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Chronological reconstruction of eolianites and transversal mobile dunes of northwest coast of Ceará State – Brazil, in the last 3000 cal yrs BP

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ABSTRACT

Dunefields are very common in the northern coastal zone of northeast Brazil. They have the potential to yield important information about paleoclimate, paleo-winds and regional winds and their response to sea-level fluctuations during the Holocene. We reconstructed the coastal dunes geochronological evolution of northwest Ceará State – Brazil, in the last 3000 cal yrs BP, using detailed analyses of lithostratigraphy, microfossil (foraminifera), wind regime, dune monitoring and 8 radiocarbon dates. The chronology was based on ^{14}C dating in eolianites and monitoring transversal mobile dunes movement processes. Radiocarbon date results indicated that the dunes corresponding to eolianites revealed ages between 2760–2480 and 980–750 cal yrs BP, suggesting that the vast transversal mobile dunefields were formed after this period in similar condition to the current sea-level. We considered that the material transportation by the prevailing east winds towards the transversal dunes is estimated in the order of 11.0 m/year, thus the current aeolian system is less than 1000 yrs BP.

1. Introduction

Origin and evolution of coastal aeolian deposit rely on processes by which the wind, blowing over the beach, can lift sand out the surface and move it inward the continent, originating dunes. Goldsmith (1978) defines that the presence of coastal dunes is determined by the relationship of three factors: availability of loose sediment, wind action with reasonable strength to rework and transport the sediment, as well as appropriate surface to deposition. Coastal dunes in northeastern Brazil store valuable information concerning occurrence of records of relative sea-level variation and past climate conditions during Holocene (Castro, 2001).

A range of authors (Martin et al., 1985; Suguio et al., 1988; Bezerra et al., 2003; Suguio et al., 2003; Caldas et al., 2006; Castro et al., 2014; Spotorno-Oliveira et al., 2016) have documented higher-than-present Holocene sea-level events based on more than 1000 radiocarbon dates. The Holocene climatic optimum in Brazilian coast occurred approximately between 5100 and 4590 cal yrs BP (Castro et al., 2014). The marine level was 3.0 m above the current, resulting in paleolagoons. In front of the paleolagoons, barrier-island and beach-ridge systems were formed. As the sea-level lowered, the lagoon environment was occupied by eolianites and mobile transversal dunes (Castro, 2004).

The northeast Brazilian coast is the only region in the country where eolianites occur. They comprise arenaceous deposits of quartz-bioclastic composition, cemented by calcium carbonate (Castro, 2004). This unit establishes a unique record of aeolian activity with peculiar features, which are rare on the Brazilian coast. Such characteristics, preserved in its structures and composition, highlight a large potential to provide relevant information about coastal dunes evolution, paleoclimate and sea-level fluctuations.

Sayles (1931) used the term eolianites for the first time to describe rocks composed of consolidated, wind-blown sediment. Xitao (1988), in his study of the eolianites of Fujian (China), claims that the distribution of these aeolian deposits occurs in diverse climate regimes, similar to coastal dunes. In terms of spatial distribution, the concentration of eolianites on mid-latitude is related to the low input of terrigenous sediments due to warm and dry weather (Brooke, 2001). Therefore, the concentration of eolianites in the study area derives from dryer weather conditions over late Holocene.

Coastal eolianites are formed by material from the deflation of beach deposits and subtidal sediments when exposed to wind during marine lowstand episodes (Abegg et al. 2001). The input of normal wave-induced shore and reworking of washover deposits are the main sources of material during relative sea-level highstands. However, greenhouse eolianites have been discovered in recent years, going against the assumption that eolianites deposition is constrained to

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icehouse periods, with large glacio-eustatic relative sea-level fluctuations (Kindler and Davaud, 2001). Thus, large glacio-eustatic relative sea-level fluctuations would not be necessary to form eolianites deposits (Hearty and O'Leary, 2008).

Along the northeast Brazilian coast, the origin of eolianites is due to the accumulation of marine bioclasts along the beach, including foraminifers of the miliolidian and rotalaidian classes which, carried along by the winds, are then deposited on the top of pre-existing dunes (Castro, 2001; 2004). They occupy large stretches of land, occurring in outcrops that are well distributed in an oblique line at several points along the Ceará State coast. Studies seeking to analyze the paleoenvironmental formation of eolianites through ^{14}C dating are almost non-existent in Brazil (Castro, 2001).

The correlation between them and current mobile transversal dunefields has lead to the interpretation that most of eolianites records are representative of an evolution phase represented by the formation of compound dunes, with parabolic dunes accumulation at the final stage. In this study, results obtained from the first recorded eolianites on the northwest coastal dunes of Ceará State - Brazil are discussed. We considered that the formation of eolianites and the vast transversal mobile dunefields is less than 3000 cal yrs BP. Based on lithostratigraphic characteristics together with radiocarbon ages and monitoring of current transversal mobile dunes, new findings regarding to chronological reconstruction of NW coastal dunes of Ceará State - Brazil are presented.

2. Study area

The study area is located within the northeastern semi-arid coast of Brazil, in Ceará State. The largest dunefields in Brazil occur along the northern coast of this region. The coastal zone of Ceará State stretches for 578 km and consists of sandy beaches that feed vast coastal dunes in the hinterland (Fig. 1). These dunefields form mostly on the coastline with an east to west orientation and are nearly perpendicular to the easterly trade-winds. Because of the unidirectional, powerful trade-winds, the Ceará coastal dunes are large, reaching heights of 10–50 m, and exhibit high rates of advance (Castro, 2005). The coastline in the study area is almost entirely constituted by dunes - either mobile or fixed in place by vegetation or eolianites (Castro, 2001). The aeolian deposits form extensive dunefields, which are present from the back shore to about 10 km (Carvalho, 2003).

The vast prevalence of active sand dunes along the coast of northeast Brazil in a tropical climate (average yearly rainfall above 1000 mm) is a result of very strong trade winds, which mostly occur in the dry season. Many stabilized dunes are found along this coast, side by side with the active dunes (Tsoar et al., 2009). A hysteresis model based on changes in wind power can explain the co-existence of stabilized and active dunes in the same area. Vegetation on sand dunes in northeast Brazil thrives when the rainfall is above 400 mm and the wind power is low. There are many indications of wetter periods in NE Brazil during the Late Quaternary (Tsoar et al., 2009). The dunes during the wetter periods were stabilized by vegetation due to low wind strength and not because of the increased precipitation (Castro, 2001; Tsoar et al., 2009; Hesp et al., 2012).

In most of this coastal zone, there are at least four different forms of dunes of different ages. Members of the first and oldest generation are known as paleodunes and occur along the Barreiras Formation (Braga et al., 1981; Perrin and Costa, 1982; Carvalho, 2003). The second generation is made up of paleodunes ridges covered by vegetation or mobile dunes indicating variations in sea-level during the Holocene (Castro, 2001). The third generation is composed of eolianites (pinnacles dunes) with a northeast to southeast oblique orientation to the coastline. (Castro et al., 1998; Maia, 1998; Castro, 2001; Castro, 2004; Carvalho et al., 2008; Mesquita et al., 2016). The concentration of eolianites in the northern coastal zone of Brazil is related to the inner continental shelf constituted by algae, foraminifera and small proportion of Hamlimeda algae (Castro et al., 1998; Cavalcanti, 2011). Finally, the fourth and last generation is made up of the current system of transversal mobile dunefields (Castro, 2001; Claudino-Sales, 2002; Castro, 2004; Castro, 2005; Maia et al., 2005; Hesp et al., 2012).

The dominant dunes type is the transversal mobile (last generation). The crests of these dunes are perpendicular to the main direction of the dominant wind. The lengths vary from 100 to 1000 m, averaging 500 m. The heights vary from 10 to 60 m, averaging about 15 m (Castro, 2001). The dunefield is subjected to a unimodal (90°–110°) wind pattern, predominantly blowing from the east. The southwest winds constitute the secondary component of the local air stream regime. The morphology of the coastline and the highly directional aeolian transportation system allow classification as a headland bypass dunefield. Sediments are transported from the beach inland and partially returning to the sea by the drainage network (Castro, 2005).

3. Material and methods

A significant amount of eolianites samples (pinnacle dunes) collected from Paracuru, Flexeiras, Mundau, Pedrinhas, Baleia and Icarai de Amontada beaches, were examined in thin section. A total of 24 samples were studied in field work and laboratory. The cores extracted are 0.30 m wide and can reach 0.20 m length. All hand specimens were taken from freshly exposed faces. All samples collected in the field had their vertical orientation recorded and this information was transferred to all thin sections which were cut transverse to the bedding. The abundance of primary cements, among these, gravity, drapestone and pore-filling were measured in thin section using a point counter. A total of 120 point counts evenly distributed across each thin section was made to determine the percentages of the various constituents present in the eolianites deposits.

A total of 8 samples were collected at different points in the eolianites dunefields to ^{14}C analyses (Fig. 1). Radiocarbon dating was performed to determine their ages and to estimate, via a space-time evaluation, deposition rates within the current aeolian system of transversal mobile dunes. During this research stage, the collected material was sent to Beta Analytic Inc., in Miami, FL, United States. Radiocarbon ages were calculated based on percent modern carbon with reference to $\delta^{13}C$ normalized to $-25‰$. As dune sediments are composed of skeletons of mixture marine microfossils formed in shallow marine waters on the shelf, a marine reservoir age was applied to all AMS ^{14}C ages using CALIB 5.0.2 (Stuiver et al., 2000). It was chosen the standard reservoir age because, although the evidence from the region is sparse, the ages are not significantly different from 400 yrs (calib.qub.ac.uk/marine/index). All ^{14}C ages were calibrated to calendar years before 1950 CE (cal B.P) and reported as median of the probability distribution of calibrated ages with errors of one-half of the 2σ calibrated age range. The conversion was calculated from the true age of each sample leading in consideration the reservoir effect.

The orientation of transversal mobile dunes was determined using a compass which allowed to estimate paleo-winds direction during the deposition process. Information obtained in the field has indicated that northeast trade winds direction prevailed. Study of the wind regime was based upon records provided by the Department for Alternative Sources and Conservation of Energy – *Departamento de Fontes Alternativas e Conservação de Energia* – COELCE, which were taken by a weather station situated on top of a mobile dune to the east of the study area, in Taíba, Ceará State. Data from an hourly data series, which had been measured since 1997, were employed. Direct observation of the landscape was carried out through monitoring of an isolated barchan dune in Paracuru – Ceará State for a period of over two years, between April 1998 and June 2000 (Castro, 2001). That dune has a height of 5.0 m and are closely spaced, separated by a few meters only, on a dense sand sheet in the beginning of the Paracuru coastal plain. Measurements were taken in three-month intervals to detect the trajectory and direction of the movement process, which was impacted by the