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A multi-proxy evidence for the transition from estuarine mangroves to deltaic freshwater marshes, Southeastern Brazil, due to climatic and sea-level changes during the late Holocene

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ABSTRACT

The present study investigates a paleo-estuary at the Doce River Delta, southeastern Brazil, through a multi-proxy approach that links palynology, diatoms, sedimentology and geochemistry analyses (i.e., Total C, Total N, $\delta^{13}C$ and $\delta^{15}N$). These analyses, temporally synchronized with five radiocarbon ages, revealed environmental changes from marine to continental over the last ~7550 years. The studied sedimentary succession recorded the upward transition from estuarine channel (until ~7550 cal yr BP) to estuarine central basin (>~7550 to ~5250 cal yr BP) deposits, the latter containing increased mangrove vegetation, marine and marine/brackish water diatoms. The range of geochemical values ($\delta^{13}C = -30$–-10‰, $\delta^{15}N = 2 - 8$‰ and $C/N = 4$–40) also indicate marine/estuarine organic matter and C_3 terrestrial plants to that time interval. A following period recorded two phases: lake/ria (~5250 to ~400 cal yr BP) and fluvial channel (~400 cal yr BP until modern age). During this stage, mangroves were replaced by trees/shrubs and herbs/grasses due to the disconnection with the marine realm. As a result, the corresponding sediments contain only organic matter sourced from freshwater and C_3 terrestrial plants ($\delta^{13}C = -29$–-26‰, $\delta^{15}N = 0 - 8$‰ and $C/N = 10$–45). The equilibrium between fluvial sediment supply and relative sea-level changes during the Holocene controlled the morphologic and vegetation changes in the studied littoral. The estuary became established during the early Holocene as a resulted of a eustatic sea-level rise, when the fluvial sediment supply to the coast was relatively lower due to a dry period. However, during the late Holocene, the climatic force was more significant to the development of coastal morphology due to a wet period that caused an increase in sandy sediment supply to coastal system. Then, the increase of fluvial discharge associated to a relative sea-level fall caused a marine regression and shrinkage of mangroves during the late Holocene. The evaluation of mangrove dynamics according to climatic and sea-level changes mainly during the late Holocene is essential for the understanding of their survival ability under future scenarios, with a probable accelerated sea-level rise and intensification of extreme climatic events in southeastern Brazil for the next century.

1. Introduction

Climate changes and sea-level oscillations have caused significant impacts on coastal sedimentary dynamics and ecosystems along the Brazilian littoral during the late Quaternary (Suguio et al., 1985; Dominguez et al., 1992; Ledru et al., 1996; Angulo and Lessa, 1997; Behling et al., 1998b; Grimm et al., 2001; Bezerra et al., 2003; Martin et al., 2003; Cohen et al., 2005a,b; Angulo et al., 2006; Vedel et al., 2006; Behling et al., 2007; Sawakuchi et al., 2008; Lara and Cohen, 2009; Zular et al., 2013; Guimarães et al., 2012, 2013; Buso Junior et al., 2013; França et al., 2012, 2013, 2014).

It is well known that the dominant depositional systems under sea-level rise are estuaries (Swift, 1975). It evolves as the result of the interaction between geomorphological structures and dynamic processes that are marine and riverine; this interaction adds up to processes that are inherently estuarine (Jackson, 2013). Their response to sea-level changes is affected by tidal range, nearshore wave climate and river inflow, as well as by the nature and supply of sediments. All estuaries

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assumed their present form during the rise of sea-level that followed the Last Glacial Maximum (LGM), about 20 thousand years ago (Chappell and Woodroffe, 1994). However, the sea-level fall creates highly unfavorable conditions for the genesis and maintenance of this coastal system. A continued river sediment supply may result in shoreline progradation, and it can generate a delta (Suter, 1994).

Considering the relative sea-level changes during the Holocene, it crossed above the present one at 7000 BP (Suguio et al., 1985), reaching 4 to 6 m above the present one in many areas of the Brazilian coast (Martin and Suguio, 1992; Angulo et al., 2006; Rossetti et al., 2008; Reis et al., 2013), with a subsequent fall to the present time (e.g., Angulo et al., 2006). In terms of climatic changes, significant rainfall variations occurred in the Brazilian central region, and consequently it affected the volume of the rivers. Then, during the drier periods of the early and mid-Holocene (Ledru, 1993; Ledru et al., 1996; Behling, 1995; Behling and Lichte, 1997; Behling et al., 1998b; Pessenda et al., 2009), the river inflow may have been severely reduced, and it affected the salinity gradients and the sediment supply to the coastal system. In contrast, in the mid- to late Holocene, the climate was marked by wetter conditions (Ledru, 1993; Ledru et al., 1998; Salgado-Labouriau, 1997; Salgado-Labouriau et al., 1998; Ledru et al., 2009; Pessenda et al., 2004, 2009). Therefore, the interaction between the sea-level and climatic changes have affected significantly the evolution of coastal systems.

Several paleoenvironmental indicators, such as sedimentological features (Suguio et al., 1985; Giannini et al., 2007; Rossetti et al., 2012), isotopes and geochemical data (Freitas et al., 2003; Pessenda et al., 2010), pollen (Behling et al., 2001, 2004; Cohen et al., 2005a,b, 2008, 2012; França et al., 2012) and diatoms (Round et al., 1990; Bennion, 1995; Hillebrand and Sommer, 2000; Rivera and Diaz, 2004; Hassan et al., 2006; Korhola, 2007; Zong and Horton, 1998; Zong et al., 2010; Castro et al., 2013) have been used individually to investigate the past climate and the sea level fluctuations, as well as local environmental changes.

In this context, this paper integrates lithology, diatom and pollen data previously published by Castro et al. (2013) and Cohen et al. (2014) with Total Organic Carbon (TOC), Nitrogen (N), stable isotopes ($\delta^{13}C$ and $\delta^{15}N$), C/N and radiocarbon date in order to present an evolutionary model for the State of Espírito Santo littoral, southeastern Brazil, according to the interplay between climatic changes and relative sea-level oscillations during the Holocene.

2. Study area

The study site is located in the deltaic plain of the Doce River (Fig. 1). This is a feature with a maximum width of about 40 km and length of about 150 km (Suguio et al., 1982; Bittencourt et al., 2007) that occurs near the town of Linhares (around 30 km), State of Espírito Santo, Southeastern Brazil. The Doce River Delta occurs within an incised valley that cut down into Miocene strata (Dominguez et al., 1981).

2.1. Geological setting

The area is composed of a Miocene plateau constituted by continental deposits of the Barreiras Formation, whose surface is slightly sloping to the ocean. Four geomorphological units are recognized in the area: (1) a mountainous province of Precambrian rock; (2) a tableland with the Barreiras Formation (Neogene) (Arai, 2006; Dominguez, 2009); (3) a coastal plain (Martin et al., 1987; Cohen et al., 2014); and (4) an inner continental shelf (Asmus et al., 1971).

Currently, the Doce River shows a mostly W–E trending "straight" pattern, and it flows over basement crystalline rocks into the littoral plain through a low valley with Holocene terraces. The terraces consist of a mixture of sediments from the Barreiras Formation, which were transported by rivers originated in mountainous areas and Neogene tablelands. The Barreiras Formation is constituted by sandstones, conglomerates and mudstones attributed mainly to Neogene fluvial and alluvial fan deposits, but possibly including deposits originating from a coastal overlap associated with Neogene marine transgressions (Arai, 2006; Dominguez, 2009). The delta plain deposits are composed mainly of moderately sorted, coarse- to very-coarse grained sands of beach ridges distributed along the coastline. Downstream, sandy silts of the Doce River spread over floodplains. Residual and very poorly-preserved mangrove vegetation close to marine influence occurs at the margin of coastal lagoon systems. Elongated coastal sand barrier occurs parallel to the shore and are separated from the mainland by a lagoon. It displays 37 and 3.6 km in length and width, respectively, and presents multiple beach ridges. These likely represent successive shoreline positions formed during the coastline progradation associated with the RSL fall (Otvos, 2000).

The studied delta plain covers an area of ~2700 km^2. It displays fluvial channels and an extensive network of paleochannels. The abandoned channels are straight to meandering, and they maintain the shape and typical concavity of the original channel, resulting lakes. Avulsion may have been responsible for the partial or complete abandonment of several channels due to rapid sand accumulation (Cohen et al., 2014).

2.2. Climate

Southeastern Brazil is characterized by a warm and humid tropical climate, with annual precipitation averaging 1400 mm (Peixoto and Gentry, 1990). Seasonal climate is controlled by position of the South Atlantic Convergence Zone (SACZ), which controls moisture at this latitude and Inter Tropical Convergence Zone (ITCZ) or meteorological equator that divides the year into a rainy (austral summer) and a dry season (austral winter) (Carvalho et al., 2004). The SACZ is evident along the year, but more intense during the summer, when it is connected with the area of convection over the central part of the continent, causing episodes of intense rainfall over much of southeastern South America (Liebmann et al., 1999). The ITCZ corresponds to the belt of minimum pressure and intense low-level convergence of the trade winds over the equatorial oceans which reaches the northeast Brazil, producing the rainy season of northern State of Espírito Santo — Brazil (Garreaud et al., 2009). The rainy season occurs between November and January, with a drier period between May and September. The average temperature ranges between 20° and 26 °C (Carvalho et al., 2004).

2.3. Modern vegetation

The vegetation is characterized by tropical rainforest, with plant families such as Fabaceae, Myrtaceae, Sapotaceae, Bignoniaceae, Lauraceae, Hippocrateaceae, Euphorbiaceae, Annonaceae and Apocynaceae (Peixoto and Gentry, 1990). An herbaceous plain, mainly represented by Cyperaceae and Poaceae with some trees and shrubs, occurs at the edges of the proximal delta plain. The transition from the distal deltaic plain to the shoreline is dominated by *restinga* vegetation with tolerance the stresses of sand mobility and salt spray (Moreno-Casasola, 1986), represented by shrub vegetation and coastal herbs over sand plains and dunes without tidal influence colonized by *Ipomoea pescaprae* (Convolvulaceae), *Hancornia speciosa* (Apocynaceae), *Chrysobalanus icaco* (Chrysobalanaceae), *Hirtella Americana* (Chrysobalanaceae), *Cereus fernambucensis* (Cactaceae), *Anacardium occidentale* (Anacardiaceae) and *Byrsonima crassifolia* (Malpighiaceae). Palm trees, as well as orchids and bromeliads growing on trunks and branches of larger trees, are also present along the shoreline. The vegetation inside the lakes and at their margins comprises *Tabebuia cassinoides*, *Alchornea triplinervia* and *Cecropia sp*., and emergent, submerged, floating-leaved and floating plants, such as *Typha* sp., Cyperaceae, Poaceae, *Salvinia* sp., *Cabomba* sp., *Utricularia* sp. and *Tonina* sp. The marine and fluvial marine areas are colonized by mangroves. These, located around 60 km