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Mixed Oceanic and Freshwater Depositional Conditions for Beachrocks of Northeast Brazil: Evidence from Carbon and Oxygen Isotopes

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Abstract

Holocene beachrocks of Northeast Brazil are composed predominantly of quartz (90%) with minor carbonate fragments (6% algal detritus) and feldspars (4%). The cement shows three textural varieties: (1) calciferous, surrounding siliciclastic grains; (2) micritic, with an acicular fringe; and (3) cryptocrystalline calcite in pores. Sandstone structures and composition show evidence of submerged and low-energy beaches. Cement is formed by ~20 mol% $MgCO_3$; the $\delta^{13}C$ in cement ranges from −1.3‰ to +3.5‰ PDB and $\delta^{18}O$ varies from −2.1 to +1.2‰$_{PDB}$. The cement was precipitated under high CO_2 pressure, as a result of the interaction of $CaCO_3$- saturated seawater and nonsaturated groundwater, in a beach environment.

Introduction

BEACHROCKS, a common feature of the northeastern coastline of Brazil, have invoked a large number of studies because of their utility in the interpretation of coastal dynamics. They consist of sandy deposits, cemented by $CaCO_3$ and of variable length and extent, considered to represent an ancient coastline. The beachrocks are considered as a "roof ridge" of sandstone. In the area studied (Fig. 1), they occur parallel to the coastline as narrow, linear (two or three) ridges, separated one from another by sand and/or mud depressions (Mabesoone, 1964). The first line, completely emerged, is located adjacent to the beach. The second, 800 m distant, emerges only at low tide. The third line, occurring as far as 1 km offshore, is totally submerged. Beachrocks also have been observed onshore during the drilling of artesian wells and excavations for foundations.

Radiometric ages of these rocks at the Boa Viagem and Piedade beaches are 4830 ± 210 and 6200 ± 250 years B.P., respectively, placing them in the Holocene (Dominguez et al., 1992). In addition, younger beachrocks representing carbonate precipitation (a common feature of tropical beaches) during the last 20 years also have been identified on the basis of low degrees of diagenesis, organic activity, and human artifacts (Assis, 1990; Chaves, 1995).

This study, carried out on beachrocks in coastal areas of the state of Pernambuco, Northeast Brazil (Fig. 1), synthesizes their mineralogical and geochemical characteristics in order to model their depositional environment. The conclusions derived here have been substantiated by stable-isotope geochemistry.

Petrography and Mineralogy

Beachrocks are subhorizontally oriented, with an easterly dip of 3°. The surfaces are irregular and display potholes, reflecting differential erosion and perforations by organisms, as well as grey diaclasis, cross-stratification, and rare laminations. Vermetidae bioturbation and intercalated coarse layers are often observed.

The beachrocks are grey sandstone with carbonatic cement. The grain size varies from medium to pebbly, often with coarse and heterogeneous granulation, which is a common feature of beach sediments related to changes in the velocity of the marine currents. The dominant detrital components are quartz and minor fractions of rock fragments and feldspars, including zircon, epidote, hornblende, muscovite, garnet, rutile, sillimanite, and opaques present as traces. Bivalves, mollusks, gastropods, Halimeda, pelecypods, corals, thorns of equinoids, and fossil fragments are biotic components.

The cement (30 vol%) displays three kinds of texture and diagenetic microfacies. The first and dominant texture is formed by isopach crystals of

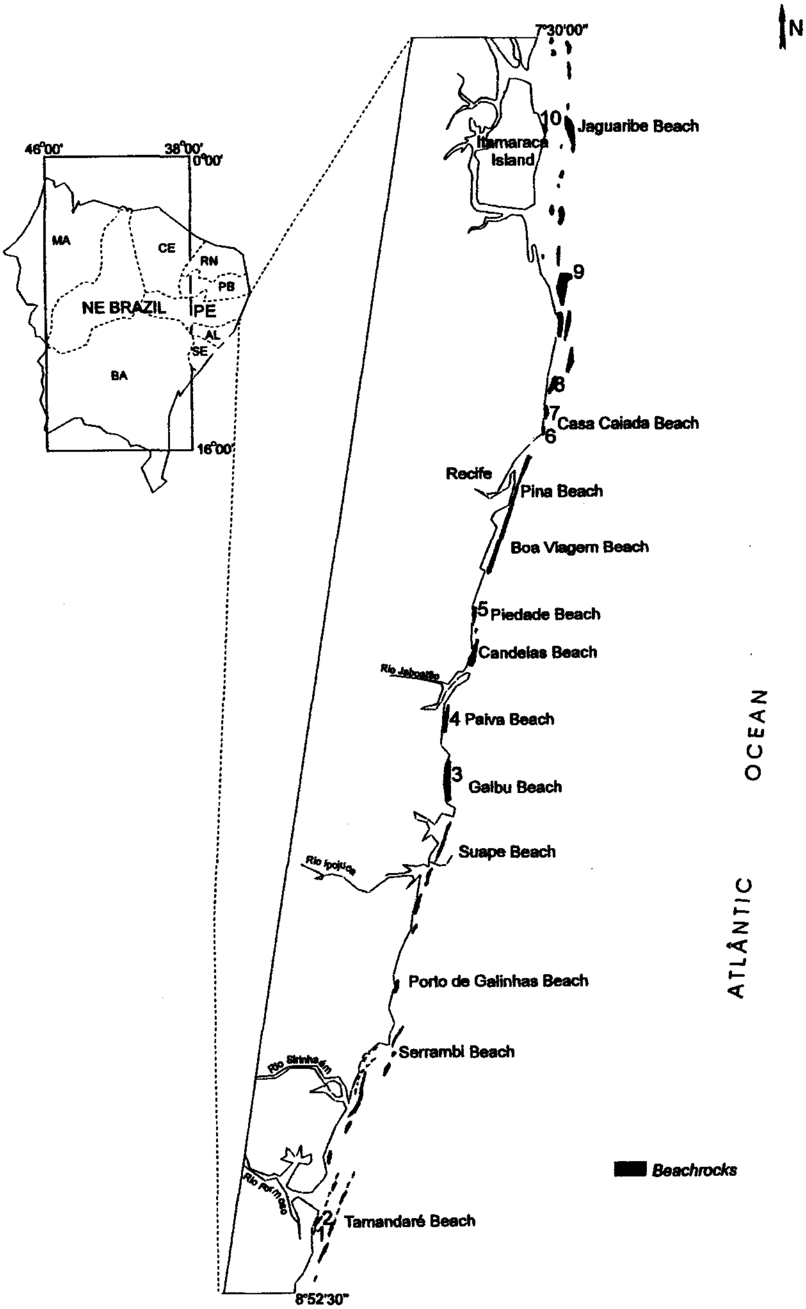

FIG. 1. Study area and sampling sites in the state of Pernambuco, Northeast Brazil. See Table 1 for analyses.

Mg calcite, enclosing bioclasts and/or clastic grains, forming uniform fringes. The second texture is represented by a cryptocrystalline, intergranular, cement-like micritic envelope, and the third is formed by intergranular cryptocrystalline Mg calcite cement, which fills the pores. Most grains display tangential contacts, indicating a low degree of diagenesis.

TABLE 1. Mol% $MgCO_3$,[1] $\delta^{13}C$, $\delta^{18}O$, Temperature, and Z-Values for Samples of Beachrock Cement of the Pernambuco Coastline, Brazil[2]

Sample	Beaches	Mol‰, $MgCO_3$	$\delta^{18}O$ PDB	$\delta^{18}O$ SMOW	$\delta^{13}C$ PDB	T, °C	Z
1	Tamandaré	18	+0.76	+31.65	+3.52	12.9	134.88
2	Tamandaré	20	+0.37	+31.24	+2.92	14.5	133.46
3	Gaibu	20	+0.82	+31.70	+3.12	24.8	134.09
4	Paiva	20	−0.29	+30.55	+2.12	17.2	131.49
5	Piedade	18	+1.15	+32.04	+3.24	11.4	134.50
6	Casa Caiada	18	−1.63	+29.18	+1.26	23.1	129.06
7	Casa Caiada	18	−0.78	+30.06	+1.33	19.3	129.63
8	Rio Doce	18	−1.29	+29.53	+0.93	21.5	128.56
9	Pau Amarelo	20	−2.10	+28.69	+1.77	25.3	129.87
10	Jaguaribe	20	−1.34	+29.48	−1.35	22.0	123.88
OB1[3]	Serrambi	20	+0.43	+30.81	+2.97	10.2	133.60
OB2.4[3]	Serrambi	20	+0.45	+30.83	+2.95	10.2	133.56
OB1E.3[3]	Serrambi	20	+0.73	+31.12	+2.84	10.2	133.48
1B3E.3[3]	Serrambi	20	+0.59	+30.98	+3.09	10.1	133.92
1B3S[3]	Serrambi	20	+0.36	+30.74	+3.00	10.2	133.62
R-1-1[4]	Boa Viagem	18	—		+3.36	—	—
R-2-1[4]	Boa Viagem	20	—		+3.35	—	—
R-2-2[4]	Boa Viagem	15.9	—		+3.01	—	—
RB-1[4]	Boa Viagem	16	—		+3.60	—	—
RB-2[4]	Boa Viagem	15.6	—		+3.62	—	—
SA-1[4]	Suape	15.6	—		+3.62	—	—
SA-3[4]	Suape	15.8	—		+3.56	—	—
SA-8[4]	Suape	14.7	—		+3.87	—	—

[1]From X-ray diffraction.
[2]T, °C = 16.0 to 4.14 (O^{18}_{PDB}–O^{18}_{SMOW}) +0.13(δc–δw)^2; $Z = a\ (C^{13} + 50) + b\ (O^{18} + 50)$; $a = 2.048$; $b = 0.498$ (Keith and Weber, 1964).
[3]From Assis, 1990.
[4]From Suhayda et al., 1977.

The cement is formed of 55% Mg calcite and 45% aragonite, containing 18 to 20 mol% $MgCO_3$ (see Table 1), similar to that observed at beaches in Piedade (Coutinho and Farias, 1979), Serrambi (Assis, 1990), Boa Viagem, and Suape (Suhayda et al., 1997). According to Alexandersson (1972), Mg calcite values between 12 and 18 mol% $MgCO_3$ are associated with intertidal and supratidal zones forming micritic envelopes. A high content of Mg calcite in the first line can be explained by surface diagenetic conditions resulting from acceleration in cementation (Coutinho and Farias, 1979).

Paleocurrent determinations indicate the presence of two groups. The first group has a mean azimuth value of 346°, whereas the second is 30° Az, reflecting the general direction of currents during deposition, flotation, and dispersion in the fluid. Cross-stratification is characteristic of the partially submerged beach deposit under low-tide conditions, whereas parallel stratification is related to high tide. The SE-NW currents controlled structures of the Pernambuco coastline, similar to the situation in the state of Rio Grande Norte, according to Oliveria (1978).

Carbon and Oxygen Isotopes

Stable-isotope analyses of carbon and oxygen in carbonates determine the existence of isotopic equilibrium in the environment of formation. Urey (1947) established the use of C- and O-isotopic ratios as a significant approach in the estimation of marine paleotemperatures. The isotopic signatures of sediments and calcareous rocks can be quite useful in identifying and dating the post-depositional stabilization process (Veizer, 1992). In the present study, cement was carefully separated from shell fragments and algae in order to avoid contamination and erroneous results dur-

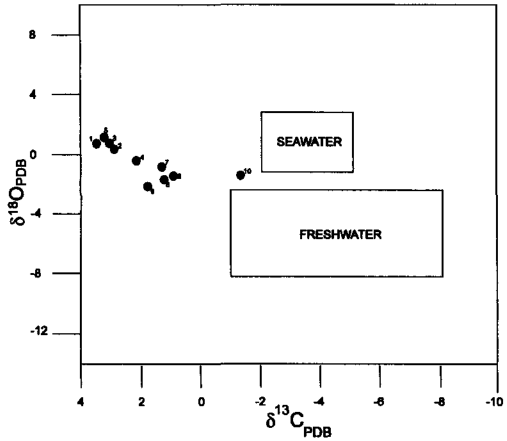

FIG. 2. Oxygen- and carbon-isotope plot for beachrock samples in this study. Seawater and freshwater fields are from Keith and Weber (1964) (see Table 1 for analyses).

ing isotopic analysis. The resulting material was separated into 0.5 and 0.063 mm fractions, Samples were treated with 100% orthophosphoric acid at 25°C; the CO_2 released was analyzed in a VG ISOTECH SIRA II mass spectrometer at the Stable Isotope Laboratory (LABISE), Federal University of Pernambuco, Brazil. Results are presented in Table 1.

The $\delta^{13}C$ value for cement ranges from −1.3‰ to +3.5‰$_{PDB}$ and the $\delta^{18}O$ varies from −2.1‰ to +1.2‰$_{PDB}$. The ambient water temperature (calculated after Arthur et al., 1983) has been estimated to range from 11.4° to 25.3°C, representing stillstands during prolonged marine transgressions. The inferences are consistent with values obtained by Manso et al. (1995).

Carbonate sediments deposited from oceanic bicarbonates in isotopic equilibrium with atmospheric CO_2 should show $\delta^{13}C$ values close to the standard (~0) (Craig, 1961), distinct from high-^{12}C freshwater, which shows negative $\delta^{13}C$ values (Clayton and Degans, 1959; Keith and Weber, 1964). The beachrock samples from the littoral zone show positive $\delta^{13}C$ values, with only one exception, and negative to positive $\delta^{18}O$ (PDB) values (Chaves, 1995).

The carbon-isotopic ratios indicate cement precipitation in a shallow, predominantly marine environment with minor freshwater influx (Figs. 2 and 3). These inferences are consistent with analyzed oölites from the Bahamas (Lowestam and Epstein, 1957); aragonitic cement in the Persian Gulf (Shin, 1969); high-Mg calcite in Jamaican cements (Land, 1971); beachrock cements in Grand Cayman Island (Moore, 1975); beachrock cements of the Salvador (Campos, 1972), Serrambi (Assis, 1990), and Pernambuco coastlines (Chaves et al., 1995); and limestones of the Gramame and Maria Farinha formations (Sial et al., 1994). The $\delta^{13}C + \delta^{18}O$ diagram (Fig. 3) shows that analyzed specimens straddle the fields of freshwater limestone, green algae, mollusks, and foraminifers of shallow-water origin (Milliman, 1974), underlining the significant presence of Halimeda and *Archaias angulatus* in the platform, inducing biogenic fractionation, biochemical non-equilibrium, and consequently carbonate-cement precipitation (McConhaughey, 1990a, 1990b).

The isotopic values plot across the marine and freshwater fields (Fig. 4) and define a close affinity with the Barbados and Bermuda trends (James and Choquette, 1990). The data plots indicate overlapping, covariant mixing trends of organic matter and seawater (A trend) as well as a meteoric effect (B trend). Thus, the beachrock formation was influenced by a mixed oceanic and freshwater environment. Gradual depletion in $\delta^{13}C$ can be attributed to an influx of freshwater. In the absence of soil conductive for organic growth, no significant effect of organic matter is observed along the Pernambuco coastline, in contrast to the beachrocks of Barbados and Bermuda.

The mix formed in the interstitial zone by seawater saturated in Ca^{++} and CO_3^{--} with subsaturated fresh groundwater reflects equilibrium of the CO_2 partial pressure in each system. The evaporation of seawater produces a CO_2 equilibrium that causes cement precipitation from marine carbonate. The isotopic values indicate precipitation of carbonates under marine conditions, corroborated by high-Mg calcite and aragonite present in the cement of the beachrocks along the littoral zone of the state of Pernambuco. The most striking isotopic evidence is a N-S increase in the *z*-values (defined by Keith and Weber, 1964), which suggests an increase in freshwater influence, reflected in the carbonate-cement composition (Table 1, Fig. 5).

Discussion and Conclusions

The texture of cement in coastal areas of the state of Pernambuco identifies two distinct envi-

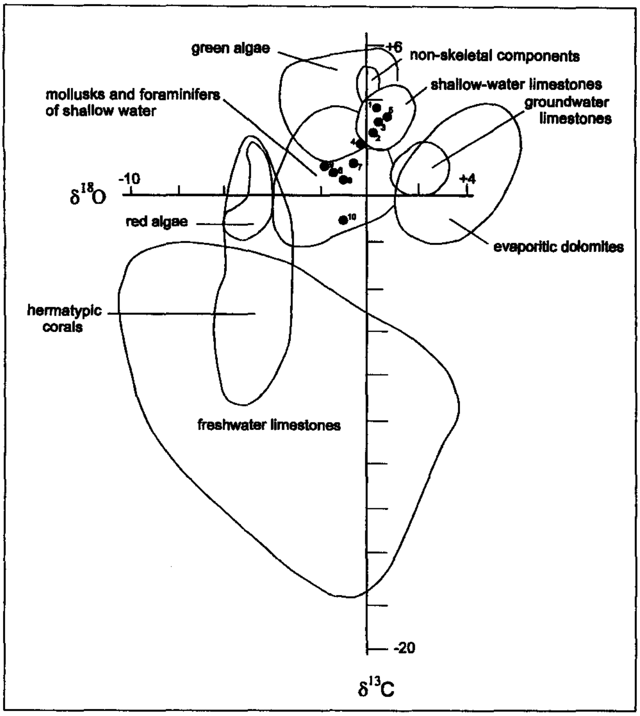

FIG. 3. Oxygen- and carbon-isotope plot (PDB, ‰) for beachrock samples from this study (black dots). See Table 1 for analyses. Fields for Quaternary carbonate sediments are from Milliman (1974).

ronments—marine phreatic and marine mixed with freshwater. The association of groundwater with marine phreatic water and pure marine water also is reported elsewhere by Russell (1963) and Stoddart and Cann (1965). The inferences also are substantiated by the isotopic data presented above.

The presence of high-Mg calcite and aragonite in the cement suggests a significant influence of marine water. Predominant acicular fibrous crystals of Mg calcite in cement imply saturation or subphreatic conditions by initial precipitation from stillstands during extensive marine transgression.

The isotopic data lead to two possible origins for the cements. The first cement (observed in some rocks exhibiting the effects of intense diagenesis) has an isotopic signature characteristic of the marine environment. This can be attributed to CO_2 partial pressure that was insufficient to permit mixing between seawater and fresh groundwater, and to interaction with the atmosphere, favoring $CaCO_3$ saturation. The second kind of cement is characteristic of low-diagenetic or friable rocks with isotopic signatures indicating fresh groundwater (as interstitial water). The phreatic level had intercepted the sea level near the surface, resulting in cement precipitation on the terraces under high-$CaCO_3$ water-flux conditions during low tide because of the inclination between the terrace and the lower limit of the beach precipitating the $CaCO_2$ (Chaves et al., 1995).

The existence of an impermeable surface can be observed over the sediments of the terraces that trap the $CaCO_3$-saturated fresh groundwater; the latter possibly would be in equilibrium with the atmosphere during low tide, during which time the groundwater level intercepted the beach zone. This supports the possibility of evoking dissolution models of the carbonates under closed-system conditions and high CO_2 pressure without marine influence, as well as models of solution resulting from the mixing of $CaCO_3$-saturated water with nonsaturated groundwater in the beach environment. The crystallization effects of calcite in seawater caused by MG^{++} ions seem to be a direct consequence of the presence of groundwater.

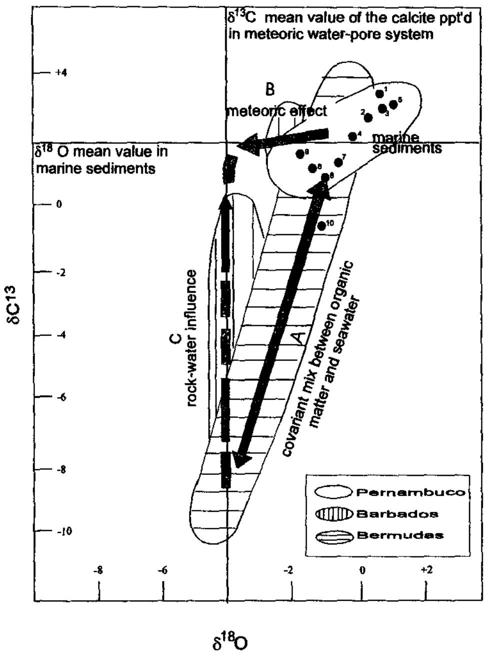

FIG. 4. Oxygen- vs. carbon-isotope plot (PDB, ‰) for the studied beachrocks. Metastable marine carbonate trends for Barbados and Bermuda are from James and Choquette (1980) (see Table 1 for analyses).

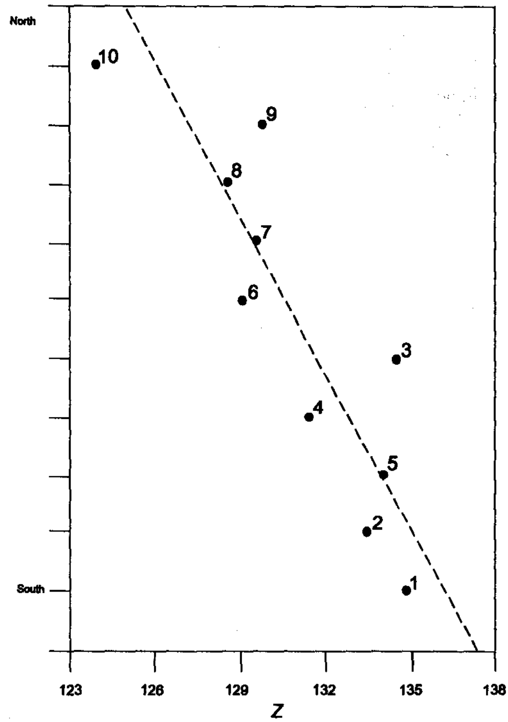

FIG. 5. Z-values for beachrocks in this study, arranged according to a sample N-S geographic distribution (Z-values calculated according to Keith and Weber, 1964). See Table 1 for analyses.

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