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Beachrocks of the northeast of Brazil: local effects of sea level fluctuations in a far-field during in Holocene

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Abstract

Along the coast of the state of Pernambuco, NE Brazil, the presence of coastal outcrops aligned with the shoreline and distributed above and below the mean sea level is remarkable. These outcrops were sampled, and petrological, isotopic, and geochronological analyses were integrated to investigate the local effects of the Holocene sea-level fluctuations. The results indicate that the rocks are recent (< 8ka), formed by cementation of beach sands (magnesian calcite cement, predominance of quartz and presence of marine bioclasts, signs of compaction, fractures, and dissolution), in a tropical climate and warm waters, which allows to classify them as typical examples of beachrocks. The carbonate cement consisted of Mg-rich calcite with values ranging from −1.1‰ to 3.5‰ for $\delta^{13}C$ and from −0.9‰ to 0.5‰ for $\delta^{18}O_{VPDB}$. These isotopic values are typical of marine carbonate cemented deposits in shallow marine environments under freshwater influence (meteoric vadose environment). In these conditions, the cementing processes occurred in the intertidal zones, which reinforce the use of these data as indicators of ancient sea levels. The sea level fluctuations could be divided, in chronological order, into three different phases, starting with a rapid sea level rise followed by a relative stabilization at a maximum level and, finally, a decreasing phase. Recent sea level fluctuations in Pernambuco are represented by beachrocks with ages between 8 ka and 800 years and a maximum level of 2 to 3 meters above the present mean level. In scenarios of a near future with a general global sea level rise pattern, significant local geomorphological changes may occur, which means a great future challenge to society.

Keywords: Beachrocks, Sea level fluctuation, Holocene, Radiocarbon dating

INTRODUCTION

Holocene sea level fluctuations yield unique datasets of earth's climate and ice sheet evolution. Those fluctuations were responsible for changes in patterns of sedimentary accumulation as the sea invaded ancient fluvial plains and flooded coastal areas that became the modern continental shelves (Blum et al., 2013; Harris et al., 2014). This period is characterized by global warming, the end of the last glaciation, and an increase of the sea level around the ocean basins. The Last Glacial Maximum (LGM) was marked by a huge volume of continental glaciers, which resulted in a sea level fall of about 120 meters below the current level (Yokoyama et al., 2000; Clark et al., 2009). After, it is estimated that, in an interval of approximately 20 thousand years, the sea level

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has undergone a rapid increase until reaching the current level (Droxler and Jorry, 2013).

Several indicators are used in the reconstruction of Holocene regional sea level curves, such as vermetids, wood fragments, and shell middens. These reconstructions are based on isotopic analyses, and data from several regions of the world are already abundant. Shell fragments sampled from beachrocks are another excellent indicator of sea level fluctuations. They were used in regions such as Saudi Arabia (Ghandour et al, 2021), Canary Islands (Calvet, 2003), Japan (Omoto, 2001), Portugal (Moura et al, 2007), Turkey (Erginal et al, 2010, 2012), Greece (Psomiadis et al, 2014), and northeast of Brazil (Bezerra et al, 2003; Caldas et al, 2006). The beachrocks indicate the position of the coastline in the past and are therefore used not only in the construction of fluctuation curves, but also in the characterization of paleotemperatures and other paleoenvironmental conditions prevailing during the diagenesis of these sedimentary rocks (Vousdoukas et al, 2007, Stattegger et al, 2013, Castro et al, 2021, Malta et al, 2021).

In the northeastern Brazil, the pioneering initiatives for the reconstruction of sea level fluctuations in the Holocene were conducted by Van Andel and Laborel (1964) and Delibrias and Laborel (1971). These seminal works determined the age of shells, vermetids, and corals by radiocarbon dating. These ages ranged from 5.9 ka BP to 1.1 ka BP. In addition, the results also indicated that the relative sea level reached its maximum position 3.6 ka BP ago, with a maximum height of 2.6 m above the current sea level. From this level, a progressive and gradual sea level fall began until the current average level. In almost half a century, despite the methodological and instrumental improvements, there were no initiatives of radiocarbon dating in local scale. This work revisited the Pernambuco coast to investigate the Holocene sea level fluctuations, using more precise and accurate instruments and techniques.

Usually, radiocarbon dating and isotopic analysis allow inference of paleoenvironmental conditions related to beachrock formation, plus the improvement of evolutionary models and predictive analyses (Lambeck et al., 2014; Stattegger et al., 2013). Beachrocks are hard coastal sedimentary formations consisting of beach sediments, lithified by the precipitation of carbonate cements on the foreshore (Vousdoukas et al., 2007).

Beachrocks form in the subsurface of beach sediments, usually at about 1 meter below the surface. Thus, they are considered as a natural indicator of different coastline positions in the past and are therefore used in the construction of sea level fluctuation curves (Bezerra et al., 2003; Caldas et al., 2006; Calvet et al., 2003; Danjo and Kawasaki, 2014; Erginal et al., 2010, 2012; Moura et al., 2007; Omoto, 2001; Psomiadis et al., 2014).

Note that the age values do not correspond to the exact moment of formation of the beachrocks, since the material submitted to dating is generally composed of biological carbonate material previously deposited in the intertidal areas of the beaches. Despite this limitation, beachrocks dating shows satisfactory data on sea level behavior (Simioni et al., 2018, Castro et al, 2021, Malta et al., 2021).

From a current perspective, beachrocks exert influence on inherent processes of coastal morphodynamics, since they mitigate coastal erosion and protect the coast from more energetic events by dissipating wave energy along the coast (Costa et al., 2019, 2017). However, discontinuous beachrocks also can promote sediment transport offshore (Cooper, 1991).

Shell fragments sampled from the interior of the beachrocks are also excellent indicators of environmental conditions during their formation. Techniques such stable isotope analysis allow to characterize the paleotemperatures and other paleoenvironmental conditions prevailing during the formation of these sedimentary rocks (Stattegger et al., 2013, 2006; Vieira et al., 2017, 2007, Malta et al., 2021).

Along NE Brazilian coast, beachrock research determined the age of shells, vermetids, and corals by radiocarbon dating and the ages ranged from 5.9 ka BP to 1.1 ka BP (Dominguez et al., 1990; van Andel and Laborel, 1964, Angulo and Souza, 2014). The results also indicated that the relative sea level reached its maximum position around 3.6 ka ago, with a maximum height of 2.6 m above the current sea level. From this maximum level onwards, a progressive and gradual drop in sea level to the current mean sea level began, named the Holocene Regression.

On a regional scale, Suguio et al. (1985) showed many sea level fluctuation curves for the last 7.0 ka, along segments of the Brazilian coast. According to them, the relative sea level would have reached 5 m above the current sea level approximately 5.1 ka BP ago. Due to this amplitude, this transgressive phase was responsible for modeling the current morphology of the Holocene coastal plains that occur along the Brazilian continental shelf.

This work presents new data related to them, with techniques such as Scanning Electron Microscopy (SEM), X-ray analyses, stable oxygen and carbon isotopes, and radiocarbon dating. Here we present and discuss a local petrological characterization, the beachrock diagenesis, and the spatial distribution of ages along about 80 km of the coast of Pernambuco, which allowed the adjustment of Holocene sea-level fluctuations.

The manuscript compiles the up-to-date data concerning the essential characteristics of the beachrocks along the Pernambuco coast, NE Brazil. Analytical techniques have allowed to infer the environmental conditions and ages of these sedimentary rocks whose occurrence and level relative to the current sea level subsidize the knowledge about the variations of sea level in the Holocene, allowing the calibration of a local curve. This initiative intends to contribute to future investigations on such sedimentary features.

METHODS

Regional Setting

The climate is tropical with high humidity and a very defined dry season, a short period during September and December. The annual air mean temperature ranges from 25°C to 30°C. Annual mean precipitation is around 2000 mm (UFPE, 2009).

In this region, the tides are classified as semidiurnal, with a mean spring and neap tidal range of 2.07 and 0.97 meters, respectively. From September to February, southeast winds with average speeds of 2.6 m/s to 4 m/s prevail (UFPE, 2009). Weaker east-northeast winds are more frequent during November and December. The offshore wave climate is mainly controlled by the trade winds, with east-southeast dominance, though during fall and winter, waves from the south also occur.

The surface waters on the continental shelf have a mean temperature of 27.0°C to 28.7°C. Salinity also has a seasonal cycle similar to temperature, with higher values in dry periods, maximum of 37.16‰, and lower values in the rainy season, minimum of 28.88‰ (UFPE, 2009). These values, like temperature, show fluctuations close to the coast due to the influence of the contribution of the coastal rivers.

The largest supply of fine material to the inner platform occurs during the winter period. Some determinations on the internal platform adjacent to Recife presented values up to 4.5 mg/l (Coutinho, 1994).

In Pernambuco, NE Brazil, coastal outcrops are an evident element of the coastal and marine geobiodiversity, representing a striking feature in the landscape (Camargo et al., 2015). Its importance is such that the name of the state capital is "Recife," which means 'reef' in Portuguese. The study area lies around 8°S, comprising 147 km (91,3 miles) of extension (Figure 1), and is inserted in a distended marginal domain of Pernambuco Basin, one of the basins of the eastern continental margin of Northeastern Brazil that is considered the last link between Africa and South America (Rand and Mabesoone, 1982).

In general, these sedimentary rocks are parallel to the shoreline and are predominantly linear, with widths up to dozens of meters in discontinuous segments and with a maximum extension around 1 km (Figures 2 and 3). The sedimentary layering has an average tilt of 10° towards the sea. Intertidal sedimentary rocks are noticed in the shallower parts, and are exposed during low tides, whereas deeper lines remain completely submerged at the greater depths (Mabesoone, 1964; Laborel, 1970).

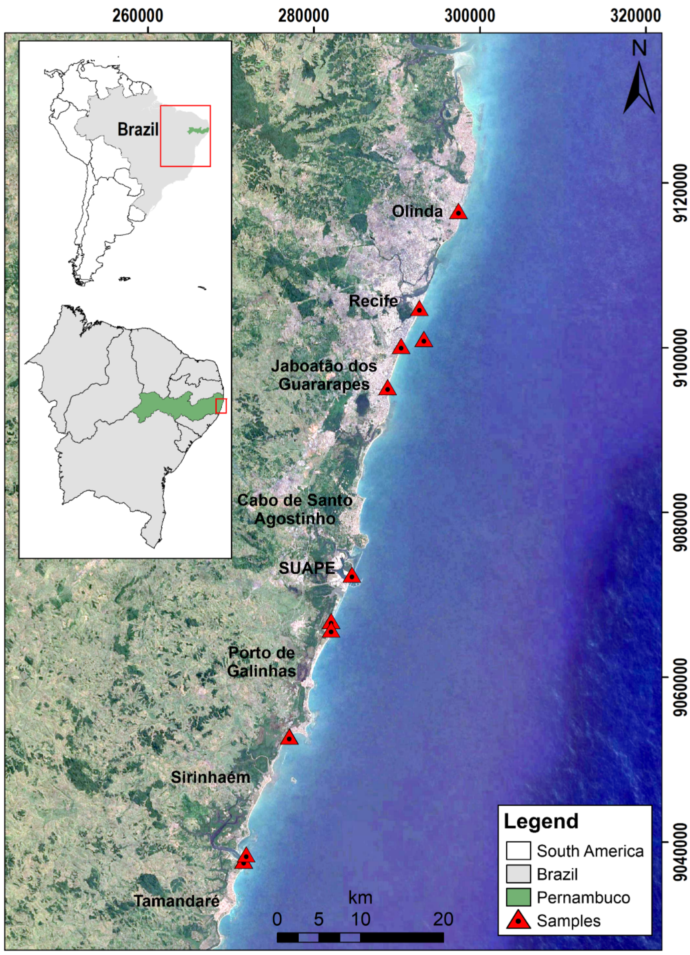

Figure 1. Location of the study area and the rock samples.

Figure 2. Three lines of beachrocks on Pina and Brasília Teimosa beaches. The referred beaches are located in Recife, PE.

Figure 3. Oblique aerial photography of beachrocks on Piedade beach. Piedade Beach belongs to the city of Jaboatão dos Guararapes, PE.

The sedimentary structures can be compared with the modern beaches, with the occurrence of low angle cross and cross-fluted stratifications. In the region, conditions were and still are favorable for reef ecosystems to develop on top of these hard substrata, and they can also occur as individual pinnacles that extend laterally at the top (Castro, 2001; Laborel, 1970). The landscape imposed by the presence of these rocks favored human occupation, since these natural environments have been related to human activities (fisheries, tourism, maritime traffic, coastal protection).

Sampling

Beachrock outcrops have been sampled at the highest level containing suitable shell fragments, always from the intertidal upper level. All sample points were expressed as elevation above or below mean sea level by correcting for tidal effects concerning the water level at the time of sampling. A total of 38 rock samples and 17 samples of levels relative to actual mean sea level were collected by standard geodetic methods using a theodolite and a DGPS. Such values were obtained for later correction, according to the tide tables of Recife and Suape Harbors.

Petrological Characterization

At the Laboratory of Electron Microscopy Scanning of the Geosciences Institute at the University of Kiel, Germany, the rock samples were examined using standard microscopic techniques with a CanScan CS-44 model. Scanning Electron Microscopy (SEM) allows us to observe details of the textural characteristics of the carbonate cement. The X-ray analysis (EDX) permitted a detailing of the analyzed material, such as the relative concentration of some chemical elements.

Isotopic Analysis

The analysis of stable oxygen and carbon isotopes were carried out in the Stable Isotope Laboratory (LABISE/UFPE) in the Federal University of Pernambuco, Brazil. A total of 27 bulk-rock samples, selected based on the large quantity of cement enclosing the grains, were assayed for $\delta^{13}C$ and $\delta^{18}O$ isotopic composition. To avoid bioclastic contamination, shell fragments were gently scraped off the samples. Between 20 and 50 mg of powdered samples were reacted with 100% orthophosphoric acid, in a high vacuum line, at 25°C, for one day. The CO_2 released during the reaction was extracted in a high vacuum line, employing cryogenic purification, according to Craig (1957). The obtained results are reported in parts per thousands (‰) respecting the international standard VPDB (Vienna PeeDee Belemnite).

The original environment of rock cement was determined by its isotopic composition of carbon and oxygen. To this end, the model proposed by Moore and Moore (2014) was adopted, which shows the isotopic compositions of C and O typical of marine origin described by the Z parameter proposed by Keith and Weber (1964), which highlights the differences between marine carbonates (Z > 120) and freshwater ones (Z < 120), which is calculated from the equation:

$$Z = a(\delta^{13}C + 50) + b(\delta^{18}O + 50)$$

Where a = 2.048 and b = 0.498

In addition, the water paleotemperature was determined using the equation of Irwin et al. (1977):

$$T = 16.9 - 4.21\ (\delta c - \delta w) + 0.14\ (\delta c - \delta w)\ 2$$

Where ($\delta c - \delta w$) is the mean difference of the measure of $\delta^{18}O_{VPDB}$ of the calcite and water.

Radiocarbon Dating

Well preserved shells were carefully collected to obtain the depositional ages of beachrocks. In the laboratory, the bivalves were removed from the indurated beachrock pieces using dentist drilling. Afterwards, every carbonate sample chosen for dating was analyzed by X-ray diffraction to detect possible alteration of the original shell composition. Recrystallized samples showing ≥ 10% of replacement of aragonite by calcite were disposed. Thus, 17 bivalves were dated to determine ages and relative levels along the Pernambuco coast.

The 14C concentration was detected by a mass spectrometer with an accelerator (AMS) model 3MV HVEE Tandentron 4130 in Leibniz Laboratory at the University of Kiel in Germany. A standard procedure was applied (Nadeau et al., 2001; Schleicher et al., 1997). The radiocarbon ages obtained from marine material were converted from 14C into calendar ages using a marine calibration curve (Reimer et al., 2009) and were presented with a confidence interval for each age dated.

The beachrocks in the intertidal positions were distributed among elevations from −0.35 to 2.1 meters related to current mean sea level, whereas in the inner continental shelf, the samples were collected at depths of −5.8 and −5.3 meters above the current mean sea level.

RESULTS

Petrological Characterization

In general, the samples had a loose packaging (Kahn, 1956), with the predominance of floating grains immersed in the matrix and/or cement (Figure 4A). Concerning the mineralogical composition, monocrystalline quartz (30% to 77%) predominated over polycrystalline quartz (1% to 50%). Feldspar grains were also present in almost all samples examined, with a concentration around 5%, represented mainly by plagioclase with iron hydroxide (Figure 4B, arrows). Heavy mineral occurrence was small, representing no more than 4.5% of the volume and with a predominance of opaque, tourmaline, garnet, epidote, and zircon (Figure 4C). Bioclasts were represented by benthic and planktonic fossils related to inner continental shelf environments. Their contribution varied between 0.5% and 9.5% of the framework and included bryozoans, gastropods, bivalves, foraminifera, red algae, and echinoidea.

The lithology of samples varied between medium to very coarse and conglomeratic, with finning upward. Generally, they presented rounded quartz grains, moderately selected, quite fractured, and with corroded edges (Figure 4E). Finally, the samples also indicated some partial dissolution of quartz grains as a remarkable characteristic. The predominant classification related to the porosity was defined as an interparticle type filled by magnesian calcite (Figure 4F).

The cement was composed exclusively of highly magnesian calcite crystals, which partially or completely fill the inter and intragranular spaces. The crystals were mostly rhombic, with diameters between 4 and 30 μm. There were also monocrystalline quartz grains encrusted by red algae involved by a fringe of prismatic crystals (Figure 5A)

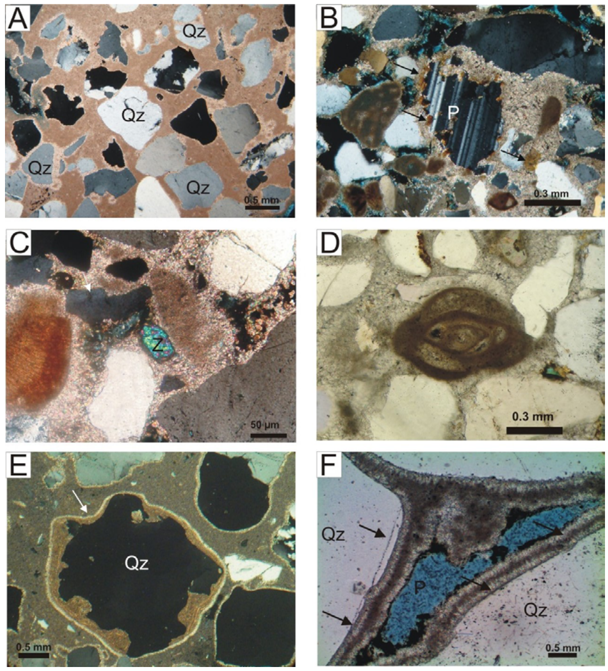

Figure 4. Analyzed rock samples. (A) Abundant presence of grains of quartz (Qz), immersed in the matrix. Crossed polarizers (PX). (B) A plagioclase grain (P) involved by carbonate cement and iron hydroxide (arrows) (PX). (C) Zircon grain (Z) (PX). (D) Presence of an exemplar of a foraminifera. Parallel polarizers (P//). (E) A monocrystalline quartz grain (Qz) encrusted by red algae and surrounded by a fringe of prismatic crystals (arrow) (PX). (F) Two prismatic crystals fringe generation separated by a micritic cuticle (arrows).

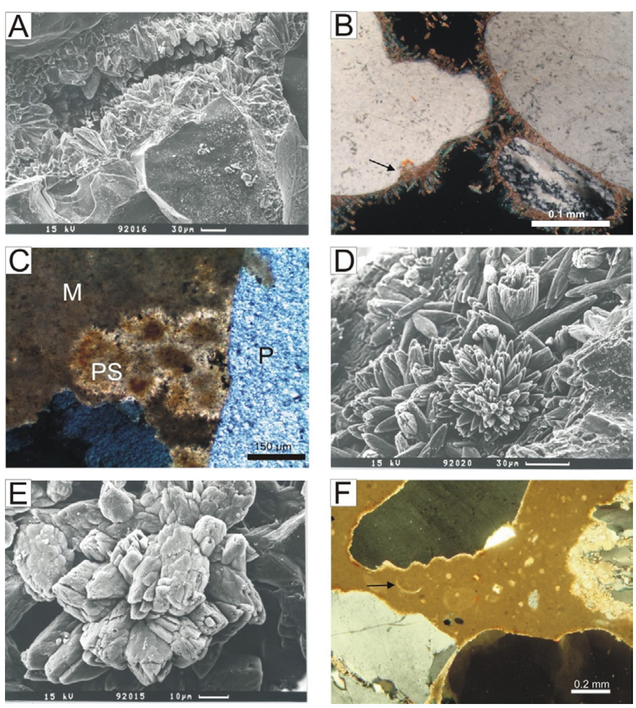

Figure 5. Analyzed cement. (A) Fringe of prismatic crystals, regular and isopach, with dimensions between 5 and 50 µm, around the quartz grains. Observe the sub perpendicular orientation of crystals with respect to quartz grains. The image was obtained using Scanning Electron Microscope (SEM). (B) Fringe of sub-perpendicular to chaotic prismatic crystals around the grains and iron hydroxide film involving the quartz grains (arrow) (PX). (C) Pore space (P) held by pseudo-peloidal aggregates (PS) and micritic cement (M) (PX). (D) Fibrous-radial aggregates arranged around the grains with the size, on average, of 60 µm (SEM). (E) Detail of equigranular crystals occupying the pore space (SEM). (F) Infiltrated marl occupying pore space with the presence of shell fragment (arrow) (PX).

The cement showed various habits and shapes (Figure 5). The main forms found were:

Cryptocrystalline cuticle: This type of texture was represented by an average of 2.5% of the total frequency in the analyzed samples, with a maximum volume of 6.3%. This cement was predominantly discontinuous with a varied thickness between 10 to 120 µm. Moreover, cryptocrystalline cuticle involved, more frequently, the siliciclastic grains, and less so, the bioclastic ones, and is covered by an isopach fringe (Figure 4F).

Isopach prismatic fringe: This texture was represented by 3.6%, on average, of the total frequency in the samples analyzed, with a maximum value of 7.5%. In general, the fringe had very regular isopach shape, but the prismatic crystals may be sub-perpendicular around the siliciclastic grains (5A and 5B), whereas in bioclastic ones, they were mostly perpendicular to the surface. Some samples also showed isopach fringes only around bioclasts. The absence or truncation of the prismatic crystals is due to both freshwater dissolution and disruption of its growth at the interface water-air, in the vadose zone (Neumeier, 1999).

Pseudo-peloidal aggregates: These shapes were associated mainly with the micritic cement and the isopach fringe. They were present in nearly half of the samples analyzed, representing, on average, 4.5% of their total volume, with a maximum of 14.5%. The pseudo-peloidal aggregates analyzed here presented a very sparse and varied arrangement and can completely fill the intergranular spaces. They were spherical to subspherical in shape, with 40 to 100 µm in diameter.

Radial fibers aggregates: These shapes were represented by 2% of the total volume analyzed, with a maximum of 5%. Radial fibers aggregates were identified only in a few samples, arranged radially from the core, and usually isolated or associated with pseudo-peloidal cement or equigranular crystals (Figures 5C and 5D).

Micritic cement: This cement category was identified in over 60% of the samples, representing 9% of the total volume, with a maximum of 22%. Its texture appears as a homogeneous dark mass, filling the intra- and inter-granular spaces. The micritic cement consisted of microcrystalline crystals with a maximum of 4 µm and small impurities formed mainly of small detrital grains (Figure 5C).

Equigranular cement: This cement category represented 6% of the total volume, with a maximum of 14%, and the microcrystalline size was predominant. In general, it was formed by aggregates of anhedral and subhedral crystals of calcite which fill the pores completely, in the form of meniscus or pendulous cement (Figure 5E).

Infiltrated marl: It comprised, on average, 14% of the constituent material in the samples with a maximum value of 25%, consisting of bioclasts (including planktonic), followed by detrital grains (mainly quartz), floating in a mixture of clay and micrite. It had a massive structure, filling the interparticle porosity and, in some cases, the intraparticle pores of bioclasts (Figure 5F). Its possible occurrence in the form of meniscus or pendulous cements is indicative of deposition in a marine vadose environment, as pointed out by Longman (1980).

Cement Δ^{18}O And Δ^{13}C Isotopic Analyses

The isotope ratios obtained from the cement (magnesian calcite) suggest an original environment compatible with the expectations (Table 1). Usually, cement formed in marine environments has $\delta^{13}C$ and $\delta^{18}O_{VPDB}$ values close to zero, whereas those formed in the freshwater environment have more negative values – between −5‰ and −15‰ for $\delta^{13}C$ and between −5‰ and −10‰ for $\delta^{18}O_{VPDB}$. Simioni et al., (2018) compile results with different signatures: marine cements, recent sediments, methane derived cements, early concretions, and meteoric cements. Therefore, the cements here were likely formed in a marine environment, which points in the direction of confirming the classified sedimentary rocks as beachrocks, originating from diagenesis in subsurface forefaces.

Table 1. Obtained values of stable isotope ratios of $\delta^{13}C$ and $\delta^{18}O$

Isotope ratios (‰)	Beachrocks	Minimum	Maximum	Mean
$\delta^{13}C$	Submerged	3.1	3.4	3.3
	Emerged	−1.1	3.5	2.5
$\delta^{18}O$	Submerged	0.1	0.5	0.4
	Emerged	−0.9	0.4	0

After obtaining the $\delta^{13}C$ and $\delta^{18}O$ values, they were used to calculate the Z parameter (Keith and Weber, 1964), a numeric interval of values useful to categorize the samples as derived from saltwater or freshwater environments (Moore and Moore, 2014). The Z values obtained from the samples analyzed are between 124.56 and 134.51 (average value of 132.6), also indicating conditions for beachrock formation in a tropical marine environment.

Based on these results, the water temperature in which carbonates precipitated could be determined, from their oxygen isotopic composition, with the principle of the exchange reactions between the oxygen of calcium carbonate and seawater, from which it was precipitated under conditions of equilibrium. The paleo temperatures deduced from the cement of the submerged beachrocks varied from 22.8°C to 24.2°C, whereas it ranged from 22.9°C to 28.2°C for emerging ones, which are values compatible with the current air and seawater temperatures in the area.

Radiocarbon Age Control

Each rock sample (n = 17) represented a source of important local effects of sea level fluctuations along the Holocene: rock ages derived from shells and rock levels related to current mean sea level (Table 2).

Table 2. Rock ages obtained by collected samples

SAMPLE	LEVEL (m)	CONVENTIONAL ^{14}C AGE	CALIBRATED ^{14}C AGE (Years B.P.)	AGE CONFIDENCE INTERVAL (Years B.P.)
1	0.1	2825	2528	2609-2449
2	−0.35	1345	848	898-804
3	−5.8	7460	7884	7935-7834
4	−5.3	7525	7946	8005-7873
5	0.89	5865	6245	6284-6200
6	0.4	5820	6209	6258-6173
7	−0.31	6145	6534	6599-647
8	0.19	1515	1019	1059-963
9	−0.3	6700	7199	7141-7528
10	−0.1	5520	5847	5775-5919
11	−0.1	5515	5844	5777-5912
12	2.1	5210	5526	5470-5583
13	1.97	5400	5721	5648-5795
14	0.4	6200	6591	6514-6668
15	−0.1	5255	5579	5516-5642
16	0.4	6140	6533	6461-6606
17	0.6	6015	6378	6313-6443

The results show the differences between beachrocks above and below the present mean sea level. The ages of samples from the radiocarbon dating ranged from 7.9 ka BP to 848 years BP, which allowed for determining the sea level fluctuations since the Middle to Late Holocene.

The oldest ages (7.9 ka BP and 7.8 ka BP) indicated that the formation of submerged beachrocks dated from the middle Holocene, when the sea level was around 4 meters lower than the current one. The youngest-aged rocks (1013 and 848 years BP) were positioned at levels of 0.1 and −0.35 meters, and were considered records of a recent regression to a high-stand level of around 2 to 3 meters. The results showed a 6-meter sea level fluctuation in an interval of 8 thousand years, despite the gap between 5.5 and 2.5 ka BP, and levels around 2 and 0.2 meters.

DISCUSSION

The results were discussed below based on the following assumptions: I. coastal outcrops arranged in lines parallel to the coast are not necessarily beachrocks (Simioni et al., 2018); II. coastal outcrops resulted from intense sediment remobilization due to sea level fluctuations (Vousdoukas et al., 2007); III. ages obtained by the radiocarbon dating method do not necessarily represent the period of beachrocks diagenesis; and IV. local effects of sea level fluctuations are the result of the integration of eustatic, isostatic, and tectonic processes (Angulo and Souza, 2014).

Petrological analysis permits classifying the samples as beachrocks, reinforcing some previous studies (Dominguez et al., 1990; Laborel, 1970; van Andel and Laborel, 1964). These samples have similar characteristics to others in northeastern Brazil: magnesian calcite cement, quartz predominance, and presence of marine bioclasts, signs of compaction, fractures, and dissolution (Caldas et al., 2006; Guerra et al., 2005; Ferreira Júnior et al., 2011; Vieira et al., 2007). The occurrence of plagioclase with iron hydroxide associated with feldspar grains can be attributed to the Barreiras Formation, commonly outcropping on the Pernambuco coast.

Regarding the paleoenvironment of rock formation, the isotopic composition (C and O) suggested carbonate precipitation in a tropical marine environment (Milliman et al., 1974). The estimated paleotemperatures as well as the isotopic compositions can be interpreted as typical signatures of tropical beachrocks, leaving no doubt about the nature of these coastal outcrops in Pernambuco.

Vieira et al. (2017) presented the values for $\delta^{13}C$ from −7.80‰ to 3.57‰, and for $\delta^{18}O_{VPDB}$ from −4.41‰ to 0.54‰ for beachrocks cement in the Rio Grande do Norte coastline. According to the author, the data revealed a uniform isotopic signature, which may be interpreted as a reflection of the homogeneous cement composition (highly magnesian calcite) as well as by the uniformity of the physical and chemical parameters that control the rocks, checked in the small range of paleotemperature values (from 23.3°C to 34.9°C).

The confirmation about their nature allowed us to consider Pernambuco's beachrocks as indicators of ancient sea levels, both in the time and space domains. Evidence of sea level fluctuations around the world is not a recent issue (Angulo and Souza, 2014). However, only with the advent of radiocarbon dating techniques and the improvement of glacial isostatic models that sea level fluctuation curves could be reconstructed and estimated, mainly for the Quaternary period of the Cenozoic era (Farrell and Clark, 2007; Lambeck et al., 2014; Mitrovica and Milne, 2002; Nakada and Lambeck, 1989; Pirazzoli et al., 1988; Walcott, 1972).

Data from several locations around the world have indicated that the curves of Quaternary sea-level fluctuations show no definitive, universal trend. According to Nakada and Lambeck, (1989), these spatial and temporal variations in sea level are produced by ice melting in the late Pleistocene as well as by the Earth's response to redistribution in surface loads. In this context emerged the concept of far-field regions, in which Late Holocene sea-level high-stands of amplitude equal to 3 meters are endemic and linked to the process of glacial isostatic adjustment (Clark et al., 1978). Unlike regions near continental glaciers (high latitudes in northern hemisphere), where continental shelf uplift was common during the Holocene, in the far-fields (low latitudes near Equator), a pronounced sea-level advance followed by regressive pulses were documented (Mitrovica and Milne, 2002; Mitrovica and Peltier, 1991). This regressive trend in sea level has been a paradigm for an eustatic approach since climate records indicate a progressive warming and continuous retreat of continental glaciers.

Other dates for the Brazilian coast have a more representative rise during this time interval, in a maximum transgression of around 5.1 ka BP, as shown by Suguio et al. (1985), Martin et al. (2003), Bezerra et al. (2003), Caldas et al. (2006), and Castro et al. (2021). However, Angulo and Lessa (1997) stated that the maximum sea level, at the end of the marine transgression, was between 3.5 m and 4 m at most. This rise characterizes a transgressive phase, which was observed in other regions around the world.

On the coast of Rio Grande do Norte, Caldas et al. (2006) showed the maximum rise in sea level by 2.8 m by dating a beachrock shell, aged 5.7 ka BP. However, Stattegger et al. (2006) warns that Brazil has sea level curves built during the Holocene without calibration, which may explain the difference in age.

The development on this topic was an interdisciplinary process of knowledge advancements related to: 1. direct sampling (deep-sea cores and rock samples) (Yokoyama et al., 2019, 2018); 2. indirect sampling (geophysical surveys of the seafloor surface and subsurface) (Desruelles et al., 2009, 2004; Moura et al., 2007); and 3. isostatic and eustatic adjustment geophysical models (Milne et al., 2005, 2002; Peltier et al., 2002).

CONCLUSION

The beachrocks have values of 60% to 85% of the framework composed of detrital grains of quartz. The carbonate cement found in the samples is composed of calcite rich in Mg. The diagenetic sequence was recognized and composed of cryptocrystalline coating; prismatic fringe isopachs; pseudo-peloidal aggregates; radial fibers aggregates; micritic cement, and equant cement. Besides these cementing phases, infiltrated marls were identified. Results from isotopic concentration of carbon and oxygen from the cements of the beachrocks studied presented values of −1.12‰ to 3.52‰, for $\delta^{13}C_{PDB}$ and −0.9‰ to 0.5‰ for $\delta^{18}O_{VPDB}$, respectively. Most isotopic values (93.75% of total) are correlated to marine cement. Only one sample of beachrock cement showed a value outside the range of recent sediments. These data indicate that the cement precipitation occurred in a shallow marine environment under the influence of fresh water from the vadose meteoric environment, which shows that the beaches were cemented in the intertidal zone.

The paleotemperature of the submerged beachrocks ranges from 22.8°C to 24.2°C. This variation is related to increased depth and indicates that the paleotemperature of the water remained relatively constant during the cementing process of the beachrocks. In the study area, the beachrocks are indicators of sea level and, from them, reconstructing this level from the Holocene is possible.

The change of morphology of the seabed is an important record of recent geological history in the study area. Thus, regarding the beachrocks, this change can be observed by radiocarbon dating, which indicates the sea level was lower than the current one. In the studied area, the beachrocks are indicators of the sea level in the Holocene. Two distinct phases were recognized: the transgressive and regressive. In the first, the sea level rises from 7.9 ka BP up to the maximum elevation, which occurred 6.2 ka BP ago, with a sea stability period between 7.0 ka BP and 5.6 ka BP. The second phase was characterized by the reverse sequence, from 5.0 ka BP causing the descent of the sea level. At that stage, there was the exposure and the formation of the current erosional features of the beachrocks of the studied area. Compared with other studies of fluctuation in the sea level during the Holocene on the northeast coast of Brazil, this study revealed some changes, in particular, the significant record of the transgressive phase which occurred 7.9 ka BP ago.

As a low-latitude coastline (8°S) in a tropical climate, Pernambuco (NE Brazil) was a region conducive to the formation of beachrocks that spatially follow the sea level fluctuations of the last 8,000 years. The profuse occurrence of beachrocks determined favorable conditions for human development. The beachrock structures were and are a source of food resources, they protect the coast, and, in many places, their presence provides natural harbors at low tide. Formed by the cementation of beach sands in tropical climate and marine conditions with tropical waters, the beach sandstones of Pernambuco are classic examples and record the local effects of sea level fluctuations in the recent past.

Future investigations could focus on issues relating to the circumstances of the transportation and deposition of sediments that help in the formation of beachrocks, extend geophysical records on the continental shelf, as well as reconstructs sea level throughout the whole state of Pernambuco, with a view to enhance the knowledge about the sea level during the Holocene.

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AUTHOR CONTRIBUTIONS

A. V. F. J.: Conceptualization; Writing Original Draft; Formal Analysis; Methodology; Visualization; Writing-Review & Editing.

J.M.R.C.: Methodology; Writing-Review & Editing.

K.S: Formal Analysis; Methodology; Writing-Review & Editing.

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