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Late Quaternary infilling of the Assu River embayment and related sea level changes in NE Brazil

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ABSTRACT

A detailed geomorphological survey using Light Detection and Ranging (LiDAR) was carried out along the western part of the Assu River valley, NE, Brazil. The study was complemented by the investigation of sedimentological, mineralogical, and sediment benthic foraminifera indicators within the 14C geochronological framework. The integration of data sets permitted the reconstruction of the main phases in the evolution of this area during the Holocene. The shallow embayment, which is now completely infilled, acquired its present form within the limits of antecedent morphology developed since the last interglacial period. The main forcing factors responsible for repositioning the shoreline, which ran along the strike-slip Afonso Bezerra fault at an angle of approximately 35° to the present coast in the Early/Mid Holocene, were as follows: (1) tectonic activity along the strike-slip Afonso Bezerra fault, (2) fast inundation of the shallow paleo-valley embayment during the last pulse of Holocene transgression ca. 8000 cal yr BP, (3) advance of the Assu river mouth through accretion of fluvial bay head delta and costal drift sediments and (4) sheltering of embayment by barrier islands which permitted a widespread development of mangrove forest during the last 3 millennia. The estimated rate of progradation of the Assu estuary that led to the present stage of terminal infilling is in the order of 3–4 m/yr.

1. Introduction

Estuarine sedimentary infills are transgressive sedimentary bodies comprised of fluvial and marine materials deposited on the pre-inundation paleovalley floor. The morphosedimentary architecture of the infill is therefore complex and controlled by several interdependent factors (Amorosi and Milli, 2001; Gregoire et al., 2017), such as the depth of paleovalley incision, sediment supply rate, rate of sea level rise (SLR), tectonics, subsidence, antecedent morphology and local hydrodynamics, which vary and evolve over multiple time scales (Pendon et al., 1998; Clement et al., 2017; Gerlach et al., 2017).

SLR since the last glacial maximum (LGM) has created an accommodation space along paleovalleys with a depth controlled by the nature of the geological substratum and the physiography of the coast and the continental shelf. In this space, sediments of mixed origins accreted subsequently in proportions that varied with space and time. In the deepest valleys, the first stage of accretion lasted approximately 5500 cal yr, covering the terminal millennium of the Pleistocene and the Early Holocene (Smith et al., 2011). The accretionary process added approximately 40 m to the sediment column in the Guadiana Estuary (SW Iberia) (Delgado et al., 2012) and mainly followed a vertical pattern (Boski et al., 2008) imposed by a rapid SLR of an average rate of ca. 12 mm yr^{-1}, in *Tahiti*, French Polynesia (Bard et al., 2010). It is now well established that the meltwater outburst from Lake Agassiz, which terminated the main period of mass transfer related SLR, increased the global sea level by 4–6 m (Murray-Wallace and Woodroffe, 2014) and forced the onset of a cold climatic event ca. 8200 cal yr BP (Bauer et al., 2004). This meltwater release and the resultant inundation drowned the terminal segments of river valleys and coastal embayment that could accommodate sediments in a newly created space. Thus a record of environmental changes within prograding sedimentary bodies can be found along costal zones around the world, such as in the Dornoch Firth River mouth in Scotland (Firth et al., 1995), the Yangtze Delta in China (Liu et al., 2004 and Liu et al., 2010), the Mekong Delta in Vietnam (Tjallingii et al., 2010), the Guadiana Estuary in the southern Portugal-Spain border (Boski et al., 2008), the Doce River Delta in eastern Brazil (Rossetti et al., 2015), the southern coast of Brazil (Rosa et al., 2011), the Little Manatee River Estuary and the Charlotte Harbor in southern

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USA (Gerlach et al., 2017), and the Potengi-Jundiai Estuary in northeastern Brazil (Boski et al., 2015b).

Delibrias and Laborel (1969) were the first to note that during a Holocene transgressive pulse along the eastern coast of South America, sea level reached the present-day height ca. 7000 cal yr BP. In the following three decades, a complex pattern of Holocene sea-level changes was found along the southern coast of Brazil, with different progradation, aggradation and retrogradation sectors (Rosa et al., 2011).

In other studies along the NE Brazilian coasts (Bezerra et al., 2003; Caldas et al., 2006), the mid-Holocene 0-m relative sea level (RSL) occurred at 7000–6700 cal yr BP. The inferred amount of subsequent RSL rise and its timing ranged from 1.5 to 3 m above the present-day sea level during the period 7000–5000 cal yr BP (Angulo et al., 2006; Suguio et al., 2013), which initiated its decrease ca. 5000 cal yr BP. Along the coastal stretch of the state of Ceará (Irion et al., 2012) and the N—S trending segment in the state of Rio Grande do Norte (Bezerra et al., 2003), the record of mid Holocene highstand is negligible or absent. More recently, in the work based on materials recovered from boreholes drilled in the Potengi – Jundiai estuary in the State of Rio Grande do Norte, Boski et al. (2015b) extended the sea level curve of northeastern Brazil for the period predating the attainment of the present mean sea level (MSL) by ca. one millennium (i.e., since ca. 8200 cal yr BP). Szczygielski et al. (2015) analyzed the Late Holocene sedimentary environments of the Parnaiba Delta, which is located along the equatorial margin of Brazil, to describe the interplay between sea level changes and coastal evolution. Nevertheless, relating relative sea level changes to the coastal evolution timescale in northeastern Brazil is still a work in progress due to the scarcity of reference points and relatively wide error margins in the proposed sea level curves.

This study aims to obtain a chronological framework for the evolution of the Assu estuary (Fig. 1), which formed during different stages of the late Quaternary shoreline progradation, within an embayment that has not been previously studied from this perspective. The embayment area, which is covered by Holocene sediments deposited during the last post-glacial transgression (embayment area is approximately 320 km^2), is now completely filled and protected by a sand barrier system. We analyzed and interpreted data sets comprising remote sensing imagery (LiDAR), foraminifera bio-indicators, textural data and radiocarbon (14C) ages of borehole samples. The results are discussed in the context of paleo-sea level changes, tectonics and sediment dynamics focusing on the period after the Holocene transgression maximum. This study attempts to elucidate the history of both the vertical accretion of sediment and the lateral displacement of coastal features.

2. Regional settings

2.1. Main characteristics of the study area

The study area is localized on the coastal plain of the Assu River, one of the main water courses of Northeastern Brazil, and totals 393 km^2 within a drainage basin of 43,681 km^2. There are 47 water dams in the Assu drainage basin, two of which are major structures, that assure continuous water flow throughout the year. These dams effectively solved the problem of alternating drought and floods but drastically reduced the delivery of sediment to the littoral thereby aggravating coastline retreat. The present waterfront of the Assu estuary extends for approximately 22.5 km (Fig. 1) in front of an ~320 km^2 area covered by Holocene sediments and drained by three estuary rivers named the Conchas, Cavalos and Assu, and several tidal channels. There are also four brackish water lagoons within the limits of the Assu estuarine area: the Lagamar, Queimado, Preta and Vargem de Cima (Fig. 1), representing relicts of the embayment formed at the maximum of Holocene transgression (Vital, 2009).

2.2. Geological setting

The study area corresponds to the Holocene coastal plain of the Assu Estuary (Fig. 1). The terminal segment of the river valley lies within the Mesozoic-Cenozoic Potiguar Basin located onshore and offshore at the eastern flank of the Brazilian Continental Margin (Araripe and Feijó, 1994; Pessoa Neto, 2007).

The litho-stratigraphy of the study area (Moura-Lima et al., 2011) encompasses several Cenozoic units from bottom to top (Fig. 1). The oldest is the Oligocene Macau magmatic unit, composed of dolerite and basalt. This unit is directly overlain by the Miocene Tibau Formation, which is composed of fine to coarse sandstone and conglomerate. The Tibau Formation is capped by the Barreiras Formation, which is composed of conglomerate, sandstones, siltstone, and mudstone and is affected by lateritic weathering (Rossetti et al., 2013). A Pliocene sedimentary unit is composed of poorly lithified conglomerate and coarse to fine sandstone with lenses of mudstone. This unit exhibits soft-sediment deformation structures.

The Pleistocene deposits are composed of old alluvial deposits that include polymictic conglomerate, conglomeratic sandstone, coarse to medium sandstone, and pelitic layers. These deposits usually show soft-sediment deformation features that have been associated with paleoseismicity (Bezerra et al., 2005, 2006).

Most of the estuarine area is covered by Holocene sedimentary units of aeolian or aquatic origin (Fig. 1). The aeolian units are represented by both vegetated and non-vegetated quartz sand dunes. In zones of active sand accretion, the vegetated dunes are partially covered by younger non-vegetated dunes stained by small amounts of ferruginous pigment brought from the outcrops of the older Barreiras or Pleistocene formations. The aquatic sediment bodies are mainly composed of fine sand frequently very rich in mica and estuarine mud, both of which contain rich mollusk fauna. These deposits represent shoreface and mudflat-mangrove environments, respectively. In the central-southern part of the estuary, alluvial sediments associated with the Assu river main channel can be distinguished by more heterogeneous grain size ranging from channel gravel beds to mud-silt layers of flood plain cover.

2.3. Atmospheric and oceanographic regimes

The study area is located in the equatorial belt and is represented by a semi-arid climate, according to Nimer (1972), and it falls into the BSw'h category according to the Köppen (1948) classification. The daily temperatures vary from 26 °C to 30 °C (with a mean temperature of 26.8 °C), and the average relative air humidity is 70%. The pluviosity ranges from 1300 to approximately 2000 mm a^{-1} (IDEMA, 1999).

The estuary is characterized by a semidiurnal, meso-tidal regime. The mean tidal range is 2.66 m, with a mean spring high tidal level of 2.85 m related to the low tide level, and a mean neap high tidal level of 2.21 m. Hydrodynamic processes are influenced by waves from the northeast that reach 10 to 80 cm near the coast in periods of 4 and 8 s (Chaves et al., 2006; Rocha et al., 2009). Waves vary seasonally. During the summer period in the southern hemisphere (December–February), waves range between 53 and 123 cm, with a minimum height of 27 cm. Longshore currents flow mainly towards the west and northwest, with a maximum velocity of 97 cm/s, whereas tidal currents have a relatively small velocity of 5–60 cm/s (Vital, 2009).

3. Methods

3.1. Cartography and fieldwork

This study was based on a combination of analyses of detailed remote sensing imagery and fieldwork carried out in several target zones. The light detection and ranging (LIDAR) imagery of the Assu estuary quadrant was provided by Petrobras in matrix format with cells of