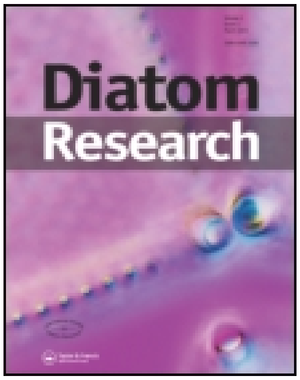

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The growth of the Doce River Delta in northeastern Brazil indicated by sedimentary facies and diatoms

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The combination of diatom analyses with sedimentary facies has been limited in studies aimed at reconstructing paleoenvironments and the history of sea-level fluctuations in coastal settings. The present study integrated facies and diatom analyses, together with ^{14}C dating and geomorphological information derived from remote sensing, to analyze the Quaternary deposits of a paleoestuary nearby the Doce River Delta in northeastern Brazil. The goal was to demonstrate the potential of diatoms as a paleoenvironmental proxy and improve the history of Holocene sea-level fluctuations in that region. The deposits, ranging from 7425–7509 to 1313–405 cal yr BP, were arranged in an overall regressive succession recorded by the upward superposition of estuarine channel, estuarine central basin, lake/ria and fluvial channel/marsh facies associations. Marine, marine/brackish and freshwater diatoms were found in these deposits. The highest concentration of diatoms was associated with the low-energy estuarine central basin deposits formed when the relative sea level was high. In the mid-Holocene, ca. 5000 cal yr BP, the coastline began its progradation due to a relative drop in sea level. This change in coastal dynamics was marked by a decrease in the concentration of diatoms and the prevalence of freshwater species over marine and marine/brackish water species. As a result of the Doce River Delta progradation, the studied estuarine channel was closed due to the accumulation of sand as beach ridges and barriers at the river mouth, a process that ultimately led to the estuary being replaced by a lake/ria.

Keywords: *diatoms, Holocene, sedimentology, isotopes, paleoenvironment, Doce River Delta*

Introduction

Diatom microfossils have been an important constituent of sedimentary deposits since the Late Cretaceous, being particularly widespread on strata of Late Cenozoic Age, when this group increased in abundance. These organisms are of great interest to the analysis of sedimentary deposits due to: (i) their excellent preservation in the fossil record; (ii) their sensitivity to changes in the physical and chemical properties of continental, marine and coastal environments; and (iii) their easy classification at the species/sub-species level by means of frustule morphology (Round et al. 1990, Jones 2007). However, the presence of diatoms is limited in environments experiencing low nutrient supply, as well as low silica and iron availability, where dissolution of the frustules occurs rapidly (Brezezinski et al. 1999, Martin et al. 1999).

The great sensitivity of diatoms to environmental parameters enables interpretation of physical, chemical and biological changes in freshwater, brackish, estuarine and marine environments (Round et al. 1990, Bennion 1995, Hillebrand & Sommer 2000, Rivera & Díaz 2004, Hassan et al. 2006, Korhola 2007). As a result, diatom microfossils have been used with success as a tool for correlating deposits formed in different environments.

Several environmental variables including sand contents and water depth affect the distribution of diatoms (Zong et al. 2010). This is also strongly affected by salinity, as reported by Sherrod (1999), Paterson et al. (2000) and Roe et al. (2009). As a result, increasing numbers of reports have documented the significance of diatoms as a proxy in paleoenvironmental studies of coastal settings, where changes in salinity are frequent as a consequence of the interplay of fluvial and marine processes (Denys & Wolf 2010).

Many studies of diatoms aiming at paleoenvironmental reconstructions have focused on Quaternary and Holocene deposits (Burckle & Akiba 1978, Pickard et al. 1986, Smol 1988, Korhola et al. 2000, Bigler 2001). In addition, diatoms have been an important proxy for reconstructing the history of sea-level fluctuations, which are useful in predictions of future global changes (Palmer & Abbott 1986, Shennan et al. 1993, Zong & Horton 1999, Roe et al. 2009, Denys & De Wolf 2010, Watcham et al. 2013). As the sea level rises along a coastline, the marine

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versus freshwater influence increases, leading to changes within diatom communities due to habitat modification (Robinson 1993, John & Pizzuto 1995, Zong et al. 2006). This is particularly noticeable in estuaries, where daily variations in river discharge have a rapid effect on diatom growth (Brezezinski et al. 1999).

Previous studies have shown the advantages of integrating diatom data with detailed analysis of sedimentary facies for improving the reconstruction of coastal dynamics and its relation to sea-level fluctuations (Ta et al. 2001, Vargas et al. 2004). This approach should be further explored in a larger variety of geological settings due to its potential for providing robust reconstructions of coastal dynamics and refinement of the history of regressive and transgressive events that have characterized sediment deposition in the Quaternary. In general, this type of approach suffers from an overall lack of detailed information on the relationship between diatom assemblages and the characteristics of the physical environment (Zong & Horton 1998, Zong et al. 2006).

This study focuses on Late Quaternary deposits in one area of the Doce River coastal plain in northeastern Brazil, where an investigation integrating diatoms, facies analysis and ^{14}C dating was carried out. These data were analyzed within a geomorphological context derived from remote sensing. The overall objective was to improve the knowledge about sediment dynamics in the Doce River Delta within the context of Holocene relative sea-level fluctuations. Applying an interdisciplinary approach to this study area was necessary because this was a very dynamic setting within the Quaternary time frame. Significant changes in sediment transportation and deposition linked to sea-level fluctuations took place as the coast prograded and formed the Doce River Delta (Dominguez et al. 1981, 1992).

Previous studies based on several biological and geological proxies have recorded transgressive and regressive events along the eastern coast of Brazil, with an important impact on coast configuration (Dominguez et al. 1981, Suguio et al. 1982, Suguio & Kohler 1992, Martin et al. 1993, 1996). However, the history of sea-level fluctuations along the Brazilian coast during the late Quaternary remains to be reconstructed both for different areas and for the application of a larger number of paleoenvironmental proxies, particularly ones that can allow more detailed interpretations of the transgressive–regressive events within a higher resolution scale than currently available. The analysis of diatoms within the context of sedimentary facies distribution over time has the potential to refine the history of sea-level fluctuations in this area. This study may also help to demonstrate the advantages of combining these tools in paleoenvironmental refinements of coastal environments.

Materials and methods

The study site is located near the district of Linhares, in the State of Espírito Santo, northeastern Brazil (Fig 1).

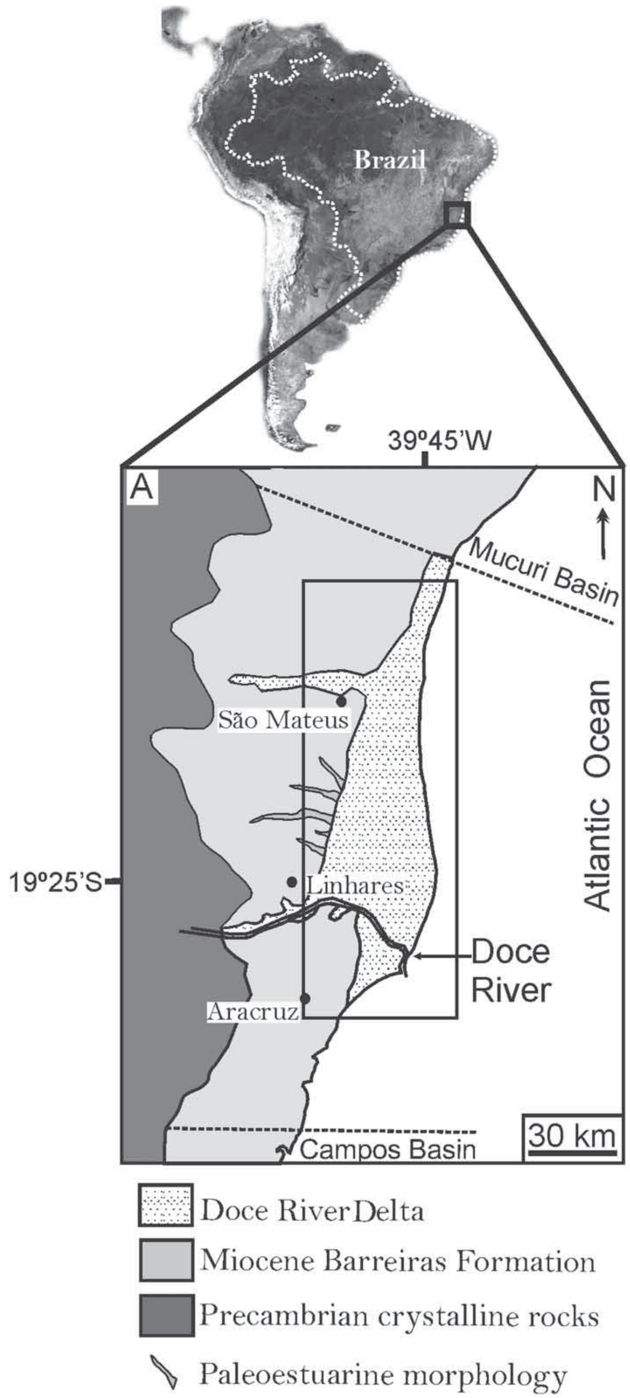

Fig. 1. Map location of the study area in the Doce River deltaic coastal plain, Linhares, State of Espírito Santo, Brazil.

This locality is ca. 500 km north of Rio de Janeiro. The climate in this region is classified as Aw in the Köppen system (Köppen 1900), with a humid summer and a dry or less humid winter. In general, mean temperature in winter is 18°C, and the average annual precipitation is 1178 mm. Pristine vegetation remains near the study area and consists of dense ombrophylous lowland forest, which is intermingled with open vegetation patches of grass and shrubs (Instituto Brasileiro de Geografia, 2004).

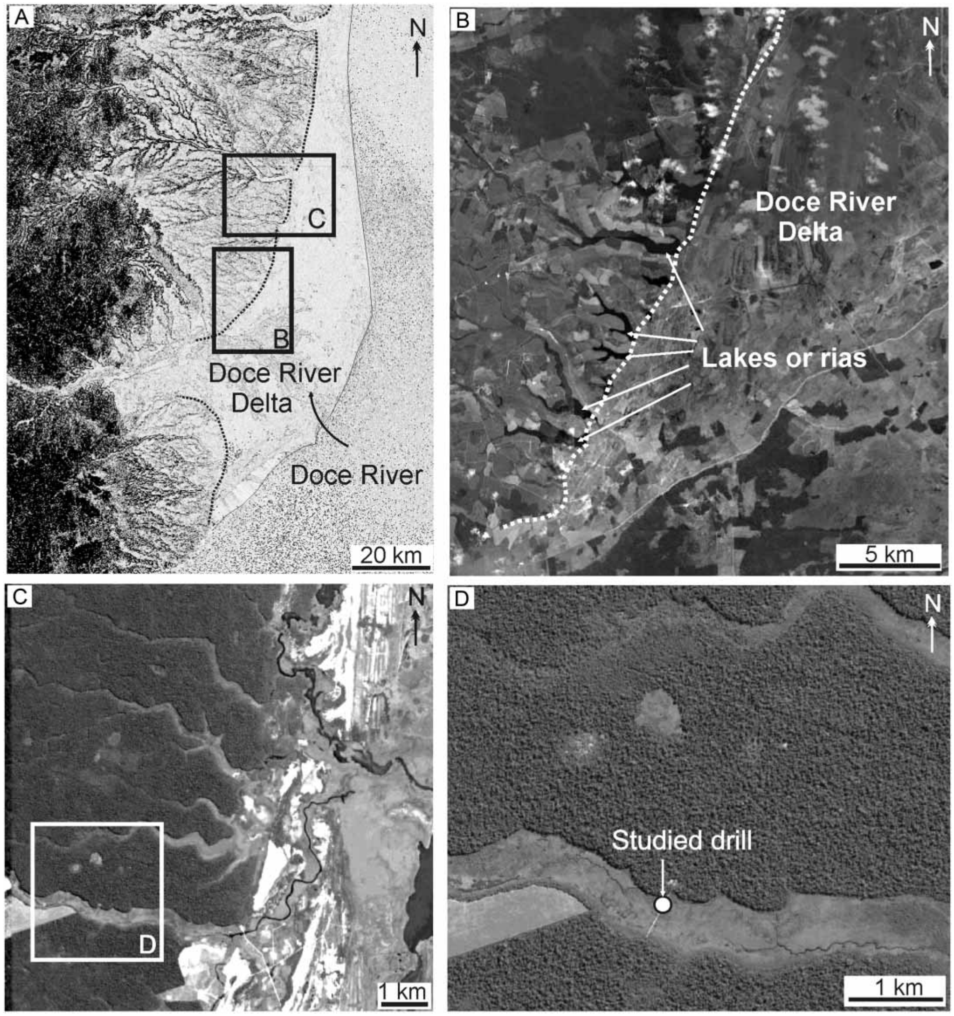

Fig. 2. Morphological characterization of the Doce River Delta in the study area. (A) SRTM-DEM illustrating the geometry of the delta (higher elevations are in darker gray tones). (B) Lakes/rias formed along the paleocoastline near the Doce River as a result of the blocking of estuarine mouths due to sand entering during delta progradation. (C) Estuaries filled with sediment formed north of the Doce River. (D) Detail of the studied drill acquired at the margin of a paleoestuary (see C for location).

Geologically, the Doce River coastal plain is located within an area formed by a complex of Precambrian crystalline rocks of the Espírito Santo Basin (Fig. 1). This is a passive margin basin formed in association with the opening of the South Atlantic in the Late Jurassic and Early Cretaceous (Vieira et al. 1994, França & Tokutake 2004, França et al. 2007). The Espírito Santo Basin is limited by the Campos Basin to the south, crystalline Precambrian rocks to the west, Mucuri Basin to the north and the Atlantic Ocean to the east (Fig. 1).

The sedimentary fill of the Espírito Santo Basin includes mainly Berriasian to Albian deposits that overly Precambrian rocks (Milani et al. 2001, França et al. 2007). In addition, the basin contains an Upper Cretaceous to Quaternary succession of the Espírito Santo Group, the latter including Pleistocene marine terraces and Holocene deposits. These strata occupy a large part of the Doce River coastal plain, recording lagoon and fluvial environments related to an intralagoon delta (Suguio et al. 1982).

The Doce River Delta, which is nearly 40 km in width and 130 km in length (Fig. 2A), is a wave-dominated delta characterized by sand accumulation as a series of beach ridges. Eastward coastal progradation has given rise to elongated lakes or rias along the paleocoastline that replaced the estuaries (Fig. 2B). A set of rias north of the Rio Doce mouth was filled up with sediment during the Holocene (Fig. 2C).

The evolutionary history of the Doce River coastal plain is related to the last transgressive–regressive events of the latest Quaternary (Dominguez et al. 1981, Suguio et al. 1982). According to these authors, the sea level was 8–10 m above the modern one during the last interglacial (ca. 120,000 yr BP), when valleys excavated in the Barreiras Formation were drowned. Pleistocene sandy terraces were formed during the subsequent regression associated with the Last Glacial Maximum around

23,000 and 18,000 yr BP, when the coastline prograded as the continental to transitional deposits accumulated over the platform. After 18,000 yr BP, the fluvial valleys were again drowned during a subsequent rise in sea level, forming estuaries (Dominguez et al. 1981, Suguio et al. 1982, Suguio & Kohler 1992, Martin et al. 1993). It has been proposed that at ca. 7700 yr BP a lagoon developed in front of the Doce River, followed by the construction of an intralagoonal delta attached to a barrier island system (Suguio et al. 1982, Martin et al. 1993, 1996). According to these authors, the main construction of the Doce River Delta would have been initiated only during the last 5000 yr BP, when the lagoonal system was gradually filled with sediments and a wide delta plain developed. The delta grew through the development of sand ridge complexes added to a barrier island, with increasing sandy deposition during the delta construction as a response of a sea-level drop. The new data of the present work contribute to refining this proposed evolutionary history.

The geomorphological characterization of the study area was based on the visual analysis of freely accessed remote sensing products, including Landsat 5-TM images (www.dgi.inpe.br) and digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) (ftp://e0srp01u.ecs.nasa.gov/srtm/). The optical images were registered and processed for red, blue and green band composition. The SRTM–DEM is the original 90-m resolution (3 arcsec) synthetic aperture radar data, acquired with the C band by the National Aeronautics and Space Administration (NASA), National Imagery and Mapping Agency (NIMA), German Space Agency (DLR) and Italian Space Agency (ASI). The SRTM data were processed using customized shading schemes and palettes to improve the view of the morphology of interest. High-resolution, QuickBird and SPOT optical images derived from Google Earth helped to provide a more detailed morphological characterization of the study area.

The study was complemented by analysis of one 11-m-thick continuous core having a diameter of 55 mm. The core was collected with a percussion drilling Robotic Key System (RKS), model COBRA mk1 (COBRA Directional Drilling Ltd., Darlington, UK). The site was chosen to record the history of a paleoestuary located ca. 5 km upstream from the Doce River Delta paleoshoreline and almost 20 km from the modern coastline (Fig. 2D). This feature, nearly 30 km in length and 330 m in width, was selected for this study because it is representative of the paleoestuarine systems of the Doce River area and is located in an area accessible by car, which facilitated the transportation of our drilling system. The faciological analysis included descriptions of features such as lithology, grain size, sedimentary structure, stratigraphic surface and fossil content, which were described using a lithostratigraphic profile.

Samples for diatom analysis were collected at ca. 10 cm intervals on average. Sampling aimed to record preferentially finer-grained lithologies consisting of mud layers and the finer-grained components of heterolithic deposits, which are more suited to the preservation of diatoms, providing more uniform results.

Diatoms were extracted from a total of 65 samples. Samples (1 cm^3 each) were pretreated with 30% H_2O_2 and 10% HCl, and mounted on standard microscope slides using Naphrax. Diatom identification was based on several published diatom morphological descriptions (Round et al. 1990, De Oliveira & Steinitz-Kannan 1992, Houk 2003, Bigunas 2005). The counting included 200–500 valves for each slide, depending on the concentration. Identification and counting were undertaken using a Carl Zeiss Axioskop 40 microscope at the ^{14}C Laboratory for the Center for Nuclear Energy in Agriculture (CENA/USP). Diatoms were identified according to frustule patterns and ornamentations, with the sum and percentage calculated by TILIA and TILIAGRAPH (Grimm & Troostheide 1994). These softwares were also used for establishing the zonation of diatoms and the constrained incremental sums of squares (CONISS) diagram. Data are presented in diagrams as percentages of the total sum of diatoms.

Six samples were dated by ^{14}C conventional analysis, with sample preparation in the Radiocarbon Laboratory at the Center for Nuclear Energy in Agriculture (Brazil) and accelerator mass spectrometry (AMS) analysis at the University of Georgia (UGAMS), USA. The samples were more or less regularly spaced to be representative of the entire core. Only richly organic mud and peat layers were considered for this type of analysis. For this reason, deposits located at the base of the core, which include sand and heterolithic lithologies, were not dated, because of their high potential to contain reworked organic material that might provide less meaningful ages. Possible contaminants, such as modern roots, were manually eliminated during pretreatment. The organic matter was extracted according to laboratory standard pretreatment with an acid–alkali–acid wash. This procedure attempted to remove recent organic matter or ancient organic matter in process of slow decomposition that was adsorbed in the sediments, and which might provide carbon younger than the average for the samples. The serial rinses eliminated all contaminants such as associated sediments and rootlets. Conventional ^{14}C ages were calibrated to calendar years BP (cal yr BP, 2-sigma) using CALIB 6.0 (Reimer et al. 2009).

Sedimentary facies

The core consists mostly of fine- to coarse-grained sands, massive muds and heterolithic deposits (Fig. 3). These lithologies are organized into fining upward successions. Sedimentary facies characteristics led us to define four facies associations, which are compatible with increased continental influence over time. The deposits record the following superposition of environments from base to top: estuarine channel (facies association A), estuarine central

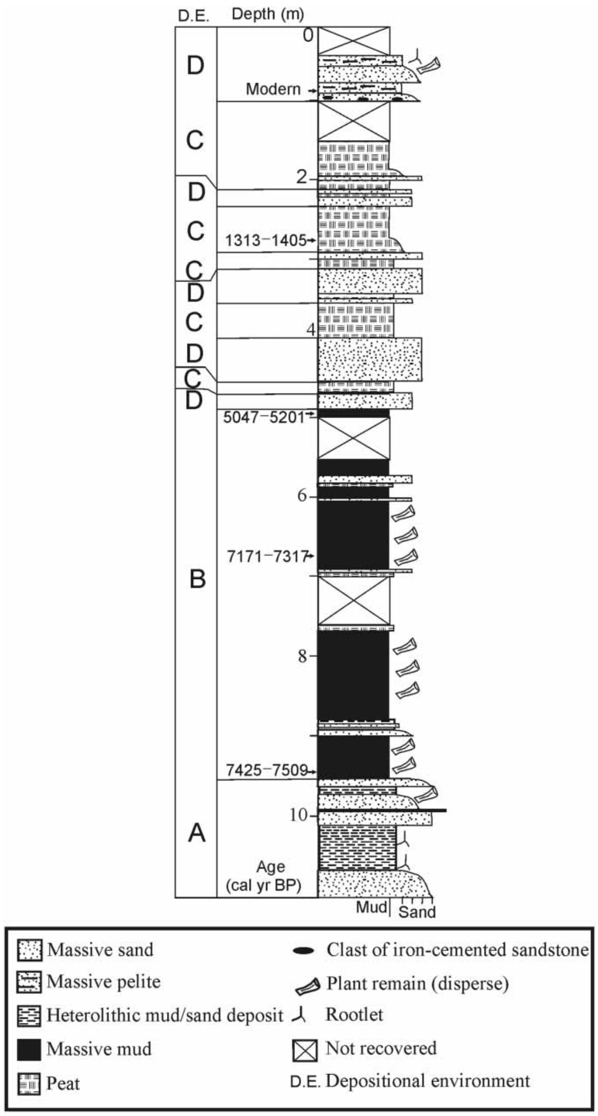

Fig. 3. Lithostratigraphic profile of the studied core, with facies and facies associations. A, estuarine channel; B, estuarine central basin; C, lake/ria; D, fluvial channel/marsh. Calibrated ^{14}C ages are also plotted.

basin (facies association B), lake/ria (facies association C) and fluvial channel/marsh (facies association D).

Facies association A (estuarine channel) occurs in the lowest part of the core, between 11.0 and 9.7 m (Fig. 3). These deposits consist of massive, fine- to coarse-grained sand, fluidized sand and lenticular heterolithic bedded deposits. They are organized into fining upward successions with sharp erosional bases. Facies association A has plant remains and laminae of fragmented organic matter.

Facies association B (estuarine central basin) occurs between 9.7 and 4.9 m depth (Fig. 3). These deposits consist mostly of greenish to gray, plastic, massive mud. Thin (i.e., <10 cm) layers of massive fine- to medium-grained sand, and thin (i.e., <0.05 m) pure peat layers are interbedded with the massive mud. Plant remains are dispersed throughout this association, forming layers <3 cm thick.

Facies association C (lake/ria) was recorded in several intervals between 4.9 and 1.0 m depth (Fig. 3). This association consists of mud, muddy peat and pure peat layers. The deposits are interbedded with facies association D, forming several fining upward successions <2 m thick.

Facies association D (fluvial channel/marsh) is found at several intervals interbedded with association C and also at the top of the core, above 1.0 m depth (Fig. 3). It includes packages up to 0.5 m thick of massive, fine- to medium-grained sand, and massive pelite with plant remains. As in association A, these deposits are sharp based, with ferruginous sand clasts (diameter < 0.02 m) locally present over the basal surface.

^{14}C dating

The lower and intermediate parts of the studied deposits yielded radiocarbon ages between 7425–7509 and 1313–1405 cal yr BP (Table 1), with a consistent vertical distribution indicating progressive age increase with depth.

Table 1. Calibrated accelerator mass spectrometry ^{14}C dating of studied core of a paleoestuary Quaternary deposit nearby the Doce River Delta in northeastern Brazil.

UGAMS Laboratory code	Depth (m)	Material analyzed	^{14}C yr BP measured	Cal yr BP
10567	0.8	Organic mud	Modern	No data
10568	2.7	Peat	1480 ± 25	1313–1405
10569	4.9	Organic mud	4500 ± 25	5047–5201
10570	6.7	Organic mud	6330 ± 30	7171–7317
10571	9.4	Organic mud	6560 ± 30	7425–7509

Deposits corresponding to association A were not dated because of their sandy nature. Three ages were obtained in deposits from association B: 7425–7509, 7171–7317 and 5047–5201 cal yr BP. The age of 1313–1405 cal yr BP was recorded in the middle of association C, whereas association D had a modern age at its bottom.

Results

The analysis of diatoms led to the identification of 33 taxa, among which marine and/or brackish diatoms are the most abundant ones (Fig. 4). Five zones were recognized at depth intervals of 11–10 m (zone 5), 10–8.9 m (zone 4), 8.9–7 m (zone 3), 7–5 m (zone 2) and 5–0.4 m (zone 1). Zone 5 was barren of diatoms and zone 1 yielded only low numbers of mostly freshwater and secondarily marine diatoms, which were not suitable for statistical analysis. Marine, marine/brackish and freshwater diatom species are present in zones 4 to 2. Marine diatoms are generally dominant, followed by marine/brackish and freshwater diatoms.

Zone 4 (10–8.9 m) consists only of marine and marine/brackish diatoms. The marine species are dominated by *Tryblionella punctata* (22.2–26.8%), *Paralia sulcata* (10.7–28.1%) and *Diploneis gruendleri* (8.2–17.9%). Marine/brackish species occur in lower percentage relative to the marine species, consisting mostly of *Tryblionella granulata* (17.2–23.6%) and *Diploneis smithii* (0.7–1.9%). Freshwater diatoms were not recorded in this zone.

Zone 3 (8.9–7 m) is also characterized by marine and marine/brackish taxa. There is a slight increase in the percentage of the most abundant marine diatoms in this zone relative to zone 4, i.e., *T. punctata* (11–47%), *P. sulcata* (8.3–29.0%) and *D. gruendleri* (8.2–33.5%). *Surirella fastuosa* f. *recendes* (0.9–8.1%) is more frequent in this zone than in the previous ones. *Nitzschia granulata* var. *hyalina* (0.5–3.2%), *Cymatotheca weissflogii* (0.8–4.1%), *Actinoptychus senarius* (0.2–1.1%), *Hyalodiscus subtilis* (0.3–0.9%) are also present. Marine/brackish diatoms are well represented by *T. granulata* (10.9–29.6%) and *D. smithii* (0.8–10.4%), the latter with a higher percentage relative to zone 4. Freshwater diatoms were also not recorded in this zone.

Zone 2 (7–5 m) contains marine and marine/brackish diatoms similar to zones 3 and 4, but with the local occurrence of freshwater diatoms. Marine diatoms are mainly represented by *T. punctata* (7.6–42.2%), *P. sulcata* (7.6–21.2%) and *D. gruendleri* (0.5–21.1%). Also present are the marine species *A. senarius* (0.5–4.9%), *C. weissflogii* (1.5–3.5%) and *H. subtilis* (0.4–3.0%), which occur in a higher percentage relative to zones 3 and 4, where they are also present. Similarly to those zones, the dominant marine/brackish species in zone 2 are *T. granulata* (13.6–29.5%) and *D. smithii* (0.2–3%), the latter at a slightly lower percentage than in zone 3. In addition, there are local occurrences of *Rhopalodia gibberula* (up to 3.8% at 6 m depth) and *Surirella linearis* (18.5% at 7 m depth). Freshwater diatoms were recorded in one sample (i.e., 7 m depth), with *Eunotia bidentula* (24%), *E. indica* (14%),

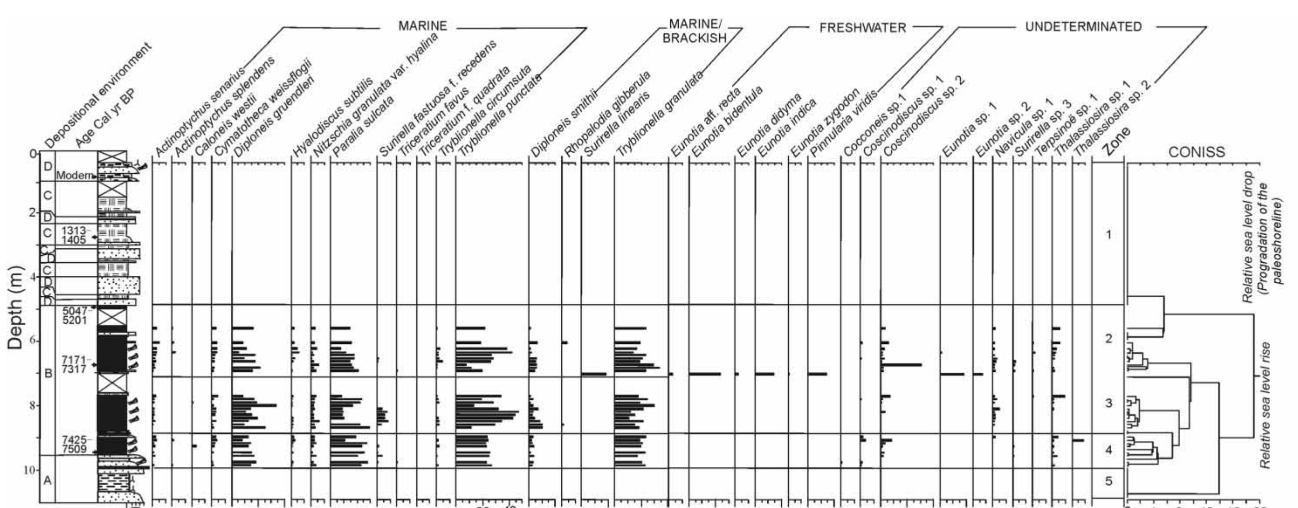

Fig. 4. Relative abundances of diatoms and the five zones recognized by the CONISS program. A, estuarine channel; B, estuarine central basin; C, lake/ria; D, fluvial channel/marsh.

Pinnularia viridis (13%), *Eunotia* sp. 1 (17.9%) and *Eunotia* sp. 2 (7.3%) being the most frequent. The species *Eunotia* aff. *recta* (0.9%), *E. didyma* (2.5%) and *E. zygodon* (0.6%) occur subordinately.

As previously described, zone 1 (5–0.4 m) did not present enough diatom valves for statistical analysis. However, the depth interval between 4.8 and 1.9 m recorded whole and fragmented valves of freshwater diatoms, consisting of *E. zygodon*, *E. didyma*, and species of *Desmogonium* Ehrenberg and *Pinnularia* Ehrenberg, as well as some fragments of marine and brackish water species of the genera *Actinoptychus* Ehrenberg and *Diploneis* Ehrenberg. No diatom valves were recovered above 1.9 m depth.

Discussion

Depositional environment

The integration of geomorphology, sedimentary facies, ^{14}C dating and diatom assemblages shows that the studied core records depositional environments that can be related to the abandonment of an estuarine channel over the mid-Holocene. Analysis of remote sensing data revealed that the studied site is within an estuarine channel that was filled with sediment as its mouth was barred by sand during the growth of the Doce River Delta. The estuarine interpretation was confirmed by subsurface analysis of sedimentary facies, and also reinforced by the distribution of diatom assemblages, as discussed below.

The upward organization of the four facies associations allows reconstruction of the evolution of the studied paleoestuary over time. Estuarine conditions prevailed at the base of the succession, being represented by facies associations A and B. The erosional base of association A is indicative of high energy flow, while the fining upward successions record several pulses of decreasing flow energy over time. These characteristics are consistent with alternating periods of erosion and deposition, as typical of channel successions (Allen 1982, McLaurin & Steel 2007). Considering the proposed estuarine setting, facies association A most likely records deposition within the estuarine channel. This interpretation is also consistent with the upward gradation of association A into B, the latter attributed to a low-energy subtidal estuarine environment, as indicated by the overall dominance of massive mud deposited from suspension. The abundance of plant debris suggests a setting close to a source of continental inflow. The central part of an estuary is a zone of maximum turbidity, where flow energy is at a minimum and mud deposition from suspension reaches its highest values due to the seaward decreasing riverine inflow added to the landward decreasing wave and tidal inflow (Dalrymple et al. 1992). Therefore, the most likely interpretation is that facies association B represents the sedimentary record of an estuarine central basin. Within the proposed environmental context, the thin sand layers in facies association B might be related to bayhead or tidal deltas.

Facies association C is attributed to a lake/ria environment, based on the predominance of muddy lithologies, including muddy peat and peat deposits. The environment had to be of low energy and reducing conditions to accumulate these lithologies. Considering this environmental setting, and combining it with the recognition of a ria morphology at this study site, it is suggested that the base of these deposits at 4.7 m depth, formed right after 5047–5201 cal yr BP, probably records a time when the estuary initiated its closure due to sand accumulation in its mouth.

The sandy nature, sharp basis and fining upward lithologies of facies association D are comparable with those in association A, which also lead to its attribution to channel deposits. Ferruginous sand clasts on the basal surface are related to reworking during the initiation of channel sedimentation, when flow energy was still high. The most likely interpretation is that association D records small channels marginal to the ria, or even channels that developed over areas already filled with sediments. It is expected that decelerating flow eventually entering this basin through these channels might have also caused sand accumulation as suspension lobes. The sand packages with sharp basis and tops might record these events.

The vertical distribution of facies associations in the studied core reflects the development of progressively more continental-influenced deposits over time. The upward grading of facies association A (estuarine channel) into B (estuarine central basin) characterizes a seaward facies shift compatible with a regressive coast. This trend continued over time, with the superposition of more continental-influenced deposits (facies associations C and D, formed in lake/ria and fluvial channel/marsh settings, respectively) over estuarine central basin deposits. Based on this information, and following a worldwide pattern, the Doce River Delta area became a regressive coast during the last 5047–5201 cal yr BP.

Diatoms as a paleoenvironmental proxy

The diatom assemblages recorded in the studied deposits are, in general, in good agreement with the interpretation derived from sedimentary facies. Among the various diatom species, many are ecologically sensitive to different environmental factors, such as salinity, pH, temperature, substrate sediment type and ground altitude (Zong & Horton 1998). While some taxa are better adapted to the marine realm, others tend to tolerate large salinity variations in coastal zones, being mostly cosmopolitan. Estuaries in particular have high productivity, but low diversity, due to the stress caused by large variations in salinity. There is a distinctive zonation in estuarine areas due to a strong salinity gradient (Dalrymple et al. 1992) resulting from the encounter between riverine freshwater discharge and marine water influx (Chen et al. 2007, Zhang et al. 2008, Zong et al. 2009), with only a few organisms adapted to such conditions. In general, marine, brackish and freshwater diatoms can be found along the entire extension of an estuarine system, i.e., inner, central or outer part (Kaiser 2005, Zong et al. 2010). However, there is a well-defined distribution trend from proximal to distal areas, with freshwater species decreasing with increasing salinity and marine species increasing seaward (Kaiser 2005). Kaiser (2005) also recorded a decrease in the number of both marine and freshwater species in brackish water environments, with the development of species adapted to wide variations in salinity and brackish water conditions.

Diatoms are useful for reinforcing the estuarine interpretation for the studied deposits and, in particular, for distinguishing zones of contrasting salinity. In general, the abundance of diatoms in zones 2–4 and their overall low diversity are compatible with the proposed estuarine interpretation. The taxa classified as marine in Fig. 4 may occasionally be found in brackish waters, although they are more often recorded in marine waters (Azevedo 1999, Souza-Mosimann & Laudares-Silva 2005). Thus, the overall predominance of *D. gruendleri*, *P. sulcata*, *T. punctata* and *T. granulata*, as well as the frequent occurrence of *A. senarius*, *C. weissflogii*, *D. smithii*, *H. subtilis*, *N. granulata* var. *hyalina* and *S. fastuosa* f. *recendes*, reflect elevated salinity and high brackish water conditions, common in estuaries.

The diatom assemblages indicate a marine and marine/brackish signature for facies associations A (uppermost part) and B, corresponding with diatom zones 2–4. This is consistent with their proposed attribution respective to estuarine channel and estuarine central basin settings, as previously interpreted here based on facies analysis. The lack of diatoms in zone 5 is related to the high flow energy inherent of the estuarine channel environment. Deposition of diatoms was only possible when the flow decreased within the channel. The dominance of marine and marine/brackish diatom species in zones 2–4 conforms to an estuarine setting characterized by the mixture of riverine freshwaters with marine inflow, typical of middle estuaries (Dalrymple et al. 1992). Many modern estuaries in southeastern Buenos Aires Province in Argentina contain brackish and freshwater euryhaline diatom taxa (Hassan et al. 2006). The dissipation of marine and fluvial flow into the estuarine central basin makes this a site favorable for mud accumulation (Barusseau et al. 1985, Nichols et al. 1991, Dalrymple et al. 1992, Reinson 1992). The frequent mixture of marine, marine/freshwater and freshwater species of diatoms in these strata confirms a setting with mixed water influences. The highest occurrence of diatoms in facies association B leads to the suggestion that estuarine central basins are favorable settings for the preservation of diatom valves, which is probably due to their low flow energy and abundant mud deposition from suspension. In addition, benthic diatoms show high potential for valve preservation in these settings with high silica availability. The Scheldt Estuary in the North Sea recorded the highest concentration of diatoms in low-energy shallow waters with constant riverine supply of dissolved silica (Arndt et al. 2007).

The mixture of marine and marine/brackish water diatoms with freshwater diatoms in zone 2 suggests deposition in the middle estuarine setting with higher fluvial inflow. The appearance of the freshwater genus *Eunotia* Ehrenberg in this zone is consistent with an upward increase in continental conditions. In general, this genus is predominantly freshwater and acidophilic, being frequently found in stagnant waters (Germain 1981). In addition, most of the species of this genus are described as aerophylic (Patrick & Reimer 1966, Rodrigues 1984, Gasse 1987). The tendency for increased upward continental conditions is also sustained by the massive occurrence of the freshwater diatoms *E. zygodon*, *E. didyma*, *Desmogonium*, *Eunotia* and *Pinnularia* in zone 1. Marine diatoms, when present in this zone, consist only of a few fragments of marine taxa as *Coscinodiscus* Ehrenberg, *Actinoptychus* and *Diploneis*.

The upward increasing continental contribution indicated by the vertical distribution of diatoms in the core agrees with the proposed replacement of the estuarine channel into a lake/ria and fluvial channels/marsh over time as the delta prograded and sand deposits barred the estuarine mouth. Interestingly, this process might have taken place gradually, because although in low concentration and fragmented, facies associations C and D still contain both marine and marine/brackish diatoms, represented by zone 1.

Refining the reconstruction of sediment dynamics based on diatoms

Because of their high sensitivity for distinguishing different salinities, the vertical distribution of diatoms in the studied deposits helped demonstrate their estuarine nature and refine the reconstruction of coastal dynamics in the Doce River Delta within the context of mid-Holocene sea-level fluctuations (Fig. 5). As presented in the foregoing discussion, the recorded vertical distribution of facies associations denotes a depositional setting characterized by an overall regressive nature. This was associated with a seaward shift in the coastline as the delta initiated its construction, which progressively reduced the marine influence in the estuarine systems and ultimately caused their total disconnection from ocean circulation as the deltaic beach ridge complexes developed.

Our data are entirely compatible with the initiation of a delta growth starting in the mid-Holocene, i.e., around 5047–5201 cal yr BP. This event followed the early to mid-Holocene transgression, when relative sea level exceeded the modern sea level by 4 to 6 m (Dominguez et al. 1981, Suguio et al. 1982, Martin et al. 1993, 1996, 2003), as recorded in many other areas of the Brazilian coast (Martin & Suguio 1992, Souza Filho 1995, Behling et al. 2001, Cohen et al. 2005, Angulo et al. 2006, Vedel et al. 2006, Rossetti et al. 2008). During

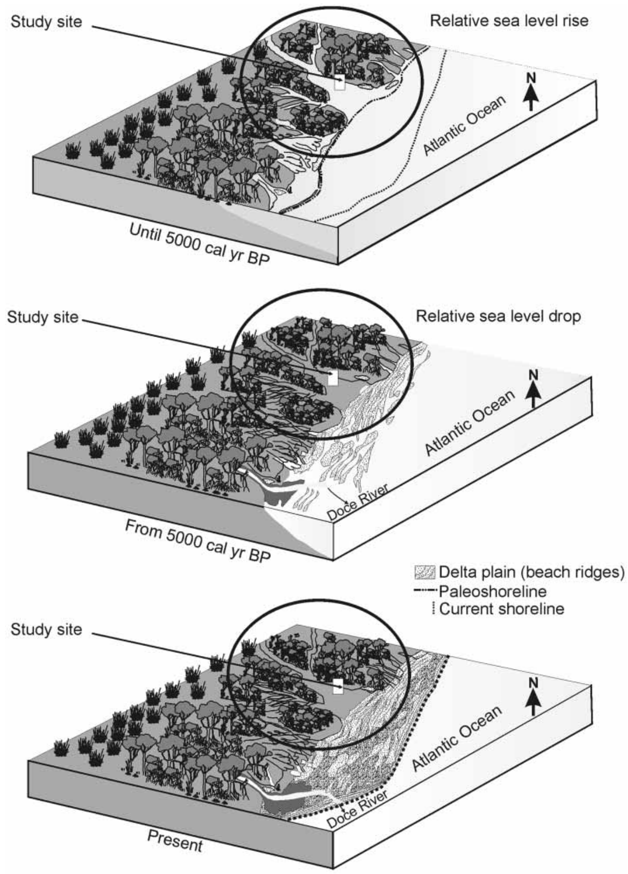

Fig. 5. Schematic representation of the depositional system proposed for the studied area in the Doce River coastal plain during the Holocene.

this time, estuaries dominated the landscape of the studied coastal area. Coast progradation took place in the mid- to Late Holocene, leading to the establishment of the Doce River Delta and closure of estuarine channels. The latter was a consequence of the development of beach ridge systems by alongshore dispersion of sands brought by the Doce River Delta, a process that caused the replacement of the estuaries into a lake/ria. As a result, wave and tide influences within the estuary were progressively reduced to the extent that an estuarine circulation could no longer be maintained at the studied site, considering its location ca. 5 km from the paleocoastline.

The prevalence of well-preserved valves of marine/brackish diatoms constitutes clear evidence that the studied site remained under influence of fully estuarine conditions until ca. 5000 cal yr BP. In particular, the occurrence of typically marine diatom taxa, such as *D. gruendleri*, *P. sulcata*, *T. punctata*, *Caloneis westii*, *C. weissflogii* and *Triceratium favus* in zones 2–4 indicates that the investigated estuarine channel remained under the influence of significant marine inflow during deposition of facies association B. In the mid-Holocene, the coast morphology changed from one dominated by estuaries into a prograding coast that ultimately resulted in the modern wave-dominated deltaic system.

Estuaries and lagoon–barrier island systems colonized by mangroves probably occurred along the Linhares littoral, which was followed by a prograding coast when there was a decrease in marine influence, mangroves shrank and freshwater vegetation expanded, as a result of a relative sea-level fall. Buso Junior et al. (2013) and França et al. (2013) have recently recorded this transition in the depositional environment of the Doce River Delta area during the Late Holocene. The present study agrees with this overall coastal dynamics, although progradation was recorded earlier in the studied core, i.e., in the mid-Holocene. The time lag in the transition from estuary to coastal progradation may be attributed either to the radiocarbon dating resolution or to the distinct sensitivity of the proxies used for paleoecological reconstruction near the Doce River Delta.

Conclusions

Diatom assemblages and sedimentary facies present in an 11 m-long core from the Doce River Delta in northeastern Brazil revealed the evolution of an estuarine system that was progressively abandoned during the Holocene as coastal progradation took place. In addition to sedimentary facies, remote sensing and ^{14}C dating, diatoms helped to reconstruct coastal dynamics due to their great sensitivity to fluctuations in water salinity. Hence, the distribution of diatom assemblages upcore agrees with the succession of sedimentary facies, which are interpreted as evolving from an estuarine channel and estuarine central basin to a lake/ria, and finally to a fluvial channel/marsh. Diatoms are missing in the lowermost zone 5, which corresponds to sediments formed in the high-energy estuarine channel setting. However, these fossil elements are abundant in zones 4 to 3, with a prevalence of marine and marine/brackish diatom taxa, with the first more diversified than the latter. Despite the similar diatom assemblages, there is a slight increase in the marine species *T. punctata* and in the marine/brackish species *D. smithii*, and a decrease in the marine species *P. sulcata* zone 3 relatively to zone 4. Zone 2 continued to be dominated by marine and marine/brackish diatoms, but with the presence also of freshwater diatoms. The top core contains low numbers of mostly freshwater diatoms and only fragmented marine diatoms due to increased continental influence (zone 1). This vertical diatom distribution served the purpose of detecting coast progradation and successfully refines the history of relative sea-level fluctuations in the Doce River Delta area. Prior to the mid-Holocene, the coast near the Doce River mouth was transgressive in nature, which would have sustained an area of an embayed morphology that was favorable to the development of estuarine systems. A relative drop in sea level occurred at ca. 5000 cal yr BP, which led to coast progradation. This process gave rise to the closure of the studied estuary mouth and its replacement by a lake/ria. The marine connection was reduced and ultimately interrupted due to the development of sandy beach ridges and barriers associated with the establishment of the wave-dominated delta system.

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