morphodynamics states has gained wide acceptance in coastal geological studies and was pioneered by Australian researchers (WRIGHT *et al.*, 1979, WRIGHT

et al., 1982; WRIGHT *et al.*, 1985; WRIGHT and SHORT, 1983; 1984). The morphodynamic state can be obtained from DEAN number (1973) as:

$$\Omega = H_b / W_s T \quad (1)$$

where H_b is the breaker height, T is the wave period and W_s is the sediment velocity fall. Values of DEAN's number that were less than 1.5 were associated with reflective states, while values greater than 5.5 were associated with a dissipative state. Intermediate states were deemed to be those that lie between 1.5 and 5.5.

The sediment fall velocity considers only the hydraulic behavior of quartz sands and no mixed sediments. The grain-size distribution of mixed sediments cannot represent the prevailing hydrodynamic conditions of the studied beaches and therefore will limit the final classification of a beach state.

Recently, many limitations have been noted regarding the utility of DEAN's number (1973), the limitations noted being particularly due to the relation between the tidal range and wave energy, but also due to the geological control and supply of sediment (LEVOY *et al.*, 2000; MASSELINK and PATTIARATCHI, 2001, JACKSON *et al.*, 2005).

MASSELINK and SHORT (1993) proposed an additional parameter for determining the morphodynamic state, the Relative Tidal Range:

$$RTR = H_o / RT \quad (2)$$

where H is the wave height and RT is the spring tidal range. This parameter has been used to quantify tidal effects on beaches with mixed wave-tide states, where $RTR > 3.0$. However, LEVOY *et al.* (2000) and ORFORD and LEVOY (2002) observed that the application of the RTR parameter has limitations along any particular stretch of coastline where there is very little difference in tide and wave parameters or where there are variations in wave energy as the tide rises and falls. JACKSON, COOPER and del RIO (2005) concluded that a similar RTR could be obtained on different shoreface slopes.

JACKSON *et al.* (2005) questioned, in particular, the ability of DEAN's number to discriminate between beach states, because beach morphology depends on many variables, including the geological control in sediment source, volume, grain size, composition and spatial distribution, as well as dynamic factors.

The objective of the study reported herein was to relate the composition and grain size of mixed beach sands to the shoreface and inner continental shelf morphology and source areas of bioclastic material associated with beach morphodynamic states, along a coastline stretch of Espírito

Santo State in Brazil. This paper aims to contribute to the discussion of morphological and sedimentological control over the morphodynamic beach states.

Study area

General geology: The Quaternary coastal plain and beaches between Barra do Riacho and Vitória, in Espírito Santo State are characterized by incipient development, being situated at the foot of the Barreiras Formation sea cliffs (MARTIN *et al.*, 1996). BIGARELLA (1975) states that the Neogene Barreiras Formation continental deposits would have been deposited under alternately humid and semi-arid climates, as alluvial fans spread on piedmont foot and reached the inner continental shelf surface, when the relative sea level was more than 100m below the present level. Wave-cut terraces were carved on this formation during subsequent episodes of relatively high sea level in the Quaternary.

At present, these abrasion terraces are submerged, lying on the bottom of the inner continental shelf and shoreface, which propitiates the incrustation of carbonate-secreting organisms. On the foreshore, they are exposed at low tide. After their death and disintegration the organisms cover the continental shelf, and are reworked by waves and tidal currents toward adjacent beaches (Fig. 1). The most important diversities in concentration and composition coincide with stretches that have more abundant incrustations, or with deeper and quieter coastal waters that are characterized by less active waves and coastal currents in association with granules and coarse sands. Approaching the strandline, more resistant mollusk and coralline algae fragments become dominant, in addition to siliciclastic grains. ALBINO (1999) found that the less resistant bryozoans and equinoderms fragments, as found in medium to fine sands, are very scarce in shallow waters. Siliciclastic sediments are represented near the Reis Magos (Nova Almeida town) and Piraquê-Açu (Santa Cruz town) rivers, and to the north, where the Doce river mouth has influence (Fig. 1).

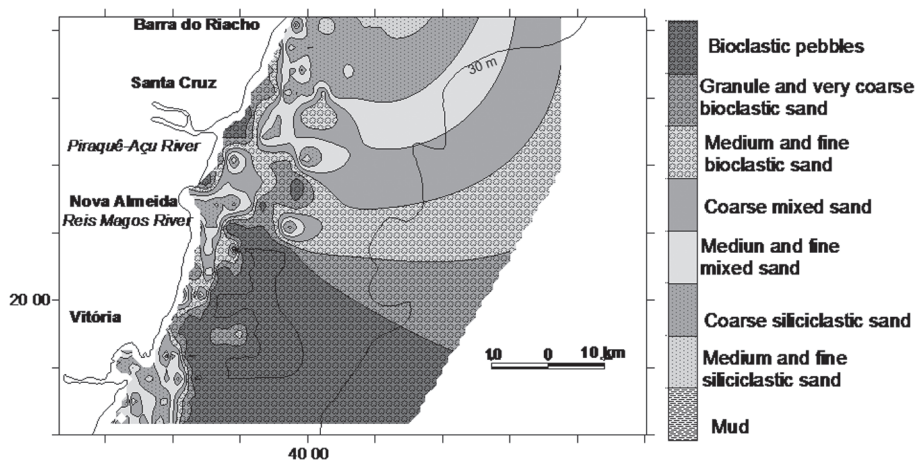


Figure 1 - Faciology of inner continental shelf bottom surface sediments between Vitória and Barra do Riacho, Espírito Santo State, Brazil. The sediments are predominantly composed of bioclastic and biosiliciclastic sands supplied by the incrustation of several carbonate-secreting organisms fixed on the abrasion terraces.

Climate and oceanography: The area studied is situated within a region characterized by rainfall in summer and spring and droughts in autumn and winter. Rainfall due to the penetration of polar air masses can occur in autumn and winter. The most frequent and intense winds come from the NE-ENE and SE, associated with trade winds and polar fronts, respectively. The former blows during most of the year, while the latter is related to periodic cold fronts. As a consequence, according to MELO and GONZALEZ (1995), the most frequent waves come from the ENE and SSE, following the dominant wind patterns. The significant wave height is about 1.2m but the most frequent are 0.9m e 0.6 m associated with ENE waves. The periods are between 5 - 6.5 s and 9.5

s, by winds from the E-NE and SE, respectively. The spring tidal range is 1.7m (DHN, 1998).

Material and methods

The beach morphodynamic states were established through measurements of topographic, sedimentological, and breaking wave conditions. DEAN'S number (1973) was calculated for each beach (Eq.1). Thirteen consecutive campaigns were conducted in 18 stations distributed along 80 km of coastline (Fig. 2). MASSELINK and SHORT'S (1993) model (Eq. 2) was applied for both minimum and maximum wave conditions.

The beach profiles were measured using EMERY's (1961) method, and the visual estimations of the breaking wave conditions followed KOMAR's (1976) proposal. The sand grain sizes were classified according to WENTWORTH's

(1922) scale, and FOLK and WARD's (1957) parameters were used for statistical treatments. The nature of the constituent particles was determined by GINSBURG's (1956) visual method.

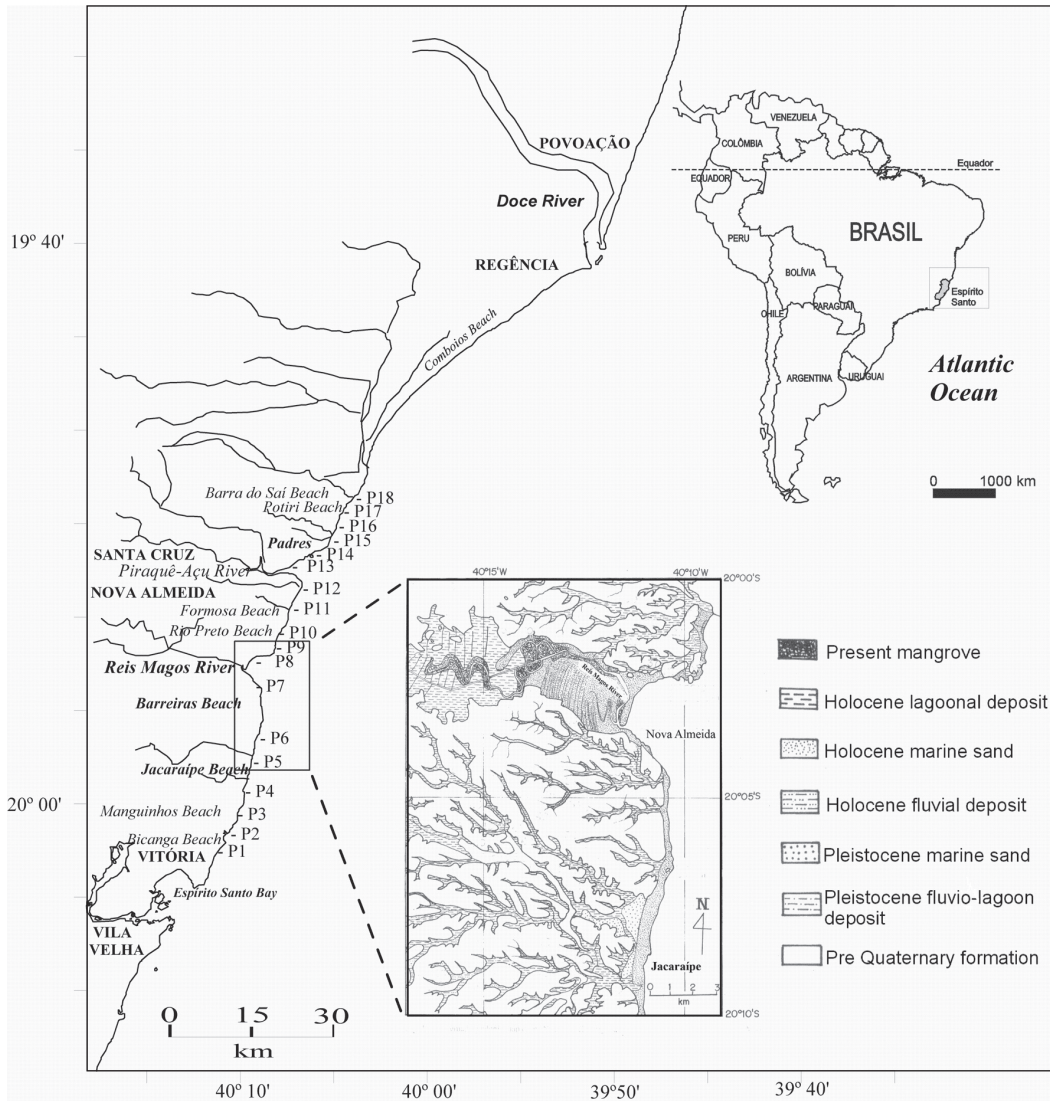


Figure 2 - The study area between Vitória and the Doce River delta plain. The Quaternary coastal plain (After Martin et al., 1996) and beaches are incipiently developed being situated in front of the Barreiras sediments, Pre-Quaternary formation.

Results and discussion

Beach topography, wave conditions and tidal level:
Because the foreshore and nearshore wave-cut terraces retained most of the sediment coming from the open sea, the nearshore terraces slope very gently in this stretch of the coast, except in some sectors where they have

been truncated by erosion. The swells that occur under severe meteorological and oceanographic conditions caused by SE winds can grow to over 2.0 m height in deep water (Fig. 3). The rough shallow bottom largely dissipates them, and the average breaking height reaches only 1m (Fig. 3). Under high tides, sea levels can surpass

wave dissipation, and the highest breaking waves can be observed (Fig. 3). The highest breaking waves were observed in April, May and November, under severe open sea conditions and high tidal level at Manguinhos (P3), Jacaraípe beach (P6), Rio Preto (P9) and Padres beach (P5). Similarly high breakers were present in September, when the waves' height on the open sea was about 1.0 to

1,5m at Rio Preto beach (P9 and P10) at Formosa (P11) during high tide. The lowest breaker was registered at the moment of low tide. MASSELINK and SHORT (1993) pointed out variation in the height and types of breakers due to the tidal level, stating that low spilling breakers occur at low tide and high surging and collapsing breakers occur at high tide.

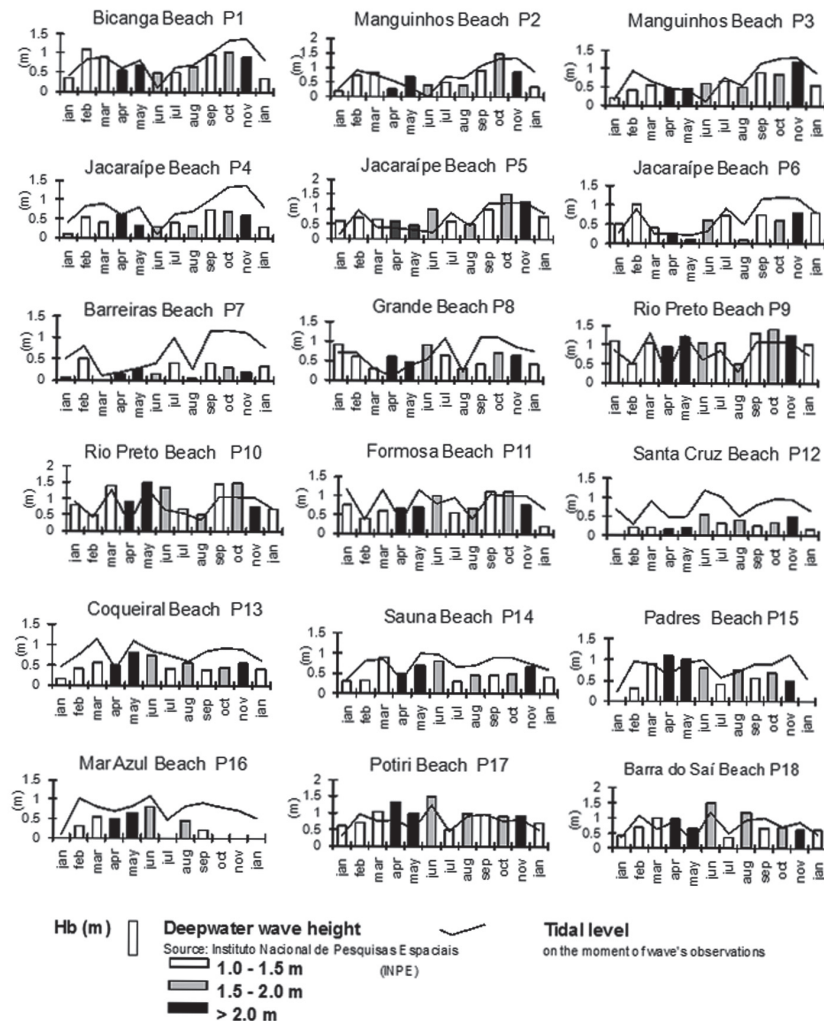


Figure 3 - Breaker wave height, deepwater wave height and tidal level at the moment of the beach observations from January 1996 to January 1997, inclusive. The deepwater wave height passes out-trough intense dissipation. The tidal level influences the Hb height variation.

Due to the dissipation of waves, most of the beach topography showed only slight seasonal fluctuations, with a tendency towards stability (Fig.4). At Rio Preto (P9 and P10), Padres (P15), Potiri (P17) and Barra do Sai (P18) beaches, where outcrops of wave-cut terraces are sparsely distributed on the nearshore, less wave dissipation

and greater variation in beach topography were observed (Figs.3 and 4).

Prograding beach profiles were found at Barreiras (P7) beach near the river mouths, mostly during episodes of rainfall that were associated with periods of cold front penetration, when an increased river discharge occurs (Fig.4).

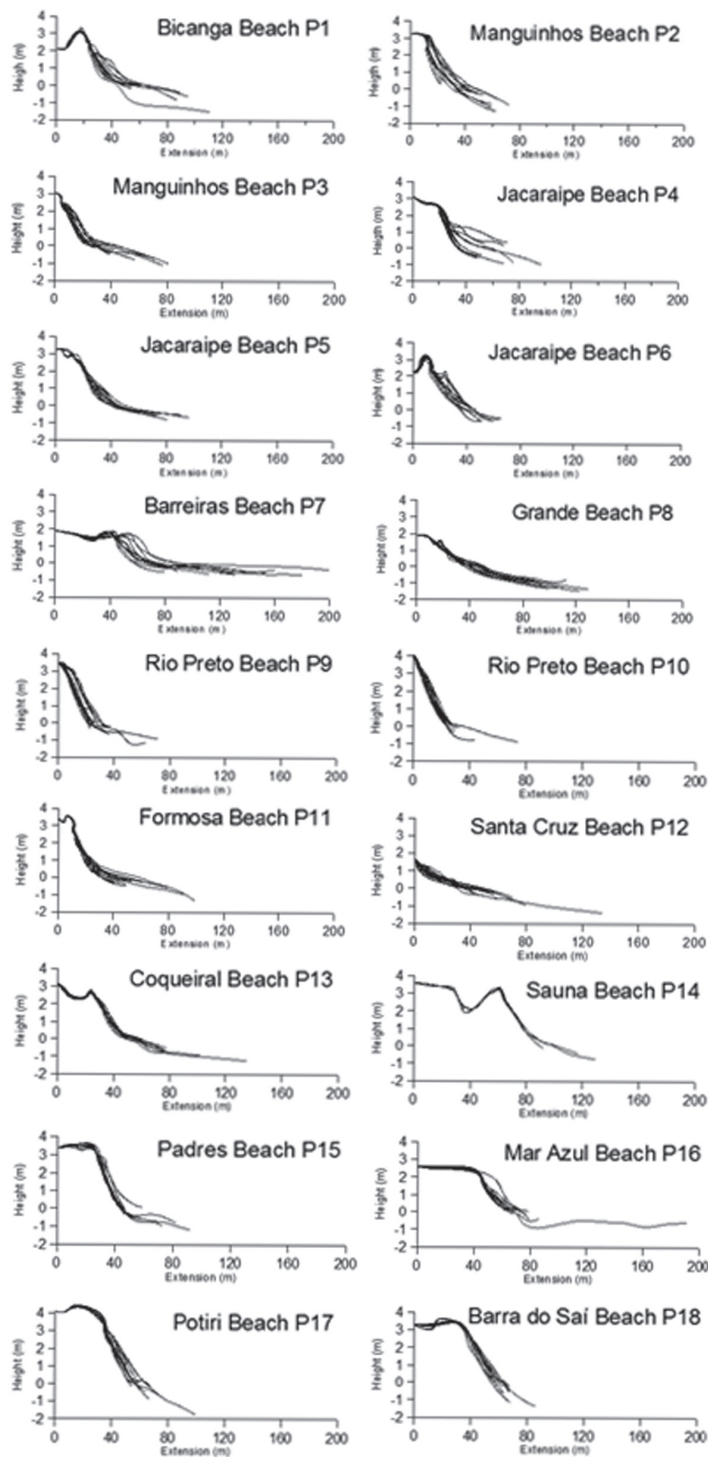


Figure 4 - Beach profiles morphologic variation between Vitória and the Doce river delta plain from January 1996 to January 1997, inclusive. In the Santa Cruz and Coqueiral beaches the sediments from Piraque-Açu river were retained on the nearshore marine abrasion terraces whereas in the Mar Azul beach the terraces were exposed during low tide.

Grain size and composition of beach sands: Marine sediments, composed mostly of bioclastic fragments, are dominant in mixed sands from Bicanga to Barra do Saí beaches (Fig.5), which exhibit little seasonal change. At the sampling stations near the Reis Magos

(P7), Piraquê-Açu (P12 and P14) and Saí (P18) river mouths, there is an alternating dominance of terrigenous or bioterrigenous fragments within the mixed sands, according to seasonal fluctuations in the rivers sediment loads or discharges.

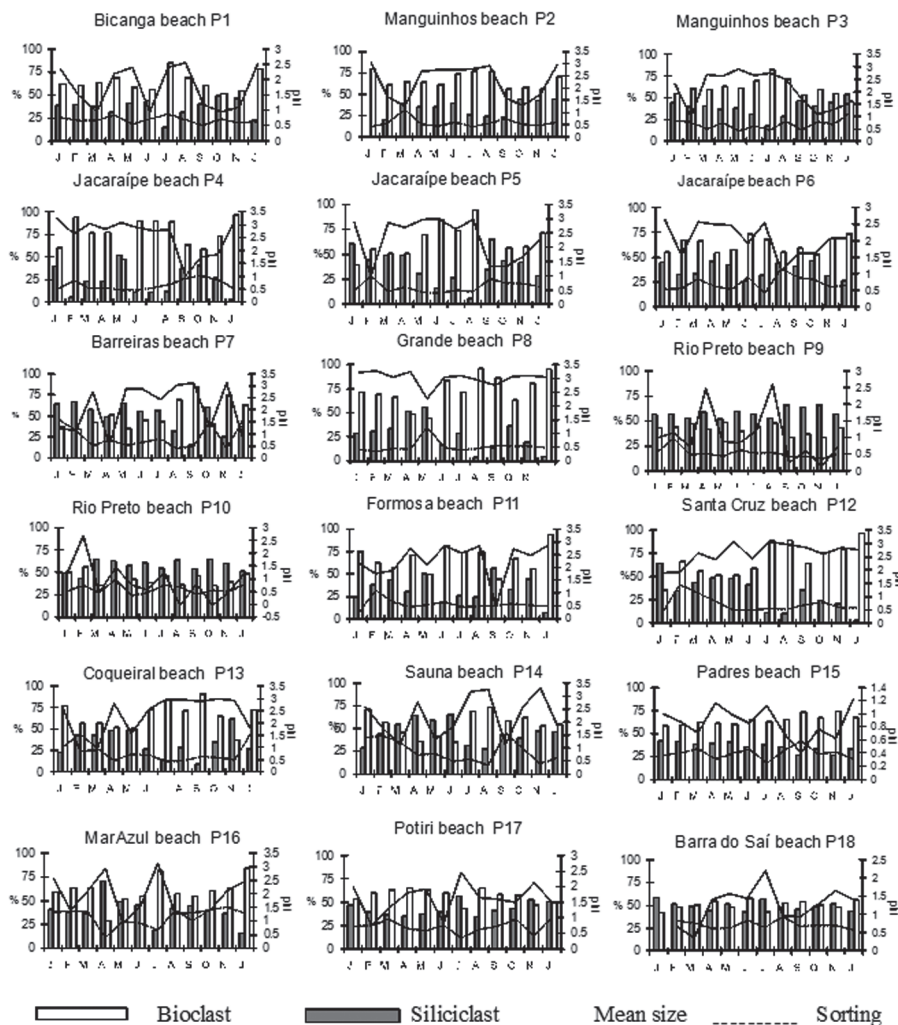


Figure 5 - Composition, mean diameter (Mz) and sorting of mixed sands for the beaches between Vitória and the Doce River delta plain. The mixed sands are predominantly bioclastic. Near the river mouth (P7, P8, P11, P12 and P3) and where the wave energy is enough to promote the fragmentation of bioclastics by siliciclastics (P9, P10, P15 and P17), the sands are silicibioclastic.

The curves of cumulative frequency of grain size for Manguinhos (P2 and P3), Jacaraípe (P5 and P6), Grande (P8), Padres (P15), Mar Azul (P16), and Potiri (P17) beaches showed an overlapping pattern (Fig. 6). A slight tendency for bioclastic fragments to be coarser than siliciclastic grains was observed in the mixed sands of Jacaraípe (P4), Santa Cruz (P12) and Sauna (P14) beaches. PILKEY, MORTON and LUTERNAUER (1967) concluded that this tendency indicated proximity of a carbonate source.

By contrast, siliciclastic grains were coarser than bioclastic fragments at Bicanga (P1), Barreiras (P7), Rio Preto (P9 and P10), Coqueiral (P13) and Barra do Saí (P18) beaches. TANNER (1995) pointed out that this can be explained by the greater susceptibility of bioclastic fragments to disintegration when they are transported together with siliciclastic grains.

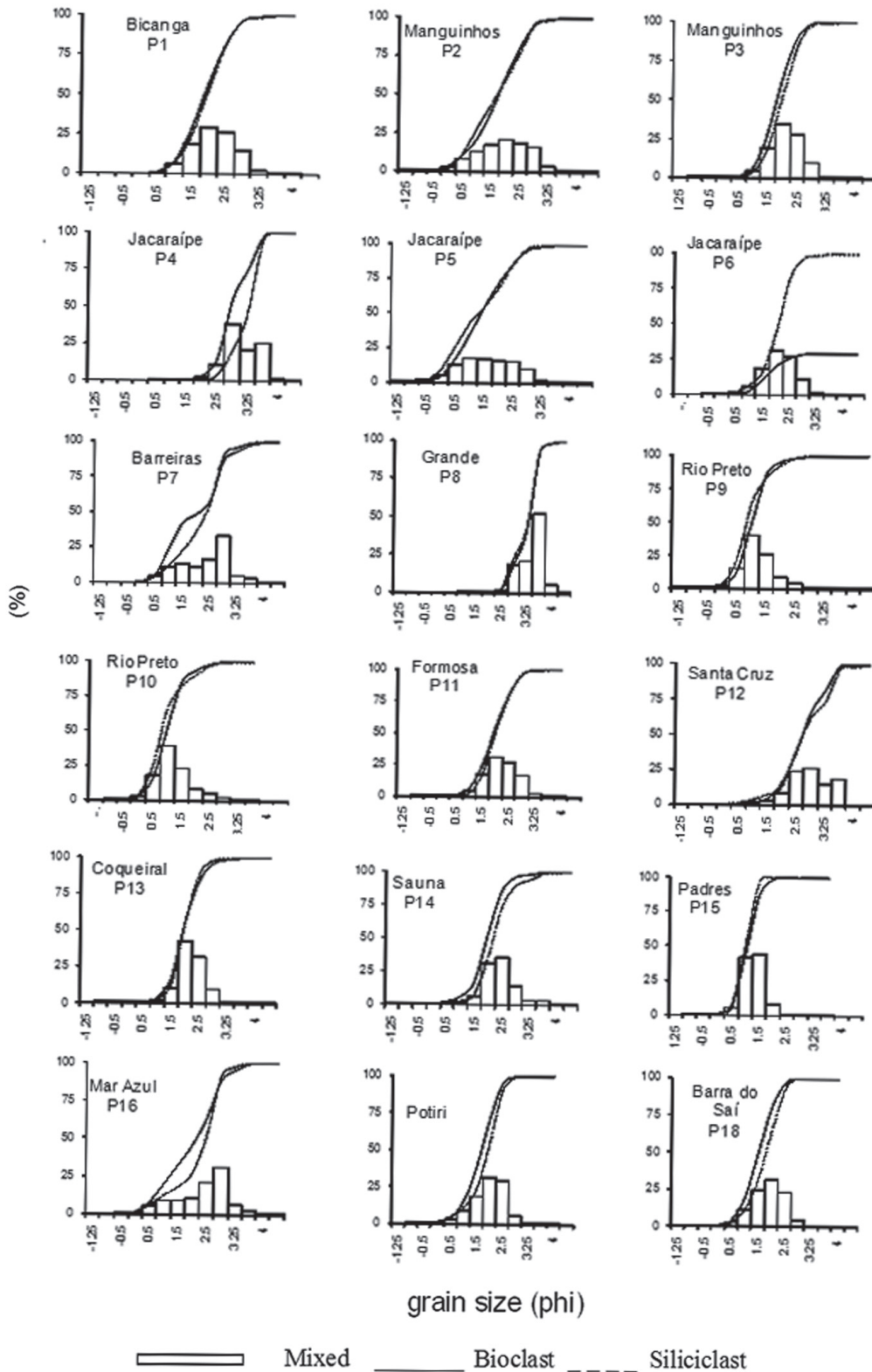


Figure 6 - Grain size distributions of the mixed sands of the beaches. The superposition among the grain size distributions indicates that carbonate sand tends to be slightly coarser compared with siliciclastic sand on beaches where there is great dissipation and/or a nearby source area.

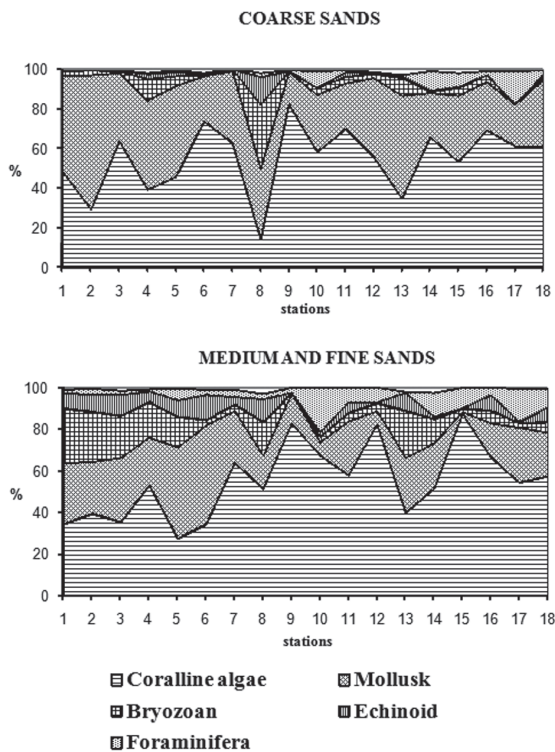


Figure 7 - Bioclasts composition of mixed sands for the beaches (P1 to P18) between Vitória and the Doce River delta plain. Espírito Santo State, Brazil. The bioclasts are composed predominantly of coralline algae and mollusk, the more resistant bioclastic.

Even bioclastic fragments show different degrees of resistance to disintegration, which explains why coralline algae and mollusk shell debris are the dominant bioclastic fragments, while bryozoan, equinoderm, foraminifera and worm tube constitutes just between 10% and 40% of medium-to-fine sands (Fig. 7). Consequently, bioclastic fragments that are more susceptible to disintegration are concentrated with finer grain sizes, while more resistant ones present coarser grain sizes (Fig. 8). Therefore mixed sand beaches will tend towards coarseness with an increase of siliciclastic, coralline algae and shell fragments.

Mixed sand beach morphodynamic state: On the Espírito Santo beaches, the values of RTR, adopting $RT = 1.7m$ (spring tidal range), oscillated between 0.35 and 1.18, to $H(\min) = 0,6m$ and $H(\max) = 2.0m$, classified according to MASSELINK and SHORT (1993) in wave-dominated beaches. The classification has shortcomings with respect to its application to the observed beaches, where the tidal level is important for the height and breaker type of waves, and for the transition of morphodynamic zones, due to the presence of the abrasion terraces wave-cut by episodes of relatively high sea level in the Quaternary. WRIGHT, GUZA and SHORT (1982) observed that transition of morphodynamic zones occurred in macro tidal regions where they identified dissipative to ultra dissipative characteristics at low tide and intermediate to reflective characteristics at high tide.

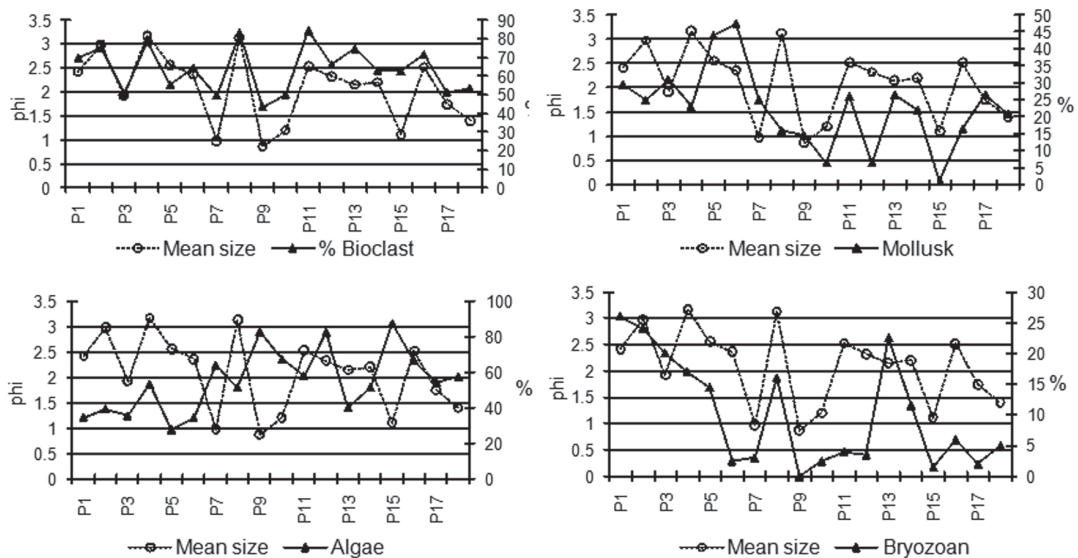


Figure 8 - Mean diameter (Mz), proportion and composition of bioclastic sands of the beaches along the city of Vitória and the Doce River delta plain. In spite of the tendency of beach sands mean size with the carbonate increase, the distributions indicate the influence of the coarser algae and the finer bryozoan fragments.

The adjacent abrasion terraces on the studied beaches restrict the morphodynamic state to intermediate with dissipative characteristics at low tide and intermediate to reflective at high tide, similar to the low-tide terrace state suggested by WRIGHT *et al.* (1979). The predicted states obtained by applying DEAN number (1973) showed a large variation in the parameters and classification of the morphodynamic state at each station (Fig. 9) since there are variations in the wave height according to the tide and large variation in the sediment velocity fall, because of the composition and grain size diversity. In general, the mean DEAN's number of 4 to 2 indicted intermediate beach states. A modal Dean's number could be identified at Padres (P15), Potiri (P17) and Barra do Sai (P18) beaches, where the Dean's number variation was smaller. At these beaches, the abrasion terraces were observed to become scarce on the foreshore or concentrated on the nearshore and lesser wave dissipation was observed,

followed by increasing beachface slopes and breaking wave heights. At Rio Preto (P9 and P10) beach, there was agreement between the observed and predicted state (Dean's number \cong 2) with the beach indicating a low-tide terrace state, due to the partial retention of sediments by abrasion terraces of the foreshore. At low tide the waves were of spilling breaking and under a dissipative beach state. By contrast, at high tide the waves coming from the open sea formed first plunging breakers in the shoreface due to abrasion terraces, and then in the foreshore they became collapsing or surging breakers. The slope of the beachface was maintained a moderate to high slope. The reflective domain is limited to the foreshore during high tide. In these beaches, less resistant fragments are disintegrated and removed, which causes retrogradation. These beach sands are dominantly composed of well-sorted siliciclastic sands with medium-to-coarse coralline algae and mollusk shell fragments.

Beach Morphodynamic State

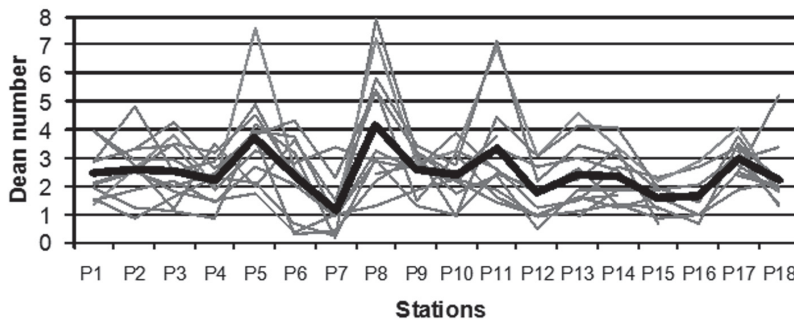


Figure 9 - Variability and mean (dotted line) DEAN number for each station. The beaches area classified as intermediate states. The large variation observed around the mean value is due to changes in the breaker high and type and grain size diversity.

At the Padres (P15), Potiri (P17) and Barra do Sai (P18) beaches during high tide, the wave energy is higher and exhibits plunging and/or spilling breakers with the development of longshore currents. Beach morphology is influenced by open-sea wave climate, with erosion dominating during months of cold front occurrence. The beach sands are characterized by mixed sand composed of algae and mollusks with seasonal variation and moderate to poor degrees of sorting.

The same morphodynamics and beach states were observed at Manguinhos (P2 and P3) and Jacaraípe (P4, P5 and P6) beaches. However, DEAN number reflects greater variation, due to the oscillations in breaker height and diversity in grain-size and composition.

The partial retention of sediments that favors the accumulation of large stocks of sand in the foreshore and

nearshore is responsible for mild slopes. These characteristics were observed at Bicanga (P1), Barreiras (P7), Grande (P8), Formosa (P11), Santa Cruz (P12), Coqueiral (P13), Sauna (P14) and Mar Azul (P16) beaches, which were classified on the basis of observation as dissipative to intermediate. These beaches are composed of fine-to-medium sands, presenting good to moderate degrees of sorting. There is a dominance of briozyan fragments, except for station P7, which is influenced by coarse siliciclastic sands supplied by the Reis Magos river. The mean Dean's number to P7 was 1.25, which was classified as representing a reflective state.

The irregular spatial distribution of abrasion terraces either on the nearshore and foreshore is responsible for the distinct beach morphologies since they determine the incidence angle, type and height of wave breakers.

Conclusion

JACKSON et al. (2005) questioned both the ability of DEAN number and the RTR presented by MASSELINK and SHORT (1993) to discriminate between beach states, because beach morphology depends on many variables, including the geological control. In the present study it is the abrasion terraces that exert the geological control, as it is evident on the morphodynamic states and sediment supply.

The classification of the coastline as wave- or tide-dominated is a simplification of the process implicated in the beach morphodynamic. To obtain an accurate picture, it is necessary to analyze the relationship between wave height and tide, as proposed by MASSELINK and SHORT (1993) and MASSELINK and TURNER (1999). However, one must note that according to ANTONY and ORFORD (2002), wave-dominated, mixed wave-tide or tide-dominated morphologies may develop along any particular stretch of coastline with very little difference in tide and wave parameters.

The mixed-sand composition contributed to the inadequacy of the models to identify the beach state, but it was possible to ascertain the presence of relationships among composition, grain size and beach state.

In corroboration with MAIKLEM's (1968) who emphasizes the importance of hydrodynamic depositional processes in the final frequencies of grain sizes in mixed sand beaches, the grain size and composition of the mixed sands studied in the could be associated to definite stages of beach morphology. Once deposited together, mixed sands with different compositions will acquire similar frequencies of grain size in response to hydrodynamic processes. The grain size is determined by the kind of bioclastic fragments present, according to their resistance to disintegration. Medium and coarse sands, composed dominantly of coralline algae and mollusk shell fragments, occur in intermediate beaches. By contrast, fine mixed sands, with bryozoan and echinoderm fragments, are found in dissipative beaches.

The heterogeneity in composition and grain size in intermediate beaches indicates that there are several sorting processes acting on mixed sands of these beaches, as is suggested by CARTER (1982). Their interpretation becomes complex, due to (i) the proximity of the source area (SWINCHAT, 1965), and (ii) wave transformation on the nearshore and foreshore due the bathymetric control.

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