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BEACHROCKS OF JAGUARIBE BEACH, ITAMARACÁ ISLAND, NE BRAZIL: PETROGRAPHIC AND GEOCHEMISTRY EVIDENCES

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ABSTRACT
Contemporaneous beachrocks that runs parallel to the coast forming long, discontinuous and narrow lines. Geochemical analyses were executed on carbonate beachrocks and water samples on Itamaracá Island, Pernambuco State, Brazil. Framework detrital composition is siliciclastic and cemented by calcite and/or aragonite. Three types and stages of cementation have been identified. The first correspond to micritic envelope; the second, acicular fringe; and the third, criptocrystalline cement filling the pores. The $\delta^{13}C$ values and diagenesis features suggest which the cementation occurs in meteoric-vadose and/or marine-phreatic by loss of CO_2 in evaporation of the interstitial water. The interaction of the carbonated fluid in subsuperficies permitted the discontinuous beachrock formation. The elevation of the mean sea level deposits new sediments, which cemented, complete preexists base of the beachrock, or creates a different, justifying the different dimensions this rocks on the littoral.

Keywords: beachrocks, stable isotopes, sedimentology

INTRODUCTION

The Jaguaribe beach, in Itamaracá Island, situates in the north littoral of the State of Pernambuco. Itamaracá is a 9 x 4 km, N-S oriented island separated from the continent by a fault that constitutes now a channel filled with seawater mixed with fresh water that come from four small mouth rivers. The seaward coastal zone of the island is characterized by beachrocks and calcareous algae bars parallel and adjacent to the coast, along all the extension of the island.
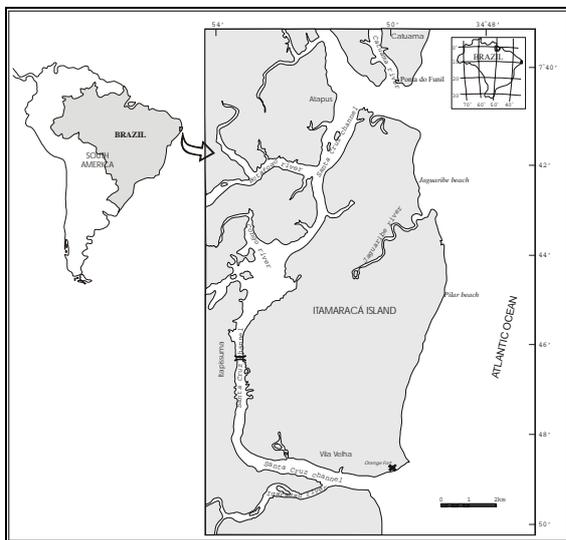

Figure 1 – Localization map.

Beachrocks are cemented beach sands, which are more common in the tropical and subtropical regions. They are composed of the same sediment that forms the surrounding loose beach sand, and may have a substantial or even dominant siliciclastic component, and they can form quickly as evidenced by the inclusion of man-made objects such as cans, coins, and other debris in the matrix of beachrocks.

The formation of beachrock probably takes place a few tens of centimeters below the surface of the beach, but in many places it is exposed through sea-level action (Fig 2).
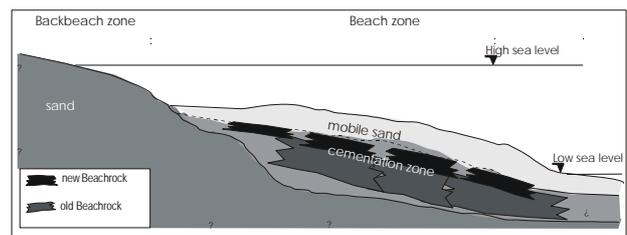

Fig 2 - Schematic representation of beachrock formation (Chaves, 2000)

Beachrocks are formed by a large number of components, which can be broadly divided into three groups: non-skeletal grains, skeletal grains and cement. The non-skeletal grains (intraclasts) are fragments of partly lithified sediment that rarely occur in beachrocks. The most common skeletal components in beachrocks are bivalves, gastropods, cephalopods, brachiopods, cnidaria, including anthozoa, echinoderms, bryozoa, foraminiferas, sponges (poriferas), arthropods and algae. Environmental factors, such as depth, temperature, salinity, substrate and turbulence, control the distribution and development of the organisms in the various carbonate sub-environments.

The cement in modern beachrock is mainly composed of aragonite and/or high-Mg calcite and/or low-Mg calcite. Mg calcite cement in beachrocks of northeastern Brazil consists mainly of slightly elongate rhombs of cryptocrystalline calcite, ranging from 1 to 6 μm (average 3.5 μm) in length. Calcite crystals are euhedral to anhedral, the latter being the most common form. Cryptocrystalline calcite cement binds coarser grains, and as cement extends into pores from substrates, it also traps silt and fine-sand-sized skeletal particles washed into pores during cementation. The result is a cement-supported fabric cryptocrystalline calcite. Both

intergranular and intragranular cryptocrystalline cement are common in the Brazilian beachrocks. Intergranular pores are seldom completely filled, especially in the lower, more friable horizons. However, intragranular porosity is often completely occluded, especially by scleractinian corals, echinoids, and borings within mollusk fragments.

Meniscus cement is absent the beachrocks from northeast Brazil, suggesting that downward percolation of pore water in the vadose zone is not a dominant process during cementation. Isopachous cement surrounding framework is common cement; in this kind of cement fringes of clear, slightly coarser and more elongate crystals of microcrystalline Mg calcite are present. These crystals invariably surround earlier-formed cryptocrystalline calcite cement, and crystals that comprise them are oriented with c-axes perpendicular to the substrate. These fringes are more abundant in higher stratigraphic horizons of the beachrock exposure (Chaves, 2000).

Fringes of clear Mg calcite consist, sometimes, of a single layer of crystals. Although crystals in these fringes are micron-sized rather than deci-micron-sized, the relationship of clear, Chaves (2000) described slightly coarser-grained crystalline fringes surrounding earlier formed cryptocrystalline calcite cement that resembles those described by MacIntyre et al. (1971), Ward (1974), James et al. (1976), and Jindrich (1983). James et al. (1976) attributed formation of fringes of elongate spar surrounding cryptocrystalline calcite to progressive and more complete cementation in older sediments. In their explanation, clear fringes form as porosity becomes occluded and flow of pore waters becomes more restricted.

Aragonite typically occurs as acicular crystals forming fringes that are normally oriented to the grain surfaces (Chaves, 2000; Fig. 3A, B). In many cases the cement fringe is isopachous, i.e. of equal thickness, indicating marine phreatic precipitation where pores were constantly water-filled. Asymmetric cement fringes and thicker underside of grains, concentrated at grain contacts (Chaves, 2000; Fig. 3C, D), are recorded in some beachrocks, and indicate precipitation in the marine vadose zone (e.g. Taylor and Illing, 1969).

High- and low-Mg calcite usually forms micritic cement coating grains or filling pores (Chaves, 2000; Fig. 3E, F). Micritization of grains is common in the beachrocks. If the meteoric groundwater is high in the backshore area, then low-Mg calcite cements may be precipitated in beachrocks in the upper intertidal zone.
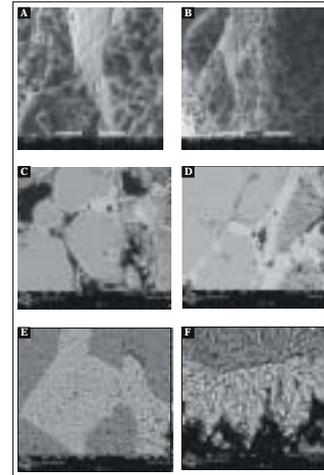

Fig. 3. Types of the beachrocks' cement. A, B - Acicular aragonite crystals; C, D - Asymmetric fringes of calcite and aragonite, respectively; E, F - High- and low-Mg calcite, in micritic and fringe forms, respectively.

BEACHROCKS TEXTURE AND GRAINS

The skeletal grains of beachrock sediments vary greatly in size and shape. The majority of grains in beachrocks accumulates when the grains have been subjected to only limited transport by wave and tidal currents, although they are formed in situ. Therefore, a measure of the grain size often gives useful informations about the energy level of the environment, or energy gradient of the area. A number of grain-size scales have been proposed as energy indicators, but one which is widely used and accepted is that proposed by Wentworth (1922). In beachrocks, grains usually vary in size from very coarse- to medium-grained sand (Fig 4).

The grain morphology is analyzed according to three aspects: shape, sphericity and roundness. The shape or form of a grain is measured by various ratios of the long, intermediate and short axes, and descriptive terms for the four classes based on these ratios are oblate (tabular or disc-shaped), equant (cubic or spherical), bladed and prolate (rod-shaped). Sphericity is a measure of how closely the grain shape approaches that of a sphere. Roundness is concerned with the curvature of the corners of a grain, and among them six classes, from very angular to well rounded, are distinguished. Grains in beachrocks show inherited features, and usually the degree of their roundness increases with duration of reworking by wave and currents.
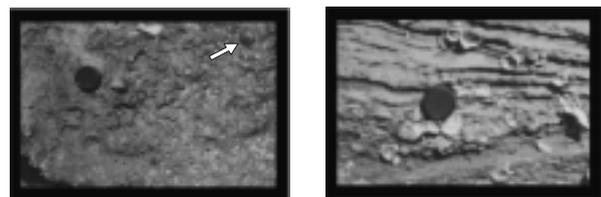

Fig. 4 - Differences of the texture and granulometry between top and bottom (Chaves, 1996). White arrow indicates the pebble on the framework.

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CONCLUSION

The precipitation of calcium carbonate cements near the water table and in the intertidal zone of Recent tropical and subtropical beach sediments is a widespread and rapid process. Study of the factors that control the distribution and rate of formation of these cemented zones is of importance to general problems of early carbonate diagenesis (Chaves, 2000).

Two processes are important in the beachrock formation: (1) purely physical-chemical precipitation through evaporation of sea water when the tide is out, and CO_2-degassing of sea water as it is pumped through the sand by waves and the rising and falling tide, and (2) dissolution of bioclastics fragments by mixing vadose meteoric and sea water. Some authors defend a microbial precipitation, involving algal photosynthesis, bacterial calcification, and decomposition of organic matter (Tucker, 1991).

Activity of Ca^{++}, and CO_3^{--}, P_{CO2} and saturation ratio of pore water reveal important time-dependent variations when compared to the tidal curve for the sampling period. Variations in the chemistry of seawater with tidal stand are not diurnal; therefore, organic processes are not the primary cause of fluctuations. Metabolic processes of marine organisms produce one daily high and low saturation level of the water. The variations appear to be related, however, to tidal stand. According this authors, most increase in saturation ratio that bear a direct correlation with CO_3^{--} occurs during rising tides, suggesting that CO_2 tends to be dissolved in pore water during the first phase of rising tides, thereby increasing saturation ratio. During falling tides, on the other hand, saturation ratio tends to decrease. Most of these decreases have a direct correlation with P_{CO2}, and CO_3^{--}.

The saturation ratio of pore water bears a close, direct relation with CO_3^{-}, while a similar relation to Ca^{++} is much less apparent. Saturation ratio also generally bears a direct relation with P_{CO2}, suggesting that CO_3^{-}- and P_{CO2} themselves are directly related to one another. The total amount of CO dissolved in pore water appears to be the primary control upon CO_3^{-}. More dissolved CO, more HCO_3^{-} (and therefore CO_3^{-}) that can form by dissociation of H_2CO_3, resulting also in higher P_{CO2}. Lowering of P_{CO2} (degassing) often corresponds to a decrease in CO_3^{--}. Degassing may result in decrease in saturation level by initiating precipitation of calcite and a corresponding drop in aCO_3^{--}.

The activity of Ca^{++} generally increases in the first phase of rising tides, and decreases in the second phase of rising tides; during falling tides, Ca^{++} generally decreases. These variations in Ca^{++}, together with variations in CO_3^{--} and P_{CO2} suggest precipitation of calcite during falling tides. As P_{CO2} does not consistently exhibit decreases during falling tides, perhaps the drop in P_{CO2} during the second phase of rising tides has a lag effect, not resulting in precipitation of calcite until the first phase of falling tides. However, the sporadic rise of P_{CO2} during the first phase of falling tides is against this idea. These short-period fluctuations in components of the carbonate system are complex and make interpretation of controls upon precipitation of calcite cement in the intertidal zone difficult. Examination of an ideal chemical cycle, which is of the same period as the tidal cycle, may be helpful in shedding light upon fundamental controls on the formation of cement. Examination of complex short-period fluctuations in carbonate chemistry of pore water, as well as somewhat simpler semi-daily fluctuations in chemical variables, suggests that degassing of CO may play an important role in precipitation of Mg calcite cement of beachrocks (Chaves, 2000).

Hanor (1978) developed a model for vertical mass transport and evasion of CO_2 gas from a beach system. In this model, upward diffusion of CO_2 through the vadose zone and eventual exchange of CO_2 from sediment to atmosphere is greatest during high stands of the tide (tidal pumping). The potential for CO_2 degassing related to tidal pumping is therefore thought to be significant. Data from Jaguaribe beach (Chaves, 2000) indicate that degassing from pore water appears to occur predominantly during the latter phase of rising tides, which is in agreement with Hanor's model. However, decreases in P_{CO2}, also occur sporadically during falling tides, and accompanying decreases in Ca^{++} and CO_3^{--} are consistent with simultaneous precipitation of Mg calcite. Perhaps there is lag time in the effect of tidal stand on degassing, whereby CO_2 evasion and precipitation of calcite cement may also occur during falling tides. An alternative and very likely explanation of the data is that another control in addition to tidal pumping is instrumental in degassing.

The amplitude of fluctuation in ΣCO_2, content of pore water is much greater than that in water of the adjacent marine environment. However, an inverse relationship between ΣCO_2 of pore water and seawater was weakly developed in part of the summer of 1999 in the Jaguaribe beach. (Chaves, 2000). This relationship may indicate vertical fluid dispersion following high tide, resulting in transport of CO_2-rich pore water to CO_2-poor water sampled atop the seaward edge of the beachrock.

Data from Jaguaribe beach (Chaves, 2000) suggest that CO_2 degassing, perhaps driven by tidal oscillation, is instrumental in cementation of beachrock. The importance of a mixing zone wherein ionic concentrations are raised to levels of oversaturation as a direct result of mixing, is thought to be less important at this site, because a well-developed mixing zone is not present in the water of a well dug seaward of the beachrock exposure, where incipient cementation of beachrock appears to be actively occurring.

Mixing may, however, affect carbon dioxide content of interstitial water. The source of CO_2 of pore water in the beaches of the Itamaracá island appears to be within the intertidal zone, as indicated by ΣCO_2 concentrations in the backbeach well D (average ΣCO_2 of 158 ppm) that are intermediate between the value for the seaward well B (279 ppm) and for water seaward of the beachrock exposure (136 ppm) (see Fig. 5 for location of the wells; Chaves, 2000). At low tide, there would be less dilution of pore water by CO_2-poor seawater, resulting in ΣCO_2 in pore water higher than that during high tide, when dilution effects are more pronounced.

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Fig. 5 - Position of the wells (A, B, C, D) in Jaguaribe beach (Itamaracá island). In this wells are colected water, cement and bioclastic fragments for chemical analysis (Chaves, 2000). Persons are step on contemporaneous beachrocks.

Fig. 6 -Diagram $\delta^{13}C$ and $\delta^{18}O$ vs. geographical position along the littoral of Pernambuco littoral. The negative values at north represent influx of the freshwater influx and/or organic matter in environment, due to estuaries and mangroves (Chaves, 2000).

Variations in pore-water chemistry of the Jaguaribe beach could conceivably be the result of sampling of a chemically stratified groundwater sequence whose phreatic surface is oscillating vertically in response to tidal fluctuations (Chaves, 2000; e.g. Hanor, 1986).

Stable isotope analyses in cement of beachrocks from the littoral of Pernambuco indicate $\delta^{13}C$ ranging from $-$1.3‰ to +3.5‰PDB, and $\delta^{18}O$ varying from $-$2.1‰ to +1.2‰ (Fig. 6). The ambient water temperature, as calculated from oxygen isotope analyses range from 11° to 25^oC, interpreted as representing stillstands during prolonged marine transgressions (Chaves et al., 1995; Chaves and Sial, 1999). The carbon-isotopic ratios indicate cement precipitation in a shallow, predominantly marine environment with minor influx of freshwater (Chaves, 1996). The C- and O-isotopic values plot across the marine and freshwater fields, and the data plots indicate overlapping, covariant mixing trends of organic matter and seawater as well as a meteoric effect (Chaves, 1996, Chaves and Sial, 1999). These data suggest that the formation of the beachrock was influenced by a mixed oceanic and freshwater environment, as also indicated by major element chemical data. Gradual depletion in $\delta^{13}C$ of the South to North can be attributed to an influx of freshwater (Chaves and Sial, 1999). The mixing of water occurred in the interstitial zone by seawater saturated in Ca^{++} and CO_3^{-} with undersaturated fresh groundwater, and reflects equilibrium of the CO_2 partial pressure in each system.
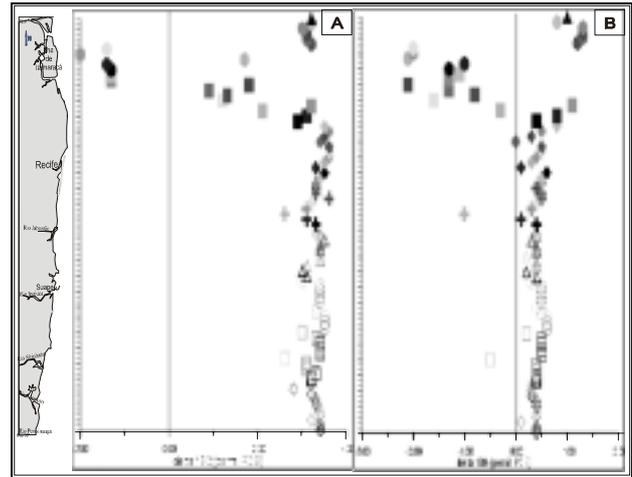
Detrital components of beachrocks from Jaguaribe beach are siliciclastic in composition, cemented by calcite and/or aragonite. In the region, the precipitation of calcium carbonate cements near the water table and in the intertidal zone of Recent tropical and subtropical beach sediments is a widespread and rapid process. Studies carried out by Chaves (2000) indicate that cryptocrystalline cement in beachrocks is composed of high-Mg calcite (average mole % $MgCO_3$ = 15.5). However, some cement is composed of Mg-bearing calcite (mole % $MgCO_3$ ranges from 4 to 10), which is higher in Sr content than its high-magnesian counterpart.

Analysis of variance indicates that mole % $MgCO_3$ in the cryptocrystalline calcite cement does not vary significantly from the landward to the seaward margin of the beachrock (and hence, from lower levels to upper levels of the beachrock). This observation is in contrast to that of Moore (1973), who discovered a significant seaward increase in the magnesium content of cement in beachrocks of the Grand Cayman island, and attributed this increase to a progressively greater seaward influence of magnesium-rich seawater upon cementation.

Oxygen isotopes analyses of water samples from trenchs dug between the post-beach and water lines has an $\delta^{18}O$ average of -1.5‰SMOW, while samples of sea and fresh water have $\delta^{18}O$ = +0.7‰SMOW and $\delta^{18}O$ = $-$2,3‰SMOW, respectively (Chaves, 2000). There is a positive correlation between $\delta^{18}O$ values and salinity, interpreted as due to evaporation effect that lead to increase in ^{18}O.

Carbonates dissolved in water from the trenchs have $\delta^{18}O$ values around $-$1.4‰PDB, and $\delta^{13}C$ values around +0.2‰PDB, and both C- and O- isotopic values have positive correlation with salinity (Chaves, 2000). Isotopic values for primary carbonate (shells, foraminifera, calcareous algae Halimeda) from beachrocks are similar with a large range of $\delta^{18}O$ values from -2.7‰ to -1.7‰PDB

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(average -2.2‰), and $\delta^{13}C$ values, which range from -2.2‰ to +1.0‰$_{PDB}$ (average +1.0‰). There is slight positive correlation between $\delta^{18}O$ and $\delta^{13}C$.

The dissolved carbonates and water samples represent the first stage in the cement precipitation, which is the final stage of diagenesis of the beachrocks. Values of $\delta^{13}C$ of carbonate cement of the beachrocks range from –2.0‰ to +3.6‰$_{PDB}$ (average +2.8‰$_{PDB}$) and $\delta^{18}O$ values vary from –2.1‰ and +1.3‰$_{PDB}$ (average +0.2‰$_{PDB}$) (Chaves, 2000). The negative C- and O-isotopic values found in the Jaguaribe beach suggest an important biogenic and/or organic matter contribution in the carbonate cement. The isotopic values indicate two distinct mechanisms of cementation of the beachrocks that can be explained in terms of a model similar to that proposed by James and Choquete (1980). According to this model, one process occurs in an isolated system in which biogenic CO_2-rich fresh water dissolves shells, shell fragments and algae of the beach. The other mechanism occurs when marine water oversaturated in carbonate (essentially HCO_3^- in a pH around 8) present in the environment, in an open system that allows to evaporation of interstitial water, leading to degassing of dissolved CO_2, and precipitation of calcium carbonate.

Aragonite cement is scarce in beachrocks of the Jaguaribe beach, and occurs as deci-micron-sized botryoidal crystals in scattered, sheltered, intragranular pores. Chaves (2000) suggested formation of cryptocrystalline high-magnesian calcite cement induced by CO_2 degassing in the vadose zone of the beach sediment. Her data indicate that:

(a) Cryptocrystalline Mg calcite cement is actively forming in the beachrocks on the north shore of the island. The fabric indicates that cement is forming mainly in the vadose zone of the beach, and chemical data from pore water indicate that cement is precipitating from solutions that are nearer to marine composition rather than meteoric or mixed meteoric-marine compositions;

(b) Continued growth of inter- and intragranular cryptocrystalline Mg calcite cement traps silt and fine-sand sized skeletal particles, which infiltrate the pores, resulting in development of cryptocrystalline cement-supported fabric. Cement-supported zones may later be eroded from older horizons of the beachrocks and incorporated as intraclasts with internal cement-supported fabrics in younger beachrock sediment;

(c) Clear fringes of microcrystalline Mg calcite cement form subsequent to cryptocrystalline cement, either as part of a continuous sequence involving increased rates of CO_2 degassing, or as a later stage of cementation influenced by the rapid degassing of seawater from upper horizons of beachrock;

(d) A well-developed marine/meteoric mixing zone may be present at deeper levels in the beach and backbeach, but such a zone does not exist at the bottom of a well seaward of the beachrock exposure, where vadose cementation of beachrock is taking place.

(e) Carbon dioxide degassing can account for variations in pore-water chemistry and precipitation of Mg calcite cement. Comparison of variations in water chemistry with tidal stand reveals that tidal pumping may influence degassing and resulting precipitation of Mg calcite cement. When chemical and tidal cycles fluctuate with the same period, CO_2 is actively dissolved in pore water during rising tides, and P_{CO_2}, aCa^{++}, and aCO_3^- increase. During the late stage of falling tides, aCa^{++}, aCO_3^-, and P_{CO_2} decrease. These variations suggest that CO_2 degassing of pore water in the beach-beachrock system may occur during falling tides, resulting in precipitation of calcite cement. However, pore-water chemistry is very complex, and when chemical cycles show variations with a period smaller than that of the tidal cycle, the control of tidal stands upon CO_2 degassing and precipitation of calcite is much less straightforward.

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