Quaternary Research 77 (2012) 251–257

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Holocene and Pleistocene sea-level indicators at the coast of Jericoacoara, Ceará, NE Brazil

Georg Irion [a,*], Jáder Onofre de Morais [b], Friederike Bungenstock [c]

[a] Senckenberg Institute of Marine Science, Suedstrand 40, 26389 Wilhelmshaven, Germany
[b] State University of Ceará/PROPGEO/LGCO, Av. Paranjana, 1700 – Campus do Itaperi – 607 40–000 Fortaleza, Ceará, Brazil
[c] Lower Saxony Institute for Historical Coastal Research, Victoriastrasse 26, 26382 Wilhelmshaven, Germany

ARTICLE INFO

Article history:
Received 3 January 2011
Available online 21 December 2011

Keywords:
Brazil
Ceará
Sangamonian
Holocene
Sea level
Beach rock
Notches

ABSTRACT

Beach-rock exposures provide a record of Holocene sea-level rise along the 560-km-long northeast-facing coast of Ceará, Brazil, that differs from the record available along the other 4300 km of Brazilian coastline further south. Whereas documentation is available from southern Brazil to show Holocene sea levels as much as 5 m above today's level, our observations along the northeastern coast indicate that sea level here was not above the present-day level during the Holocene. Near Jericoacoara, about 240 km northwest of Fortaleza, characterized by strong surf, Precambrian rocks crop out from under a temporary cover of sand in small protected locations with less surf. Here in this upper tidal zone beach rock is being formed, while it is being dismembered synchronously by erosion at lower tide levels. This shows a rising sea level. Along the entire coast of Ceará west of Ponta Grossa the absence of beach rock higher than spring tide level indicates that sea-level was not above its present-day level during the Holocene.

Notches in bedrock situated between 2 m and 6 m above spring-tide high-water level that we formerly described as Holocene, are now believed to be Sangamonian.

Introduction

Worldwide there are different regional sea-level changes since the last glacial maximum (LGM). Along the northern Canadian coast, for example, sea level has been falling throughout the Holocene due to the glacial rebound of the crust after the last glaciation (Peltier, 1988). This is comparable to the development in Scandinavia (Lambeck et al., 1998; Steffen and Kaufmann, 2005) where sea level drops today, e.g. near Tuku/Finland, 0.5 cm/a (Eronen et al., 2001).

Along the North American coast from about the Bay of Fundy/Canada to New York/USA sea level fell at the beginning of the Holocene, and started to rise about 8000 yr ago (Peltier, 1988). The same development has been recorded for Scotland (Shennan, 1987).

From about Virginia/USA to Mexico there is a constant sea-level rise similar to the Holocene sea-level development of the southern North Sea (e.g. Jelgersma, 1979; Vink et al., 2007).

In Middle America and Southern America, along the coasts of Belize, Cartagena/Columbia and Caracas/Venezuela, sea level rose between the beginning of the Holocene until 6000 yr ago, reaching a level higher than today (Wu and Peltier, 1983). Subsequently, sea level has been falling until today. This corresponds to published data of the Brazilian coast: From the border of Ceará/Rio Grande do Norte down to Patagonia, indicators of Holocene sea level point to a level that was up to 5 m higher than today's mean sea level (Suguio et al., 1985; Martin and Suguio, 1992; Angulo et al., 1999;, Martin et al., 2003; Caldas et al., 2006a,b). Similar curves have been reported on the other side of the Atlantic in Morocco and Mauretania (Wu and Peltier, 1983). These findings correspond to the model of Mitrovica and Milne (2002).

The question arises whether this situation is the same along the coast of Ceará state. Meireles et al. (2005) describe many structures such as marine terraces, abrasion flats and former cliffs on the Ceará coast, but the ages of these morphological features are still unknown. The coasts of Ceará are formed mostly by soft Holocene to Tertiary sediments with low dip inclinations and a strong input of longshore-transported sand. Beach-rock formation is intensive but only the youngest generation appears in the upper tide reach. Older beach rocks are hidden underneath the sediments of the coastal drift or, in some rare examples, crop out a few meters below the water surface (e.g. off Canoa Quebrada) or have been subjected to erosion. No beach rock was found above spring tide high-water level on the Ceará coast west of Ponta Grossa. Optimum conditions for Holocene and Pleistocene sea-level indicators are found along the coast north of the village of Jericoacoara. The single section on the Ceará coast where hard rock crops out directly at the beach provides a long-term permanent foundation for beach-rock development.

This study reports on field observations along Jericoacoara coast, describing the geological situation, erosion sea-level marks and

* Corresponding author.
E-mail address: georg.irion@senckenberg.de (G. Irion).

0033-5894/$ – see front matter © 2011 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.yqres.2011.10.007

beach-rock sediments. Documentation of the beach-rock diagenesis and the beach-rock occurrences leads to logical conclusions concerning the sea-level development for the Holocene in this area of the coastline of northeastern Brazil.

Study area, dunes, and general observations about beach rocks

Geographic and geologic setting

The study area comprises a 1-km-long section of the coast north of the village of Jericoacoara, which is situated about 240 km northwest of Fortaleza, northeast Brazil (Fig. 1). The area is underlain by Precambrian quartzite forming a steep slope or escarpment cliff of about 35 m height. The cliff is part of a district of hills, which covers an area of about 1.5 km^2, with its highest point 90 m above MSL. Farther inland lies a plain of about 25 km^2 covered by sand dunes.

The coastline is rocky, and the strong surf has developed a beach with boulders and gravels at the base of the outcropping Precambrian quartzite. The beach gravels occupy large parts of the foreshore area. Compared to most other beaches of Ceará, the beach at Jericoacoara inclines strongly and, where the hard rock reaches down to the low-tide line, the width of the foreshore is less than 30 m. In protected areas where dune sand from the hinterland is added to the coarse-grained material of the beach, beach-rock plates have developed.

The tidal conditions at Jericoacoara vary between microtidal during neap tide, with a tidal amplitude of 0.7 m, and mesotidal during spring tide with a maximum tidal amplitude of 3.7 m (Diretoria de hidrografia and navegação (DHN), 2010: — data from Porto de Luis Correia, the nearest tide gauge). During storms the high-tide level may increase by 0.5 m.

Dunes and sand

In the coastal area of Jericoacoara there are dunes similar to those of the entire coast of Ceará. The dunes are of sands that have been brought alongshore by currents, and have been blown landwards by the trade wind, which blows fairly steadily from the east at velocities near 5.5 m s^{-1} during wet season and near 7.8 m s^{-1} during dry season (Jimenez et al., 1999). On the plain east and south of the Jericoacoara coast is a 25-km² field of dunes that reach heights of 35 m and transport enormous masses of sand. The average dune advances 17.5 m a year, corresponding to a sand transport of 78 $m^3 m^{-1} yr^{-1}$ (Jimenez et al., 1999). For example, directly south of Jericoacoara a dune can be observed, slowly disappearing in to the sea. On the Precambrian rock, which forms the hills directly south of the study area, the dune sand sprawls like a blanket over the landscape and is blown over the escarpment cliff into the sea (Fig. 1). Thus, the sand supply for the beaches is blown from the landward side and episodically covers the boulders and gravels of the upper tidal zone, eventually forming beach rock (Figs. 2a/b/c). But the beach is also supplied by sand from the longshore coastal current in a restricted way. In some cases it reaches up to mean tide line but in other cases sand deposits of the longshore current do not reach higher than spring-tide low-water (Figs. 2c/d).

Beach-rock formation and beach rock as a sea-level mark

Beach-rock forms by the precipitation of calcium carbonate dissolved in the interstitial water of the sand or of a mixture of sand and gravel or shells. Gravel and shell do not glue together well because they do not have sufficient points of tangency. Nonetheless, conglomeratic beach rocks consisting of sand mixed with gravel and

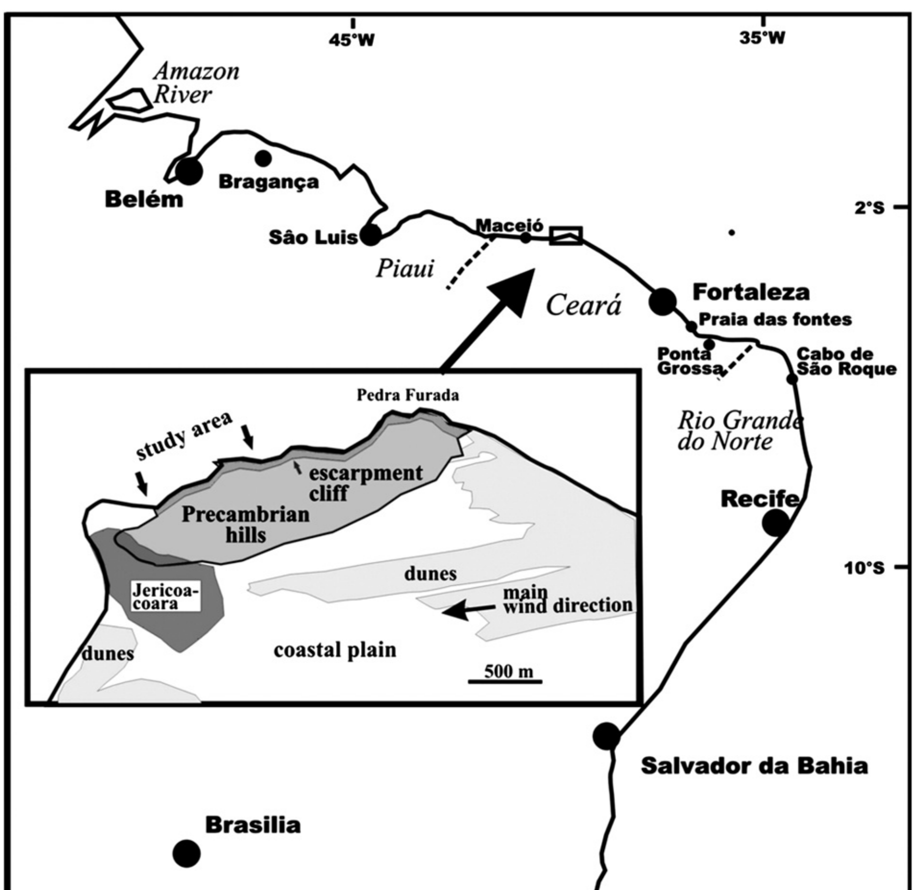

Figure 1. Map with locations and geomorphic units.

https://doi.org/10.1016/j.yqres.2011.10.007 Published online by Cambridge University Press

Figure 2. a–d. a) Dune sand on the escarpment of the Precambrian rocks on the landward side of the Jericoacoara beach (view to E). b) Dune sand supply for the beach rock of location G (view to W). c) Erosion of the beach rock – especially from underneath – near low tide line in location E (view to SW). d) During low tide sand of the coastal-parallel sediment transport appears in location C (view to N). Wind direction is from ENE.

debris of shells have been described from St. Lucia Island, Caribbean Sea (Russell, 1959), from Curacoa Island, north Queensland (Hopley, 1986), and from northeastern Brazil (Gischler and Lomando, 1997; Vieira et al., 2007). On the Ceará coast, especially in the study area of Jericoacoara, beach-rock conglomerates are also present, mixed with small amounts of sand and cemented by calcium carbonate. Morais (1967/69) who studied beach rock formations from Praia de Mireiles/Fortaleza found conglomerate cemented by calcium carbonate and also by limonite. This occurs only when ferruginous sediments of the Tertiary Barreira Formation are present.

Beach rocks are very good indicators of sea level (Hopley, 1986). Their formation is normally restricted to the tidal area. Therefore, paleo sea level may be indicated by beach rocks in elevated positions. For example Holocene high sea levels in Rio Grande do Norte are documented by beach rocks about 1.3 m higher than modern sea level (Caldas et al., 2006a). Since older beach rocks may have dissolved to a large extent, the oldest beach rocks preserved usually are not older than Holocene in age (Vousdoukas et al., 2007).

Carbonate-rich freshwater plays a certain role in the formation of beach rocks (Vousdoukas et al., 2007). Along the coast of Ceará are many places where beach rocks may be found together with freshwater influx. In Praia das fonts, 80 km southeast of Fortaleza, where beach rocks are abundant, freshwater springs deliver their water directly into the sea. Whether freshwater influx is a factor in beach rock formation in this study area near Jericoacoara is not certain.

Results

Beach rock formation on the Ceará coast

Beach rocks are scattered along the entire 560 km long coast of Ceará (Morais, 1967/69). Generally plates of many square meters are formed with thicknesses of 20 to 40 cm. Occasionally they attain thicknesses of more than 1 m. Also found are smaller patches, which may have formed e.g. on abrasion platforms or in small depressions of larger stones.

In the study area, where the tidal amplitude varies from microtidal conditions during neap tide to almost macrotidal conditions during spring tide, the beach rock is formed in the upper tidal reach only. Near high-tide level erosion is minimal, and during neap tide there is sufficient time without any disturbance for the precipitation of $CaCO_3$. Owing to the special local tidal situation, for at least 8 days of a complete tidal cycle (28 days) the water does not cover the upper third of the maximum tidal zone and the beach is left completely dry. During this time the sand and the mixture of sand, shells and gravel is stationary and undisturbed by waves. Salt water influence is absent. We suppose that these conditions plus the arid climate of the coastal zone enhances evaporation and hence the diagenetic process of beach rock formation. Also, mixing of marine and meteoric waters, CO_2 degassing of shallow groundwater and direct or indirect activity of organisms may be partly responsible for the cementation of beach rocks.

Just below the spring tide high-water line new beach rock is formed under a cover of a few decimeters of sediments. It is still porous and not as solid as a beach rock after completed diagenesis. The time span that is needed to reach the final stage of diagenesis is assumed to be in the range of a few years (Frankel, 1968; Alexandersson, 1972), but, under optimal conditions, the incipient stage of beach-rock formation may be reached much earlier — within a timespan of a few months on Ceará beaches.

Later, when beach rock has formed, the sand cover is washed away, but eventually it is covered again by sand and beach-rock formation may continue. With a rising sea level the beach rock is subject to continuous intense wave activity. The older material below the plates is washed away and as a consequence the plates break into smaller pieces (Fig. 3). In most cases the broken parts stay in place

https://doi.org/10.1016/j.yqres.2011.10.007 Published online by Cambridge University Press

Figure 3. Broken beach rock. When the underlying sand and smaller gravels have been washed away, the plates have broken into smaller pieces but stayed in place. The plate marked with the arrow is 3 m in length. The picture has been taken at location C, which is shown in Figure 4.

but some may be transported during heavy storms to the upper reach of the tide. Finally, when sea level reaches 2–3 m higher than the initial stage of its formation, the beach rock reaches the zone of extremely high surf and gets eroded as well (Fig. 2c).

The beach rock is extraordinarily hard. In most areas, as in Jericoacoara area, it does not break along the grain borders as one would expect for a sediment rock of recent diagenesis, but breaks right through the quartz grains. This may explains its resistance to erosion and the persistence of its plates.

Beach-rock platforms and the notches of the coast north of Jericoacoara

Because no official "reference datum" is available for the Jericoacoara area, we selected the spring-tide high-water level as the most obvious working datum for our field observations. We assume an error of 50–100 cm which represents our uncertainty in defining the maxium high-water line during our field work (2.12.2009).

Our reference datum probably does not need to be corrected for other factors. Tectonically, the coast of Ceará is quite stable (Riccomini and Assumpção, 1999). The supply of sand from the inland dunes is fairly steady. Compaction is minimal, as the beach is deposited on Precambrian quartzite.

The study area on the north coast of Jericoacoara contains seven locations of larger beach-rock platforms and seven significant notches. Locations are depicted in Fig. 4 and are listed in Table 1.

All beach rocks extend upwards to the spring high-tide water line or to the base of the escarpment cliff. They extend downward to either to the low-tide water line or to mean tide level. The beach-rock platforms are made up of sand plus some fine and coarse gravel, some boulders and debris of shells. Dune sands are present on the landward side at all beach-rock locations along the coast of Jericoacoara. The sediment supply originating from the dunes is essential for beach-rock formation but sand from the longshore transport may play its part as well (see chapter 2.3).

Three beach-rock platforms are described:

Location C

The beach rock of location C occupies an area of 325 m² (25 m × 13 m) between mean-tide and the high-tide levels (Fig. 3).

The distance between the mean- and high-tide lines is 13 m horizontally and 1.5 m vertically. This area is nearly totally covered by broken plates of beach rock with about 80 pieces larger than 1 m². Seaward of the beach rock, between the mean-tide level and the low-tide line (a horizontal distance of 100 m and another vertical drop of 1.5 m), the area is covered by sand that has been supplied by parallel coastal currents (Fig. 2d). On the western edge of its formation the beach rock is in its original position (Fig. 5). The plates are still fixed to the underlying Precambrian quartzite. The fine-grained material underneath is taken away by the strong surf during high water.

From their positions we conclude that the broken plates have been dislocated downwards by roughly 1 m. The underlying fine-grained material has been washed away and only the boulders of the former rocky beach are still there (Fig. 5).

A meter and a half above the highest beach rock plate, the outcropping Precambrian quartzite exhibits deep erosional channeling, evidence of the surf of a former higher sea level (Fig. 6).

Location D

At location D supply of dune sand from the hinterland is well-documented (Fig. 7). The sand originates from the sea some km east of this location. According to the general wind direction, from east-northeast, sand is blown to and above the hill, where it forms a thin irregular cover, as shown in Figure 2a, and finally the wind moves the sand onward to the coast or it flows down the hill as shown in Figure 1 (see as well Fig. 4). Figure 7a shows dune sand which flows down from the hill to the beach. Some 50 m east of it there is a dune-like sand body which is formed by wind activities from the same sand which accumulates in a thin cover on the hill (Figs. 2a and 7b) From here the sand gets in the upper surf zone and the genesis of beach rock takes place. Firstly, the beach rock is covered by sand but eventually this sand is washed away and a beach rock with a smooth surface appears. Later it may be covered again by sand

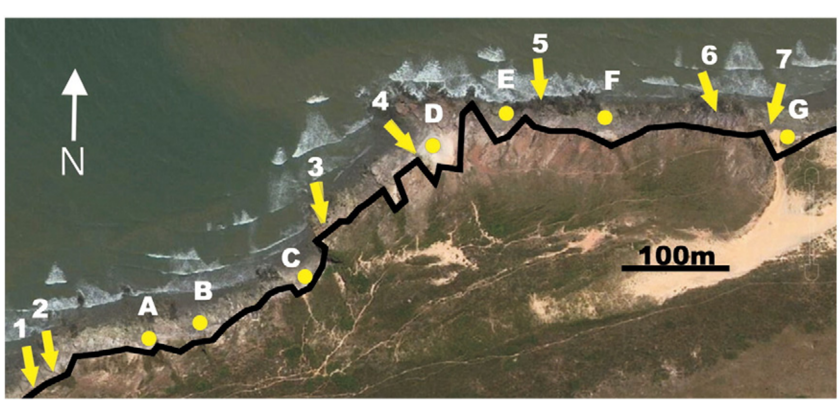

Figure 4. The coastline north of Jericoacoara with the locations of the sea-level marks. For exact positions see Table 1. A–G are beach-rock platforms. 1–7 are notches in the Precambrian rock. The black line represents spring tide high-water.

https://doi.org/10.1016/j.yqres.2011.10.007 Published online by Cambridge University Press

Table 1
Major beach-rock locations (A–G) and notches (1–7) along the Jericoacoara coast, northeastern Brazil.

Name	Position	Type of sea-level mark	Range of beach-rock distribution	Base of the notches above spring-tide high water level	Age	Fig.
1	2°47′23,7″S/40°30′52,6″W	Notch		0	Recent	
2	10 m east of 1	Notch		2–5 m	Sangamonian	
A	2°47′23,0″S |40°30′49,7″W	Beach rock	Mean tide low water to spring tide high water level		Holocene	
B	2°47′22,4″S |40°30′48,9″W	Beach rock	Mean tide low water to spring tide high water level		Holocene	
C	2°47′21,5″S |40°30′45,1″W	Beach rock/notch	Mean tide to spring tide high water level	1.5 m	Holocene/Sangamonian	3,5,6
3	2°47′19,1″S|40°30′43,9″W	Notch		0 m	Recent	
4	2°47′17,4″S|40°30′42,1″W	Notch		2 and 4 m	Sangamonian	7
D	2°47′16,8″S|40°30′41,1″W	Beach rock	Mean tide to spring tide high water level		Holocene	
E	2°47′16,0″S |40°30′39,4″W	Beach rock	Spring tide low to spring tide high water level		Holocene	2c
5	2°47′15,8″S |40°30′39,2″W	Notch		2 m	Sangamonian	
F	2°47′16,9″S |40°30′36,6″W	Beach rock	Spring low tide to sp. high tide		Holocene	
6	2°47′17,7″S |40°30′33,6″W	Notch		−2 and 6 m	Recent/Sangamonian.	
7	Above G	Notch		4 m	Sangamonian.	
G	2°47′16,9″S |48°30′31,8″W	Beach rock	Spring tide low water to spring tide high water level		Holocene	2b

and on this way the beach rock gets larger and larger. The newly formed beach rock tends to forms coherent large plates whereas older beach rock situated in the mean tidal zone consists of broken plates.

Location F

Location F shows the largest beach-rock formation of the Jericoacoara coast. It encloses an area of 1500 m². Since spring-tide high-water laps the steep slope of the bedrock cliff here, beach rock has not formed in the upper-most surf zone. Beach rock is distributed between the low-tide line and the bottom of the slope, in a 55-m-long coastwise band that is 28 m wide in the east and 26 m wide in the west. Its delineation across the width of 28 m/26 m is about 3 m. Near the bottom of the slope the plates are broken but are still more or less in situ. They show distinct erosion marks: longitudinal channels perpendicular to the beach line on their surfaces. Near the low-tide line the beach rock erosion is much more intense. In places beach rock is largely reduced or even absent.

Notches

From Precambrian rock at Jericoacoara seven major notches are listed in Table 1. They are of different sizes. The bottoms of the notches are found within a vertical range of 8 m, between −2 m and 6 m, related to spring tide high-water level. Two of them (locations 1 and 3) bottom at the present spring-tide high-water level and are of Recent age. Four notches (locations 2, 4, 5, and 7) bottom at 2–6 m above the present spring-tide high-water level and are probably of Sangamonian age or older. One (location 6) may be both Sangamonian and Recent in age.

At location 4 are sequences of two levels of notches which are concavely shaped indentation in the Precambrian rock. On the lower level, about 2 m above the recent spring-tide high-water level, there are two notches (Fig. 7a, arrows pointing from the bottom). At about 4 m above spring-tide high-water level are several small notches (Fig. 7, arrows pointing from the top) which most probably developed during constant high surf when spring-tide high-water level was 4 m higher than today, probably during Sangamonian.

Discussion and conclusions

Beach-rock development

We assume that the great difference of almost 4 m between spring and neap tide along the coast of Ceará is largely responsible for the intense formation of beach rocks here. During neap tide, the upper spring-tide surf zone remains free of any salt-water infiltration for about 8 days, during which time only meteoric waters from the surface, especially from the slope of the Precambrian, are supplied. Thus, it is probable that the combination of the specific tidal curve with the arid climate accounts for the widespread occurrence of beach rocks on the Ceará coast. Inland dunes are the principal source of sand to the beaches of Jericoacoara. Although most other published descriptions (Taylor and Illing, 1969; Moore and Billings, 1971; Beier,

Figure 5. Beach rock at location C. The in-situ beach-rock plate is situated just below the today's spring high-water line. Fine-grained material has been washed from underneath the plate, leaving the black holes shown in the picture, but quartzite boulders of a diameter up to 0.5 m stay normally in place.

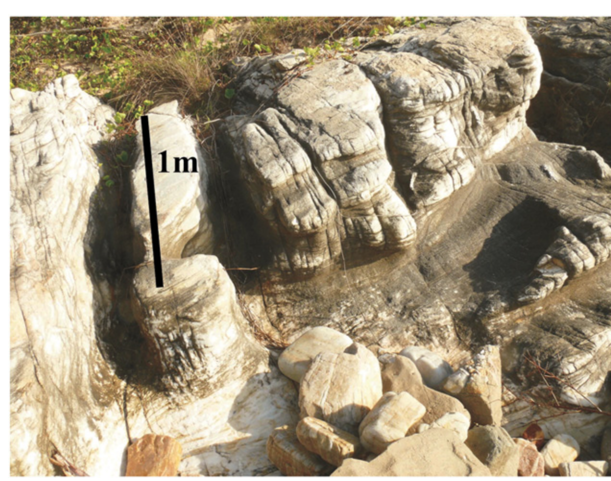

Figure 6. Erosional channels in the outcropping Precambrian quartzite at upper part of location C (view to S). The erosional channels seem to have formed earlier than the beach rock, when the sea level was at least 3 m higher than at present. We suggest that most probably, this channel was formed during the Sangamonian.

Figure 7. a) Location 4 (see Fig. 4 and Table 1). Two erosional notches of typical shape (arrows pointing from below) and notches situated higher up (arrows from above) seen from the sea. The notches are about 2 and 4 m above spring-tide high-water level and are evidence of a higher sea level. During an earlier field visit (Irion et al., 1989) we concluded that they represented former Holocene high sea levels. However, after having studied the local beach rock in more details, we now believe these notches to be of Sangamonian age. Please observe the high dune-sand transport to the beach. b) Location D. Sand dunes with sand originating from the escarpement are developed directly behind the beach and are cut by the high-tide waters.

1985; Khalaf, 1988; Gischler and Lomando, 1997; Chaves and Sial, 1998) show the development of the beach rocks from sand supplied directly from the sea by tides and longshore currents only, the beach rock developed at Jericoacoara is clearly supplied to its greater part with sand by the dunes from the hinterland (see Figs. 2a/b). After the dune sand is deposited in the upper tidal reach, the waves wash most of it away, leaving behind a thinner layer of sand adjusted to the aquatic conditions. This layer is where the beach rock is formed. Where boulders or gravels have been present, they are incorporated in the beach-rock formation as well.

When sea level rises, beach rock becomes vulnerable to breakage since underlying sands and gravels are washed away by wave activity. They are dislocated downward approximately 1 m. As sea level shifts upwards, beach rock now forms in the newly flooded zone along the upper tidal reach (Fig. 8).

A sea level higher than the present one at any time during the last 7000 yr can be excluded, since along the Jericoacoara coast no beach rock has been found higher than spring-tide high-water level. This observation coincides with our earlier observations, made during field trips on the 500-km-long coast between Ponta Grossa and the border with Piaui (Fig. 1), where no beach rock was found higher than the present sea level.

Sea levels 2–6 m higher than today's are evidenced, we believe, by indentations in the Precambrian bedrock. Assuming that the features shown in Figures 6 and 7a are indeed indicative of higher sea levels, then we suspect that these higher levels were of Sangamonian in age.

Sea-level curve of the coast of Ceará

Clearly, a rising sea level on the coast of Ceará is the most plausible explanation for beach-rock formation at the upper part and simultaneous beach-rock destruction at the lower part of the beach at Jericoacoara. We presume that the recent sea-level rise is representative of the general rise of sea levels along most of the Ceará coast since about 7000 yr ago, and that sea level during the Holocene has not been higher here than it is now. Hence, the sea-level curve for the coast of Jericoacoara is more or less in accordance with the eustatic sea-level curve. This is in agreement with the observations of Moerner et al. (1999) for the coast between São Luis and the Amazon where the sea-level curve did not reach higher levels during the Holocene than that of today, and with those of Cohen et al. (2005) who concluded from their studies of mangrove sediments near the city of Bragança (location shown in Fig. 1) that Holocene sea level did not reach higher than 0.6 m above present mean sea level.

This picture is not typical of the entire 4300-km-long coast of Brazil farther to the south. Somewhere between Ponta Grossa and Cabo de Sâo Roque, the Brazilian coast line seems to have transitioned (during Mid-Holocene?) from a stable continent, to the west-northwest, over into a rising continent, in the south. Traces of Holocene sea level can be found that are higher than today's: highest in south Brazil (Angulo and Lessa, 1997) and perhaps as far north as Salvador do Bahia (Martin and Suguio, 1992); and somewhat lower (although still higher than today's) near Recife (Peltier, 1988, 1998) and in Rio Grande do Norte (Caldas et al., 2006a).

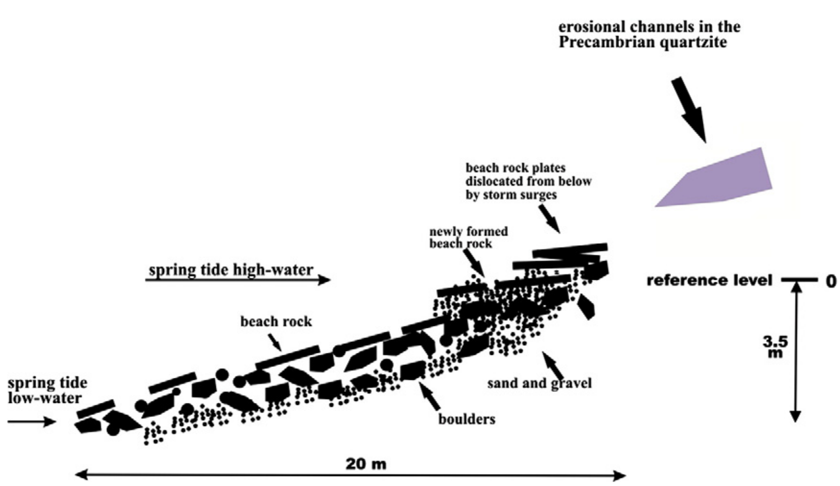

Figure 8. Schematic cross section through a beach on which beach rock has been heavy eroded near low tide level (left) and newly formed at spring-tide high-water level (right). The beach rock is formed on gravel and boulders. Farther to the right, above the spring-tide high-water line, there are erosional channels in a Precambrian quartzite which stem most probably from former Sangamonian beach activities.

https://doi.org/10.1016/j.yqres.2011.10.007 Published online by Cambridge University Press

Summary

A singular opportunity to evaluate the history of Recent and Pleistocene sea levels on the northeastern-facing coast of Brazil is provided by a 1-km-long outcrop of Precambrian quartzite that forms a solid foundation and substrate for the formation of beach rock, and functions as a registry upon which other indicators of past sea levels have been inscribed. The combination here of an almost 4-m tide range, semi-arid climate, and an abundant supply of fresh sand provides optimal circumstances for the development of beach rock. The newer beach rock has been formed recently in the uppermost tide range, partly because most of the sand is supplied from dune fields that lie landward of the beach, and because the prolonged exposure of the upper beach during the neap phases of the tidal cycle allows time for cementation. Older beach rock, present in the tidal zones below the newly formed beach rock, is strongly eroded and broken into pieces by wave actions and is not regularly replenished with new material because the in-supply of longshore-transported marine sands is thwarted by strong wave activities on the rocky beach. Because no beach rock is found in higher positions than spring-tide high water on the coast of Ceará state, we conclude that sea level has never been higher here during the Holocene. Thus, we postulate that sea level for the coast of Jericoacoara shows a continuous rising tendency during the Holocene, which corresponds closely with the global Holocene eustatic rise in sea level. Furthermore, we infer that evidences of former sea levels significantly higher than today's, such as notches and channels in bedrock, are of Sangamonian age or older.

Acknowledgments

We thank FUNCAP (Foundation of the State of Ceará to support Scientific Development) and CNPq (National Council for Scientific and Technological Development) for supporting the study. We are also grateful to the reviewers for their helpful comments which greatly improved the manuscript.

References

Alexandersson, T., 1972. Intragranular growth of marine aragonite and Mg-calcite: evidence of precipitation from supersaturated seawater. Journal of Sedimentary Petrology 42 441460.

Angulo, R.J., Lessa, G.C., 1997. The Brazilian sea-level curves: a critical review with emphasis on the cuves from Paranaguá and Cananéia regions. Marine Geology 140, 141166.

Angulo, R.J., Gianini, P.C.F., Suguio, K., Passenda, L.C.R., 1999. Relative sea-level changes in the last 5500 years in southern Brazil (Laguna-Imbituba region, Santa Catarina State) based on vermitid ^{14}C ages. Marine Geology 159, 323339.

Beier, J.A., 1985. Diagenesis of Quaternary Bahamian beachrock: petrographic and isotopic evidence. Journal of Sedimentary Petrology 55 (755), 761.

Caldas, L.H.O., Stattegger, K., Vital, H., 2006a. Holocene sea-level history: evidence from coastal sediments of the northern Rio Grande do Norte coastal, NE Brazil. Marine Geology 228, 3953.

Caldas, L.H.O., Oliveira, J.G., Medeiros Jr., W.E., Stattegger, K., Vital, H., 2006b. Geometry and evolution of the Holocene trangressive and regessive barriers on the semi-arid coast of NE Brazil. Geo-Marine Letters 26, 249263.

Chaves, N.S., Sial, A.N., 1998. Mixed oceanic and freshwater depositional conditions for beachrocks of Northeast Brazil: evidence from carbon and oxygen isotopes. Geology Review 40, 748754.

Cohen, M.C.L., Souza Filho, P.W.M., Rubén, J.L., Behling, H., Angulo, R.J., 2005. A model of Holocene mangove development and relative sea-level changes on the Bragança Peninsula (Northern Brazil). Wetland Ecology and Management 13, 433443.

Diretoria de hidrografia e navegação (DHN), 2010: http://www.mar.mil.br/dhn/chm/tabuas/index.htm.

Eronen, M., Glückert, G., Hatakka, L., van de Plassche, O., van der Plicht, J., Rantala, P., 2001. Rates of Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. Boreas 30, 17–30.

Frankel, E., 1968. Rate of formation of beach rock. Earth and Planetary Science Letters 4, 439–440.

Gischler, E., Lomando, A.J., 1997. Holocene cemented beach deposits in Belize. Sedimentary Geology 110, 277297.

Hopley, D., 1986. Beachrock as sea-level indicator. In: Plassche, O.v.d. (Ed.), Sea Level Research: a Manual for Collection an Evaluation of Data. Geo Books, Norwich, pp. 157–173.

Irion, G., de Morais, J.O., Wunderlich, F., 1989. Geologische Studien an einem Küstenstreifen NE Brasiliens (Ceará). Natur und Museum 119, 158–166.

Jelgersma, S., 1979. Sea-level changes in the North Sea basin. Acta UniversitatisUpsaliensis, Symposia Universitatis Upsaliensis Annum Quingentesimum Celebrantis 2, 233–248.

Jimenez, J.A., Maia, L.P., Serra, J., Morais, J., 1999. Aeolian dune migration along the Ceará coast, north-eastern Brazil. Sedimentology 46, 689–701.

Khalaf, I., 1988. Quaternary calcareous hard rocks and the associated sediments in the intertidal and off shore tidal zone of Kuwait. Marine Geology 80, 1–27.

Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europa. Geophysical Journal International 134, 102–144.

Martin, L., Suguio, K., 1992. Variation of coastal dynamics during the last 7000 year recorded in the beach-ridge plains associated with river mouths: example from the central Brazilian coast. Palaeogeography, Palaeoclimatology, Palaeoecology 99, 119–140.

Martin, L., Dominguez, J.M.L., Bittencourt, A.C.S.P., 2003. Fluctuating Holocene sea-levels in eastern and southeastern Brazil: evidence from multiple fossil and geometric indicators. Journal of Coastal Research 1, 101–124.

Meireles, A.J.A., Arruda, M.G.C., Gorayeb, A., Thiers, P.R.L., 2005. Integração dos indicadores geoambientais de flutuações do nível relative do mar e mudanças climáticas no literal cearense. Mercator – Revista de Geografia da Universidade Federal do Ceará 109–134 ano04, número 08.

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quaternary Science Reviews 21, 2179–2190.

Moerner, N.A., Rosseti, D., Toçedo, P., 1999. Sea level changes in NE Brazil, regional eustasy and local tectonics. In: Fletcher, C.H., Matthews, J.V. (Eds.), The non-steady state of the inner shelf and shorelines: coastal change on the time scale of decades to millennia in the Late Quaternary. : Abstracts with Programs, Inaugural Meeting of ICP Project 437 Costal Environmental Change During Sea-level High-stands. University of Hawaii, Honolulu, pp. 111–112.

Moore, C.H., Billings, G.K., 1971. Preliminary model of beachrock cementation, Grand Cayman island, B.W.I. In: Bricker, O.P. (Ed.), Carbonate Cements. Johns Hopkins Press, Baltimore, MD, pp. 40–43.

Morais, J.O., 1967/69. Contribuição ao Estudo dos Beach Rocks do Nordeste do Brasil. Trabalhos Oceanográficos da Universidade Federal de Pernambuco, Recife 9, 70–94.

Peltier, W.R., 1988. Lithospheric thickness, antarctic deglaciation history, and ocean basin discretization effects in a global model of postglacial sea level change: a summary of some sources of nonuniqueness. Quaternary Research 29, 93–112.

Peltier, W.R., 1998. Global glacial isostatic adjustment and coastal tectonics. In: Stewart, I., Vita-Finzi, C. (Eds.), Coastal Tectonics — Geological Society London: Special Publication, 146, pp. 1–29.

Riccomini, C., Assumpção, M., 1999. Quaternary tectonics in Brazil. Episodes 22 (3), 221–225.

Russell, R.J., 1959. Caribbean beach rock observation. Zeitschrift fuer Geomorphologie 3, 227–236.

Shennan, I., 1987. Holocene sea;level changes in the North Sea Region. In: Toolez, M.J., Shennan, I. (Eds.), Sea-level changes, pp. 109–151. 1987.

Steffen, H., Kaufmann, G., 2005. Glacial isostatic adjustment of Scandinavia and northwestern Europe and the radial viscosity structure of the Earth´s mantle. Geophysical Journal International 163 (2), 801–812.

Suguio, K., Martin, L., Bittencourt, A.C.S.P., Dominguez, J.M.L., Flexor, J.-M., Azevedo, A.E.G., 1985. Flutuações do nível relativo do mar durante o Quarternário Superior ao longo do litoral Brasileiro e suas implicações na sedimentação costeira. Revista Brasileira de Geociencias 15, 273–286.

Taylor, J.C.M., Illing, L.V., 1969. Holocene intertidal calcium carbonate cementation, Qatar, Persian Gulf. Sedimentology 12, 69–107.

Vieira, M.M., De Ros, L.F., Bezerra, F.H.R., 2007. Lithofaciology and palaeoenvironmental analysis of Holocene beachrocks in Northeastern Brazil. Journal of Coastal Research 23, 1535–1548.

Vink, A., Steffen, H., Reinhardt, L., Kaufmann, G., 2007. Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany and southern North Sea). Quaternary Science Reviews 26, 3249–3275.

Vousdoukas, M.I., Velegrakis, A.F., Plomaritis, T.A., 2007. Beachrock occurence, characteristics, formation mechanisms and impacts. Earth-Science Reviews 85, 23–46.

Wu, P., Peltier, W.R., 1983. Glacial isostatic adjustment and the free air gravity anomaly as a constraint on deep mantle viscosity. Geophysical Journal of the Royal Astronomical Society 74, 377–450.