

# Diagenesis of Holocene Beachrock in Northeastern Brazil: Petrology, Isotopic Evidence and Age

## *Diagênese do Holoceno do rochedo da praia no Nordeste do Brasil: Petrologia, Evidência Isotópica e Idade*

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### Abstract

This work aims to understand beachrock formation during Holocene through petrology, geochemistry and dating of a core located 5,43m deep in relation to present-day sea-level in the Piedade Beach in Jaboatao dos Guararapes- PE. The core is located 143 meters distant from the coast line towards mainland. Four lithofacies have been identified, taking into account differences in texture and sedimentary structures. The framework grain size ranges from medium to very coarse sand, indicating variations in depositional energy. Petrographic data indicate that the beachrocks have values of 64.23% to 70.69% of framework composed of quartz grains. Carbonate cement (represents 13.5%) consisting of high magnesium calcite surrounding grains as isopachous fringe (4.15% to 11.95%), micritic cement (0.60% to 6.42%) and equant cement (0.26% to 7.01%), indicates marine environment precipitation. The results of the isotopic composition of carbon and oxygen present values of 3.09‰ to 3.89‰, with an average of 3.63‰ to  $\delta^{13}\text{C}_{\text{PDB}}$  and of -0.91‰ to 0.96‰, with an average of 0.54‰ to  $\delta^{18}\text{O}_{\text{PDB}}$ , suggesting that the cement is formed in a shallow marine environment with freshwater influence. The values obtained in paleotemperature vary from 21°C to 30°C, with an average of 23°C, with little variation indicating precipitation in a shallow water environment. In the study area, the beachrocks are indicators of sea level and the results suggest that between 7.509 years B.P. and 5982 years B.P. there was a marine transgression process, with sea level 9.18 m lower than the current sea level.

**Key-words:** Cement; Holocene; Sealevel

### Resumo

Este trabalho tem como objetivo compreender a formação do leque rochoso durante o Holoceno através da petrologia, geoquímica e datação de um núcleo localizado a 5,43m de profundidade em relação ao atual nível do mar na Praia da Piedade em Jaboatão dos Guararapes-PE. O núcleo está localizado a 143 metros da linha da costa em direção ao continente. Quatro litofácies foram identificadas, levando em consideração diferenças de textura e estruturas sedimentares. O tamanho do grão da estrutura varia de areia média a muito grossa, indicando variações na energia deposicional. Dados petrográficos indicam que os beachrocks apresentam valores de 64,23% a 70,69% de estrutura composta por grãos de quartzo. O carbonato de cimento (representando 13,5%) consistindo de grãos de calcita de magnésio como franja prismática isópaca (4,15% a 11,95%), cimento micrítico (0,60% a 6,42%) e cimento equante (0,26% a 7,01%), indica precipitação no ambiente marinho. Os resultados da composição isotópica de carbono e oxigênio apresentam valores de 3,09 ‰ a 3,89 ‰, com média de 3,63 ‰ a  $\delta^{13}\text{C}_{\text{PDB}}$  e de -0,91 ‰ a 0,96 ‰, com média de 0,54 ‰ a  $\delta^{18}\text{O}_{\text{PDB}}$ , sugerindo que o cimento é formado em um ambiente marinho raso com influência de água doce. Os valores obtidos em paleotemperatura variam de 21°C a 30°C, com média de 23°C, com pouca variação indicando precipitação em um ambiente de águas rasas. Na área de estudo, os beachrocks são indicadores do nível do mar e os resultados sugerem que entre 7,509 anos B.P. e 5982 anos B.P. houve um processo de transgressão marinha, com nível do mar 9,18 m abaixo do atual nível do mar.

**Palavras-chave:** Cimento; Holoceno; Nível do mar

### Introduction

Beachrocks are known as sedimentary rocks developed from calcium carbonate precipitation (Turner 2005), emerged or submerged in relation to present sea level and located parallel to coast line with a shape of linear tracks disconnected by mud and/or

sand depressions. More than 90% of beachrocks are located between latitudes 40°N and the Capricorn Tropic, in tropical and subtropical regions, with a minority in temperate and cold regions (Danjo & Kawasaki 2014). The process responsible for sediment lithification is not yet totally known. It may occur due to processes like percolation and lithification in depth,

water evaporation and heating in the surface, fresh and marine water mixing and metabolic activities from algae or bacterium (Coutinho & Farias 1979). After lithification, beachrocks may suffer modifications due to natural agents like fluvial transport and wave action, as well as modifications from anthropic behavior like landfills and dredging, with probable influence on dynamics of physical and chemical processes related to their formation.

In Brazil, beachrocks are located in shoreface, foreshore and shallow continental shelf from Ceara State until the north coast of Sao Paulo State, being permanently submerged in Parana state (Simioni *et al.* 2011). In the northeastern region, the first study of beachrocks was accomplished by Darwin (1841) who identified these rocks as calciferous sandstones with shell fragments and a few pebbles. According to Branner (1904), these rocks are representative of ancient beach lines consolidated by calcium carbonate.

Beachrocks represent a category of sediments lithified in shoreface and foreshore through cementation process. According to Voudoukas *et al.* (2007), through the kind of cementing agent it is possible to understand the origin of coastal carbonates. According to Aliotta *et al.* (2009), beachrocks cement origin involves the carbonate precipitation from marine water as interstitial water circulation. Several cementation processes in carbonates occur in shallow depths, in diagenetic environments equivalent to marine meteoric and mixing vadose and phreatic zones (Longman 1980). Therefore, the carbonate origin is determined from water chemical conditions during cement precipitation process.

Beachrocks provide the register of climatic and oceanographic changes occurred in coastal waters (Erginal *et al.* 2013). From radiocarbon dating of bioclasts and carbon and oxygen isotopic signature of cements, may determine Holocene events like marine regression/transgression and glaciations/deglaciations, besides natural catastrophes, flood periods and other events. Such events still registered in stratigraphic sequence of these rocks, characterized by changes in composition and grain size of their sediments.

In order to investigate the Holocene beachrock evolution, in Pernambuco state, an investigation of geochemical composition, stable isotopes and petrographic analyses, as well as radiocarbon dating were applied in this research. Therefore it was possible to better understand the diagenetic processes involved in beachrock formation and consequently, recognize their origin.

The Piedade beach is located in the city of Jaboatao dos Guararapes, in the coast of Pernambuco state, northeastern Brazil (figure 1). The study area has an annual average temperature around 27°C and rainfall approximate 2.000 mm/year, distributed unequally between the dry and rainy seasons. One of the important aspects of studying beachrocks is based on the processes of shallow carbonate cementation (Longman 1980). The beachrocks located in this area have never been analyzed.

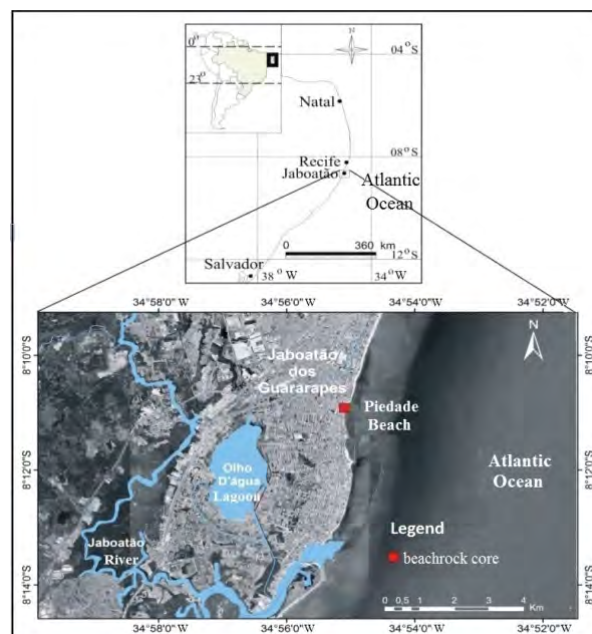


Figure 1: Location of the study area with drill cores located on Piedade beach, Jaboatao dos Guararapes/PE.

## Methodology

We used a core (2.60m) located 5.43m deep relative to the average present-day sea level at Piedade Beach, situated in Jaboatao dos Guararapes-PE, about 143 meters away from the shoreline towards the open ocean, being the same granted by Ensolo Company. In the field work, a core depth measurement related to the average present-day sea level was made, using a reference level basin like reference. It was used a bench mark in relation to core located at 5.43m above present-day sea level, with space between the bench mark and core top of 1.68m. The core top presented an elevation difference of 3.75 meters in relation to the ground and 6.35m to the core base. Adjusting the respective elevations with the bench mark, the top presented 10.10m and the base 11.58m below the present-day sea level.

To describe the diagenetic processes involved in beachrock lithification, ten thin sections, obtained from samples located at 0.20m intervals along the Piedade beach core, were described on a petrographic microscope.

The geochemical stage comprised carbon and oxygen isotopic analysis and chemical elements analysis in samples obtained at 0.10m intervals, along the core. Nineteen core samples were macerated and sifted with separation of 2g for each sample through an analytical balance. Afterwards, with the use of the magnifying glass, the bioclasts were separated from matrix rock to avoid errors in data since their formation occurs before cementing. The contents resulted from such process reacted with orthophosphoric acid at 100% under high vacuum conditions at 25°C. The carbon dioxide released after being cryogenised was clean and analyzed in a mass spectrometer VG-ISOTECH SIRA II, in Stable Isotope Laboratory (NEG-LABISE) at

Federal University of Pernambuco. The results from these analysis are related in parts per thousand (‰), according to the international isotopic standards of International Atomic Energy Agency (IAEA) in Vienna.

Ten samples containing 6g in dust shape each were selected and dried in kiln at 100°C. One portion of the dry samples was placed to a muffle at 1000°C for 2 hours for combustion. Other dry sample portion was placed in an aluminum capsule and pressed in hydraulic press with 25 tons of force in order to make semiquantitative chemistry analysis for heavy and some light elements. The product of scanning the loss combustion value was introduced and the values were calculated one more time for 100%. Chemistry analysis was made using a fluorescence spectrometer of X-ray Rigaku RIX 3000 model, equipped with Rh tube containing 6 crystal analyzers and the results expressed in weight (%).

Through the radiocarbon dating it was possible to detect  $^{14}\text{C}$  concentration in beachrock encrusting shells. This process was made at Leibniz Laboratory of the University of Kiel, in Germany. In three core samples, the  $^{14}\text{C}$  concentration was determined by AMS technique which radiocarbon ages calibrated using the *Radiocarbon Calibration Program* (CALIB).

The scanning electron microscopy (SEM) was used to observe crystal morphology and texture relationships in carbonate cement. Eight samples were selected for this purpose. It was used the equipment JEOL-6460.

## Results and discussion

### Petrography

The petrographic analysis revealed that the beachrock presents a framework constituted of quartz grains (minimum of 64.23% and maximum of 70.69%), with monocrystalline type most frequent (minimum of 58.91% and maximum of 63.76%) and, in less quantity, the polycrystalline type (minimum of 2.18% and maximum of 9.99%), with type packaging with long and tangential contacts between the grains indicating early cementing processes (figure 2).

Some bioclasts were found in all thin sections, with percentage in framework ranging from 1.63% to 8.59% and being constituted of bivalve, foraminifera, gastropods (figure 3), red algae, among others. Low concentrations of heavy minerals were observed (figure 4) as well as low concentration of plagioclase feldspars, with values ranging from 0.32% to 6.87% and from

0.70 to 4.13%, respectively. Iron oxide present in three samples, have low concentration, with variation from 0.24% to 0.57%, being a diagenetic constituent instead of a framework component (figure 5). The dominant porosity is intergranular (minimum of 6.76% and maximum of 15.88%).

The beachrock cements show three different morphologies composed of high magnesium calcite: (i) isopachous prismatic fringe (figures 6 and 7), (ii) micritic pore filling cement (figure 6 and 8) and (iii) mosaic of equant crystals (figures 5 and 9).

Isopachous prismatic fringes occur with variation from 4.89% to 11.95% in thin sections, constituting the most abundant cement in each sample, generated according to (Longman 1980), in marine phreatic zone (symmetric fringes). The regular distribution of isopachous prismatic fringes is the main characteristic of precipitation in marine phreatic environment (Longman 1980), where the sea water is conducted into sediments through waves, tides and currents.

Micritic carbonate presented variation from 0.83% to 6.42%. Its presence indicates carbonate precipitation under marine conditions (Erginal *et al.* 2010).

The equant cement ranges from 2.65% to 6.77%, indicating precipitation in a predominantly shallow marine environment responsible for the high magnesium calcite formation (Longman 1980). It is composed of calcite crystal aggregates responsible for complete filling of porosity ranging from microcrystalline to mesocrystalline sizes.

The absence of organic structures in the studied beachrock suggests that abiogenic precipitation in shallow marine environment with fresh water influence were responsible for cement precipitation.

Four lithofacies have been identified in the core, based on grain size and sedimentary structures. The Lithofacies 1 is at core base, about 0.40 meters thick (5.95 - 6.35 m) and was classified as sandstone composed of medium sand and bioclasts. The Lithofacies 2 is 0.67 meters thick (5.95 - 5.28 m) and was classified as a medium to very thick sandstone with trough-cross stratification indicating deposition in upper shoreface. Lithofacies 3 with thickness of 0.78 meters (5.28 - 4.5 m) is composed by thick sandstone layers, low porosity and with the presence of swash-cross stratification interpreted as shoreface deposition. The Lithofacies 4 is 0.75 meters thick (4.5 m - 3.75 m), named sandstone composed of coarse porous sand.

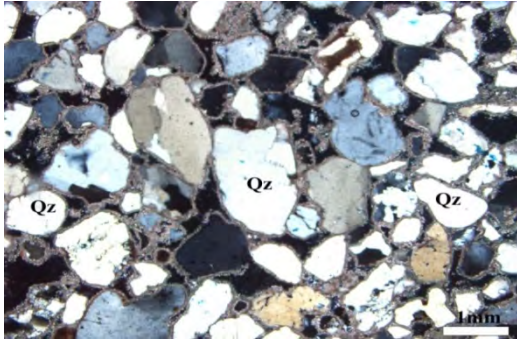


Figure 2: General view of clasts and their cementing. Thin section image indicating predominance of quartz grains (Qz) in the framework (sample 1).

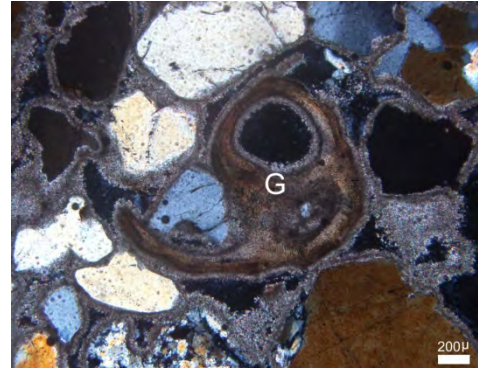


Figure 3: A gastropod skeleton (G) found in sample 3, with an isopachous fringe surrounding the bioclasts.

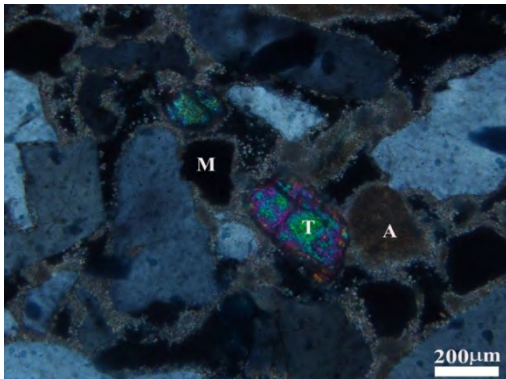


Figure 4: Opaque mineral (M), tourmaline grain (T) and red algae (A) found in sample 1.

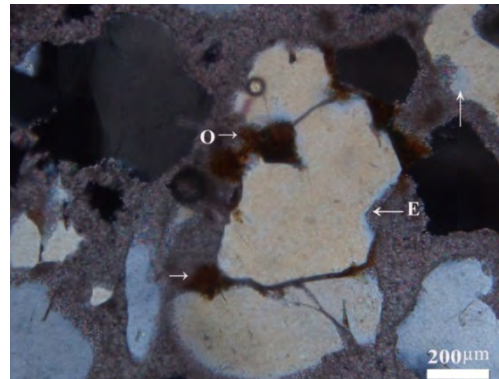


Figure 5: Equant crystals (E) filling pore spaces between quartz grains and iron oxide (O) in sample 6.

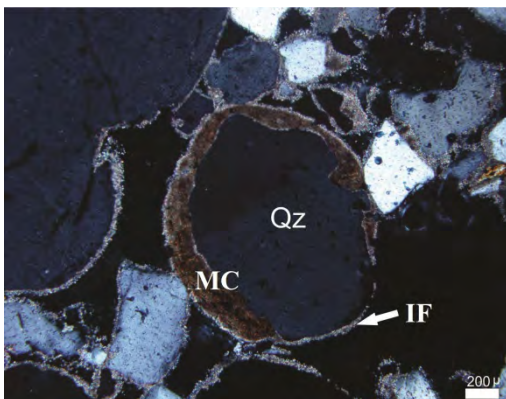


Figure 6: Micrite (MC) and isopachous fringe (IF) forms a coating on the grain (Qz).

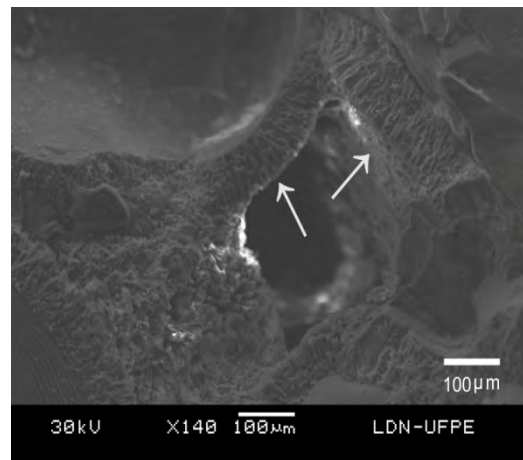


Figure 7: Isopachous prismatic fringe in sample 3.

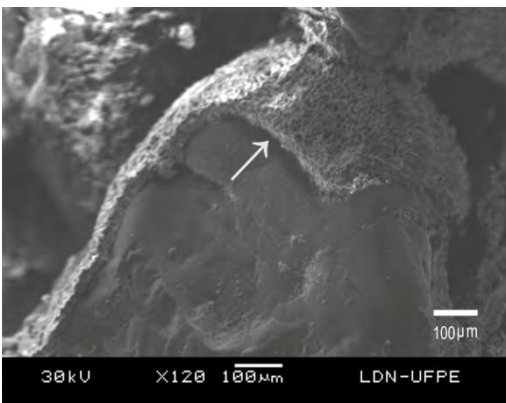


Figure 8: Micrite coating quartz grain in sample 5.

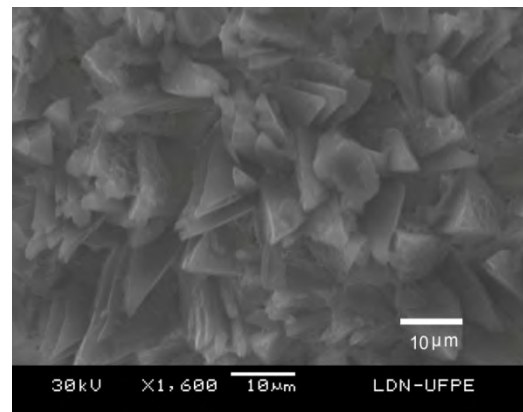


Figure 9: Detail of equant crystals in sample 2.

## Geochemistry

### Carbonate Oxygen Isotopes

The carbonate cement presented  $\delta^{13}\text{C}_{\text{PDB}}$  values between 3.09‰ and 3.89‰, with average of 3.63‰, and  $\delta^{18}\text{O}_{\text{PDB}}$  values from -0.91‰ to 0.96‰, with average of 0.54‰, indicating marine environment precipitation. According to Coudray & Montaggiani (1986), a value of 0.54 ‰  $\delta^{18}\text{O}_{\text{PDB}}$  is characteristic of the intertidal zone (table 1).

The studied beachrocks isotopic distribution at Piedade Beach reveals mostly positive carbon and oxygen values. The only negative value of  $\delta^{18}\text{O}_{\text{PDB}}$  could indicate fresh water influence in the cement precipitation.

Isotopic values in beachrocks carbon cements reported in different places around the world are registered in table 2.

Table 1: Isotopic data of Z and paleotemperature values related to beachrock core samples of Piedade Beach.

Samples	Depth(m)	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}$	Z	T(°C)
AM 19	4.20	0.668	3.718	135.24	23
AM 18	4.30	0.574	3.636	135.03	23
AM 17	4.40	0.441	3.584	134.85	24
AM 16	4.50	0.497	3.317	134.34	24
AM 15	4.60	0.488	3.724	135.16	24
AM 14	4.70	0.281	3.602	134.81	25
AM 13	4.80	0.381	3.696	135.05	24
AM 12	4.90	0.317	3.644	134.92	24
AM 11	5.05	0.332	3.677	134.99	24
AM 10	5.15	-0.916	3.093	133.17	30
AM 9	5.25	0.424	3.653	134.99	24
AM 8	5.55	0.865	3.891	135.69	22
AM 7	5.65	0.935	3.877	135.70	22
AM 6	5.75	0.955	3.767	135.49	21
AM 5	5.85	0.599	3.383	134.52	23
AM 4	5.95	0.956	3.807	135.57	21
AM 3	6.05	0.808	3.509	134.88	22
AM 2	6.15	0.842	3.686	135.26	22
AM 1	6.25	0.873	3.706	135.32	22

Table 2: Paleotemperature and carbon and oxygen isotopic values from beachrocks in the literature.

Reference	Locality	$\delta^{13}\text{C}_{\text{PDB}}$ (‰)	$\delta^{18}\text{O}_{\text{PDB}}$ (‰)	T(°C)
BARROS et al. (2003)	Ceara (Brasil)	+1.9 a +3.1	-0.5 a + 0.4	15 a 19
	Lagoinha/Uruau	+0.5 a +3.4	-1.8 a + 1.2	14 a 24
CALVET et al. (2003)	Ilhas Canarias (Espanha)	+4.0 a +4.9	-4.2 a + 2.4	17 a 25
CHAVES & SIAL (1998)	Pernambuco (Brasil)	-1.3 a +3.5	-2.1 a +1.2	10.1 a 25.3
FRIEDMAN (2011)	Java (Indonesia)/Bardawil	- 18.0	-14.8	-
	(Delta do Nilo. Egito)	-39.3 a -3.3	-36.6 a + 3.8	-
HOLAIL & RASHED (1992)	Egito (Africa)	+1.0 a + 2.1	-0.4 a +1.2	-
	Mediterraneo/ Mar Vermelho	+2.1 a + 4.5	-0.1 a +1.2	-
VIEIRA & DE ROS (2006)	Rio Grande do Norte (Brasil)	-7.8 a +3.6	+0.5 a +4.4	23.3 a 34.9

Beachrock cement  $\delta^{18}\text{O}$  values reported by Holail & Rashed (1992) in the Mediterranean and Red Sea, reveals value average of 0.5‰ similar to the cement data obtained in the Piedade Beach. According to the mentioned authors, low oxygen isotopic heterogeneity could indicate absence of a progressive temperature change or water composition during cement growth.

The  $\delta^{18}\text{O}$  data related to aragonite cements in Canary Islands, in Spain, showed lower values (-4.2‰ to +2.4‰) when compared with values obtained by the present study (cf. Calvet et al. 2003). According to these authors, the oxygen isotopic values measured are possibly related with factors like: salinity of sea water in the Canary Islands, temperature of sea water in intertidal zone of beaches in La Palma and meteoric water influence.

Extremely negative values of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  in Java, Indonesia, and in Bardawil, in Egypt, are related to beachrock formation due to catastrophic events from temperature increase generated by impacts and explosions where negative extremely values of  $\delta^{13}\text{C}$  indicate that dolomite carbon is from de methane, which had formed at the expense of original gypsum and dolomite (Friedman 2011).

In Ceara, the  $\delta^{13}\text{C}$  values varied from +1.9 to +3.1‰, at Lagoinha Beach, indicating shallow marine water precipitation while  $\delta^{13}\text{C}$  values from +0.5 to +3.4‰, in Uruau Beach, could be related with freshwater influx, causing change in carbonate cement associated with exposition after regression of shoreline or elevation correlated to Quaternary tectonic activity (Barros et al. 2003).

The high magnesium calcite composition in beachrock cements studied in Rio Grande do Norte (Vieira 2005) consists in a possible explanation for the observed homogeneity in samples (-7.8‰ to +3.6‰ for  $\delta^{13}\text{C}$ , +0.5 to +4.4 for  $\delta^{18}\text{O}$ ), as well as the uniformity of physico-chemical parameters that control beachrock cementation attested by little variation of paleotemperature values (23.3°C to 34.9°C).

Beachrock studied by Chaves & Sial (1998) in coastal areas of Pernambuco state presented isotopic values of  $\delta^{13}\text{C}$  from -1,3‰ to +3,5‰ and of  $\delta^{18}\text{O}$  from -2,1‰ to 1,2‰ interpreted as cement precipitation under high pressure of  $\text{CO}_2$  as result of marine water saturated in  $\text{CaCO}_3$  interaction and poorly saturated interstitial water in a beach environment.

Using isotopic value curves obtained from oxygen and carbon associated with the description of four facies along the core of Piedade Beach, it was possible to estimate the temperature (paleotemperature) and environmental conditions during cement precipitation (figure 10).

Short break of  $\delta^{18}\text{O}_{\text{PDB}}$  values (-0.91‰ to 0.96‰) found along the core indicates that water temperature maintained practically constant during carbonate precipitation despite the fact of freshwater supply and evaporation influence in  $\delta^{18}\text{O}$  variation. The highest isotopic oxygen value (0.96‰) was found in lithofacies 1, at the base of the core that presented values practically constant with small increase indicating meteoric water

influence until reaching maximum value. The lowest value (-0.91‰), however, was found in lithofacies 3 and could be explained by high water evaporation process due to low porosity and sandstone permeability.

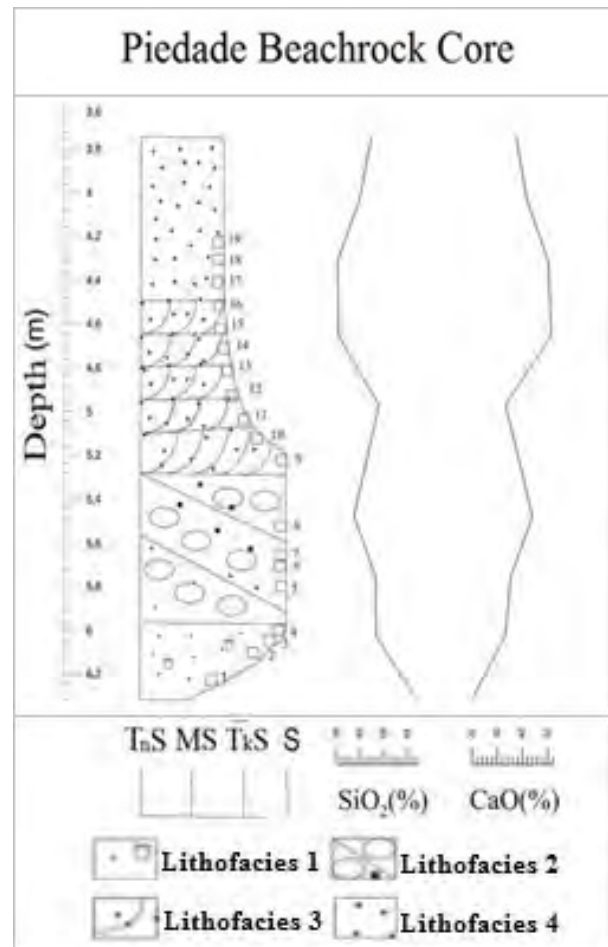


Figure 10: Beachrock core in Piedade with  $\text{SiO}_2$  and  $\text{CaO}$  measured values in %.

The correlation between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values in submerse beachrocks in the Piedade Beach shows correlation coefficient ( $R^2$ ) equal to 0.5483, indicating a positive correlation with 54% of  $\delta^{13}\text{C}$  variation resulting from  $\delta^{18}\text{O}$  variation showing a resemblance of 54% between the data (figure 11).

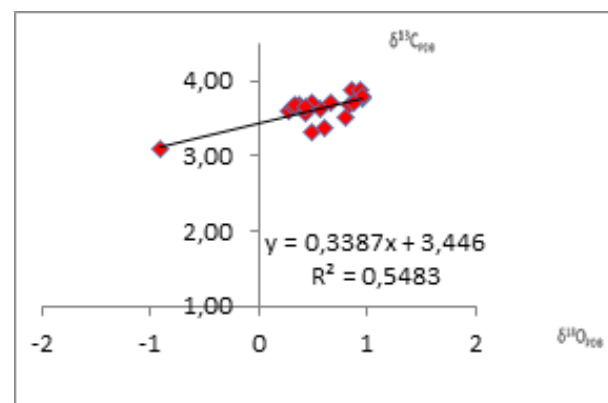


Figure 11: Correlation between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  in submerse beachrocks in Piedade.

The Z value calculated for the studied samples indicate a marine origin for the cements. The Z parameter was proposed by Keith and Weber (1964) with the purpose of distinguishing between marine ( $Z > 120$ ) and fresh-water limestones ( $Z < 120$ ). Values of Z found in this work varied from 133.17 to 135.70, with average of 135,0 indicating therefore marine environment formation.

Sedimentary rock cements depend on the chemical and physical characteristics of water at the moment it was precipitated. Following the model proposed by Moore (2004), it is possible to interpret the conditions under which the studied beachrocks were formed based on carbon and oxygen isotopic signature. About 63% of samples from the Piedade Beach correspond to marine cement; 16% are classified as recent sediments and the other 21% are not inserted in any group staying out of the ranges established that could indicate new environment formation (figure 12).

The results of the obtained paleotemperature showed that during sea-level highstand in the Holocene, the water temperature values ranged from 21°C to 30°C with an average around 23°C (figure 13). Comparing the values of modern water temperature and paleotemperatures, their mean presents a difference of 3°C, with mean of modern temperature around 26°C, whereas the mean of paleotemperature is 23° C.

The paleotemperature values in the Uruau Beach, in Ceara, varied from 14°C to 24°C, indicating successive phases of carbonatic cement precipitation (Barros et al. 2003). Vieira (2005) obtained values from 23.3°C to 34.9°C with average of 25.7°C with small paleotemperature variation explained by the exclusive high magnesium calcite composition in beachrock cements of Rio Grande do Norte State.

### Chemical Elements

The distribution of chemical elements in marine sediments and rocks can be used as indicators of environmental conditions during their deposition and lithification (Ward et al. 1995). Chemically, beachrock around the world differs in composition. Beachrock at Okinawa, Japan consists of calcium carbonate or silica (Danjo & Kawasaki 2013).

At Piedade beach sediments are used to distinguish lithofacies based on SiO<sub>2</sub> and CaO content that have high significance in the majority of samples, with percentage that varied between 38.4 and 71% for SiO<sub>2</sub> and between 20.5 and 51.4% for CaO (table 3). High concentration of SiO<sub>2</sub> is derived from terrigenous clastic, while high concentration of CaO is indicative of biogenic carbonate.

Table 3: Concentration in (%) of chemical compounds found in beachrock core samples in Piedade beach core.

	AM 1	AM 3	AM 5	AM 7	AM 9	AM 11	AM 13	AM 15	AM 17	AM 19
<b>MgO</b>	0.7	1.0	1.1	1.5	1.1	1.6	1.6	1.4	1.2	1.1
<b>Al<sub>2</sub>O<sub>3</sub></b>	1.3	1.3	0.8	0.7	0.9	0.6	0.6	1.0	0.9	1.0
<b>SiO<sub>2</sub></b>	71.0	54.6	54.3	45.3	55.8	38.9	38.4	47.6	52.4	53.0
<b>P<sub>2</sub>O<sub>5</sub></b>	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.1
<b>SO<sub>3</sub></b>	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.6	1.2
<b>K<sub>2</sub>O</b>	0.4	0.7	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.2
<b>CaO</b>	20.5	33.2	35.4	44.0	33.3	51.4	50.2	41.8	37.7	37.6
<b>Fe<sub>2</sub>O<sub>3</sub></b>	0.4	0.5	0.5	0.3	0.4	0.4	0.4	0.6	0.5	0.5
<b>TiO<sub>2</sub></b>	0.1	0.2	nd	0.1	0.3	0.1	0.2	0.1	0.3	0.1
<b>SrO</b>	tr	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1
<b>Cr<sub>2</sub>O<sub>3</sub></b>	0.1	0.1	0.1	tr	nd	0.1	0.1	tr	0.1	0.1
<b>ZrO<sub>2</sub></b>	tr	tr	tr	tr	nd	tr	Nd	tr	0.1	Nd
<b>PF</b>	5.0	7.7	6.8	6.8	7.0	5.6	7.3	6.1	5.9	4.9
<b>TOTAL</b>	99.9	99.99	100.0	100.0	100.0	99.9	99.9	99.9	100.0	100.0

tr : trace ; nd: no value ; PF: fusion point.

The equivalent curves of SiO<sub>2</sub> and CaO were established with values in percentage, related to core lithofacies of Piedade Beach. The chemical components concentration shows an increase in CaO from the medium to the upper portion of the sedimentary sequence (figure 14).

The percentage of components CaO along the core are generally lower than the value of SiO<sub>2</sub> (71%), in sample 1, corresponding to lithofacies 1 at the base of the core. The lowest value (38.4%), occurs in sample 13 corresponding to lithofacies 3. The highest value

of CaO (51.4%) was detected in sample 11, in the lithofacies 3 and the lowest value (20.5%) detected in the lithofacies 1, at the base. The concentration of CaO at the base of the beachrock demonstrates the early cementation process while high concentration of SiO<sub>2</sub> reflects the framework rich in quartz grain.

The oxic conditions are established due to interstitial water circulation through pore space in the coastline sediments, favoring chemical elements migration through the Holocene stratigraphic sequence. Oxic and anoxic facies conditions are deeply related to grain porosity.

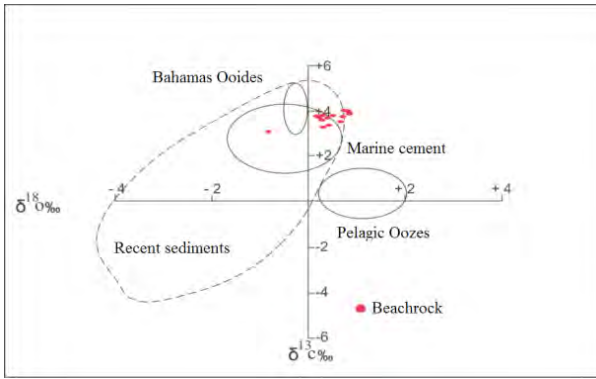


Figure 12: Cross-plot of carbon versus oxygen isotopes from cement of beachrocks as introduced by Moore (2004), including the marine cement fields.

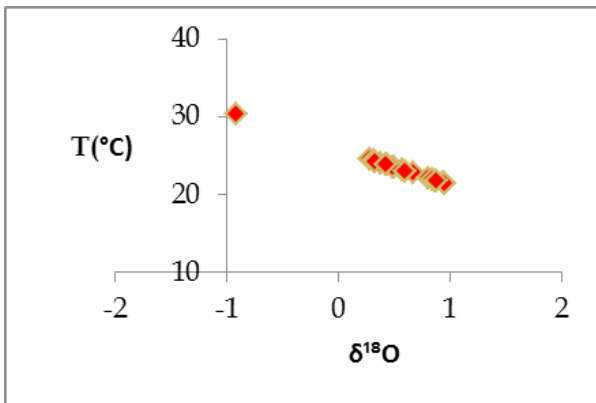


Figure 13: Distribution of temperature and  $\delta^{18}O_{PDB}$  values.

**<sup>14</sup>C DATING**

Using <sup>14</sup>C radiocarbon dating in beachrock encrusted sea shells and using their correlation with beachrock depth sample data in relation to present-day sea level, it is possible to identify marine regressive and

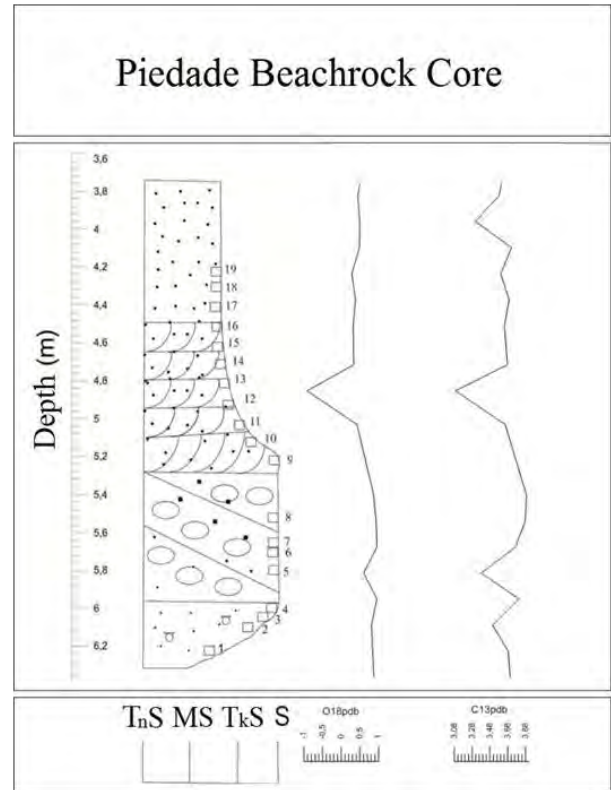


Figure 14: Beachrock core in Piedade and isotopic curves of oxygen and carbon.

transgressive periods. In this work, three samples were dated (samples 1, 3 and 7) with their respective ages calibrated equivalent to 7.509 years B.P, 6.949 years B.P. and 5.982 years B.P, at equivalent depth of -11,58m, -11,27m e -10,10m (table 4).

Table 4: Referent ages to core samples in Piedade Beach dated by shells through <sup>14</sup>Cmethod.

Sample	Deep	<sup>14</sup> C age (ky B.P.)	Calibrated age (ky B.P.)	Calibrated age 1σ (ky B.P.)
AM 7	10.10 m	5655	5982	5924-6041
AM 3	11.27 m	6515	6949	6887-7012
AM 1	11.58 m	7065	7509	7469-7550

Data obtained from <sup>14</sup>C dating in beachrock samples in the Piedade Beach indicate deposition in lithofacies 1 equivalent to core base an older age (7.509 years B.P) and deeperposition in relation to actual sea level (-11.58 m), followed by the younger lithofacies above, showing that from base to core sample 7 the sediments are 1.527 years younger (table 4).

The values related to rises of mean sea level and age data from beachrock samples in the Piedade Beach suggest a Holocene marine transgressive period equivalent to interval of 7.509 years B.P and 5.982 years B.P with sea level depth ranging from -11.58m to -10.10m, indicating sea level 9.18m below present sea level (figure 15).

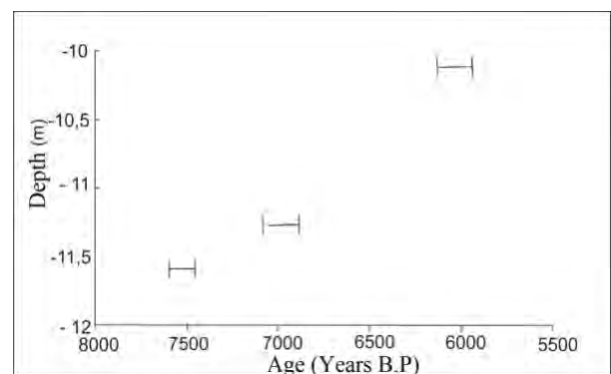


Figure 15: Holocene sea level for the coast of Pernambuco. Symbols cover 1σ range of calibrated AMS radiocarbon ages.



Boica *et al.* (2011) evidenced in the Guanabara Bay in Duque de Caxias region, at Rio de Janeiro, an initial Holocene transgressive period 6.290 years B.P. with value equal to +3.7m followed by a regressive period in 5.250 years B.P. with rise equivalent to +2.1m, indicating a negative oscillation of 1.6m of mean sea level in relation to present-day sea level.

Results obtained from mollusk shells dating from beachrocks in Cabo Frio Beach suggest that a relative sea level variation around 6,0m occurred locally between 13.130 and 11.149 years B.P., marking the transition between the end of the Pleistocene and early Holocene in the coast of Rio de Janeiro state (Castro *et al.* 2012).

### Final considerations

The modern sedimentary rocks in the Piedade Beach are dominated by shoreface and upper beachface facies. Sandstones predominate with grain size ranging from medium to very coarse sand. The cement distribution in beachrock samples indicated the likely origin of these deposits. The concentration of CaO and MgO confirm the early cementation process without clear evidence of biogenic activity. It can be determined through the identification of micritic high-Mg calcite, that the cement is typical of marine phreatic zone.

Isotopic values for carbonate cement ranging from 3.09‰ to 3.89‰ for  $\delta^{13}\text{C}_{\text{PDB}}$ , with average of 3.63‰, and from -0.91‰ to 0.96‰ for  $\delta^{18}\text{O}_{\text{PDB}}$ , with average of 0.54‰, indicates marine origin for cements. According to carbonate cement Z parameter average of 135,0 indicate marine environment formation.

Interpretation of the  $^{14}\text{C}$  dating results, associated with lithofacies relations permitted conclude that Piedade Beach suffered a transgression between 7.509 years B.P. and 5.982 years B.P., also identified in seal level curve elaborated for Pernambuco state.

Urban progressin Pernambuco coast, mainly at Piedade Beach, validates the scientific research to accomplish future scenarios that relate Holocene evolution of this marine coast. The scientific research of beachrocks may contribute to the prevention measures against “sea level advances” and erosive processes if included in the coastal management of Pernambuco beaches.

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