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Change of sediment transport direction within the Rio Jaguaribe estuary, NE Brazil, by means of clay mineralogical analyses

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ABSTRACT

The estuary of the Rio Jaguaribe (NE Brazil) is filled by a sediment sequence of more than 23 m and characterised by estuarine plains that – today - extend 30 km upstream.

We investigated the sedimentary dynamics in the Rio Jaguaribe estuary since the early Holocene by means of clay mineralogical analyses, as well as sediment analyses from 11 sediment cores. The clay mineralogical approach proves to provide the most robust results. A transition of the illite/kaolinite peak area ratio from 0.3 to 1.8 within the vertical depositional record suggests a change of sediment transport direction over time. Whereas in the lower sequence marine influence dominates, characterised by the relatively high kaolinite content originating from the weathered Barreira formation at the coast, in the upper sequence sediments of fluvial origin dominate, which are characterised by the relatively high illite content originating from the crystalline rocks in the source area of the Jaguaribe river. The depositional architecture of the Holocene sediments of the Jaguaribe estuary shows a seawards prograding infill, assumed to have occurred since the mid-Holocene and supports studies suggesting a stagnating or slightly falling relative sea level (RSL) since ~7000 BP.

1. Introduction

Most active river mouths in coastal regions of the world can be characterised as either deltaic or estuarine.

In an estuarine setting, the tidal regime dominates the river mouth. Generally, most estuaries exhibit at least a meso-tidal range (e.g. Boersma, 1969; Dalrymple et al., 2003; Storms et al., 2005; Palamenghi et al., 2011; Li et al., 2014; Bi et al., 2017). The tidal wave entering the funnel shaped estuary inland can penetrate several tens of kilometres into the hinterland.

The fluvial and marine sediment sources fluctuate in importance during times of rapid and essential change in sea level or continental runoff, but also vary on a daily, weekly, seasonal, and annual scale (e.g. Stouthamer and Berendsen, 2007; Milli et al., 2013; Sampath et al., 2015; Mourelle et al., 2015). The origins of estuaries are mainly determined by the topography of low lying glacial and river valleys and transgressive conditions when the coastline shifts inland and the seaward fluvial delivery of sediment is reduced (e.g. Dalrymple et al., 1992). Consequently, estuaries are most abundant during warm, interglacial periods when continental ice masses recede and global sea level is high (Kennish, 1976; Schäfer, 2020). On a geological timescale, most estuaries persist for only a few thousands to a few tens of thousands of years. Essentially all estuaries in existence today owe their origin to rapid sea level rise since the last glacial maximum, when continental shelfs were flooded and shifting coastlines approached their current positions (e.g. Smith et al., 2011; Hijma et al., 2012; Thurman and Trujillo, 2013; Morrison and Ellison, 2017). The subsequent evolution of estuaries is controlled by the balance between the formation and infilling of accommodation space (e.g. Nichols, 1989). With changing sea level, estuaries migrate inland or seaward if not constrained by inherited factors as the geological setting, coastal geomorphology, and alterations in river water supply, sediment supply or even anthropogenic

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structures (Cooper, 2006; Whitfield and Elliott, 2011). Therefore, the changing proportion of fluvial or marine sediments in the geological record can be an indication for relative sea level (RSL) history.

Estuaries are very efficient sediment traps (e.g., Boyd et al., 1992; Dalrymple and Choi, 2007). Typically, they have a tripartite structure (Dalrymple et al., 1992): an outer portion, which is marine dominated with net bedload towards the bay head, a lower energetic central portion with bedload convergence and an inner portion, which is marine influenced but river dominated. For the analysis of sediment source and pathways not only in estuaries, but also along coasts and in rivers all over the world clay mineral analysis of surface sediments has proven as a valuable tool, e.g. for the Weser and Elbe estuary (Germany) and the southern North Sea: Irion (1984), Irion et al. (1987), Irion and Zöllmer (1990), Irion and Zöllmer (1999), Pache et al. (2008) and Adriaens et al. (2018), for the Amazon and the North Brazilian coast: Irion and Zöllmer (1990), Morais de et al. (2006), Guyot et al. (2007), for the Yangtze River and the China Sea: Liu et al. (2012), Lan et al. (2012), Bi et al. (2017), for the Tirumalairajana Estuary (India): Venkatramanan et al. (2013) and for the Arctic Ocean: Saukel et al. (2010).

Applying clay mineral analysis, we aim to investigate the transport mechanism change in relation to the formation of accommodation space in the Jaguaribe estuary at the Northeastern Brazilian coast (Fig. 1) during the Holocene. Relative changes of the ratio of clay minerals are a clear signal for changes of clay mineral associations and therefore changing pathways of sediment supply at the sample location in the geological record. The overall domination of fluvial or marine sediments can be an indication for decelerated or accelerated sea level rise or fall and for a change of continental runoff. We hypothesise that the world-wide change of Holocene sea level rise around 6000 BP/7000 BP (e.g. Pirazolli and Pluet, 1991) also has changed the sedimentation dynamics in the estuary and potentially caused an alternation of the domination of continental runoff versa domination of sediment supply from the sea, which we expect to be mirrored in the depositional record of the estuary superimposing the short-term changes of sediment input.

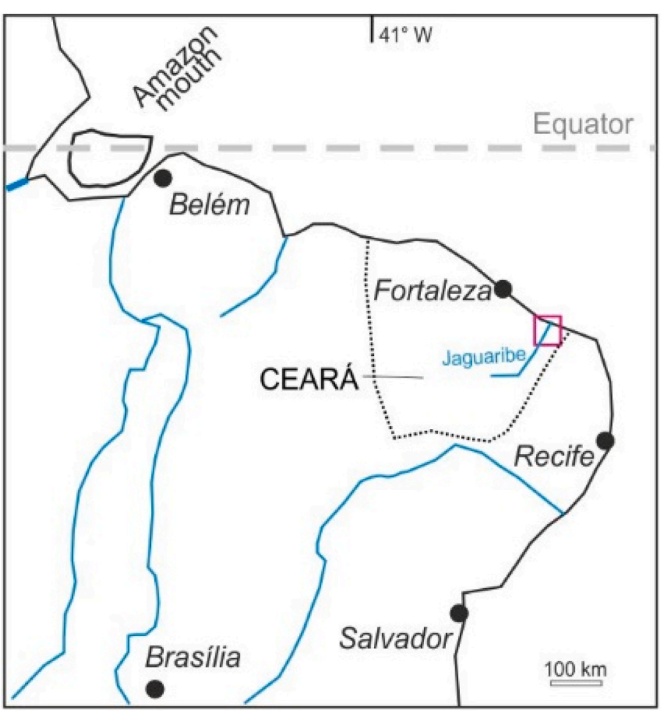

Fig. 1. The Rio Jaguaribe in Ceará state in north-eastern Brazil. The study area is framed in pink.

2. Geographical and geological setting of the study area

2.1. *The Jaguaribe estuary at the north-eastern coast of Brazil*

The Jaguaribe estuary is situated at the north-eastern semi-arid coast of Brazil in Ceará state (Morais de et al., 2019; Soares et al., 2021) (Fig. 1). The Jaguaribe valley extends around 633 km and covers approximately 72,000 km^2 (Dias et al., 2013) with a mangrove dominated estuarine plain (see Fig. 2). The coastline is characterised by sandy coastal plains with large aeolian dune fields, built up by the nearly year-round constant northwesterly trade winds (Dias et al., 2013). The adjacent continental shelf is narrow (18 km) and relatively shallow (maximum depth is 25 m; Caldas et al. (2006). The basin has an average annual rainfall increasing from 400 mm inland to approximately 1000 mm at the coast (Lacerda et al., 2013).

The sediments in the estuary are supplied by aeolian sand by north-westerly trade winds and during seasonal floods by fluvial sediments (Paula et al., 2009). Compared to other rivers of the tropical areas the supply of fluvial sediments to the Jaguaribe estuary was - prior to anthropogenic river regulation - low and highly seasonal due to the arid conditions in the area and driven by sporadic floods that deposited large amounts of sediment during short time scales (Morais and Pinheiro, 2011; Paula et al., 2009).

The maximum tidal amplitude at the coast is 3.2 m (Diretoria de hidrografia e navegação, 2013). An average wave height of 0.84 m is known from the coast of Galinhos, which is about 160 km to the southeast of Rio Jaguaribe (Bittencourt et al., 2002). Thus, following Hayes (1979) and Davis and Hayes (1984) the coast of Jaguaribe is a tide dominated mesotidal coast. The average tidal range in the inner estuary is approximately 2.3 m (Silva et al., 2012). The tidal wave reaches 34 km upstream to Itaiçaba where it is stopped by a dam (Fig. 2) built in 1922. Accordingly, the mangrove swamps of the estuary extend ~30 km upstream. They are interspersed with many channels resulting in a small-scale change of sediment deposition within the mangrove forests, swampy flood plains fringing the mangroves and tidal channels within the mangroves and flood plains.

Where river discharge and tidal currents are relatively low, coastal currents tend to build depositional features such as spits across the mouth of the estuary, thus restricting the entrance. In the Jaguaribe estuary abundant quantities of sand were brought into the northern coastal portion of the estuary by alongshore drifting and barrier spit and dune development. The river mouth is partly separated from the open sea by an about 10 km long, 3 km wide and 20 m high dune ridge, which has built as consequence of unidirectional tidal currents and trade winds, both operating in the SE-NW direction (Testa and Bosence, 1999; Dominguez, 2009) (Fig. 2). It is likely that major spit elongation and dune development coincided with the initiation of a lower rate of sea level rise and that both the spit and the estuary had contemporaneous positive budgets (cf. Psuty et al., 2000).

2.2. *Ria lakes*

Both sides of the lower Jaguaribe valley are characterised by so-called Ria lakes. These are erosional depressions generated by drainage systems during low sea level periods (glaciation). In the course of Holocene sea level rise these former drainage systems were flooded and transformed into lakes.

2.3. *Bedrock and clay mineralogy*

There is a clear illite dominance in the sediments of the Jaguaribe River which results from its drainage from the mountainous hinterland of Northeastern Brazil, characterised by mica rich rocks of the Pre-cambrian basement as schist, granite, granodiorite, diorite, gneiss, paragneiss and migmatite. Tintelnot (1995) reports illite/kaolinite peak area ratios of 1.31 from the surface sediments up to 100 km inland of the

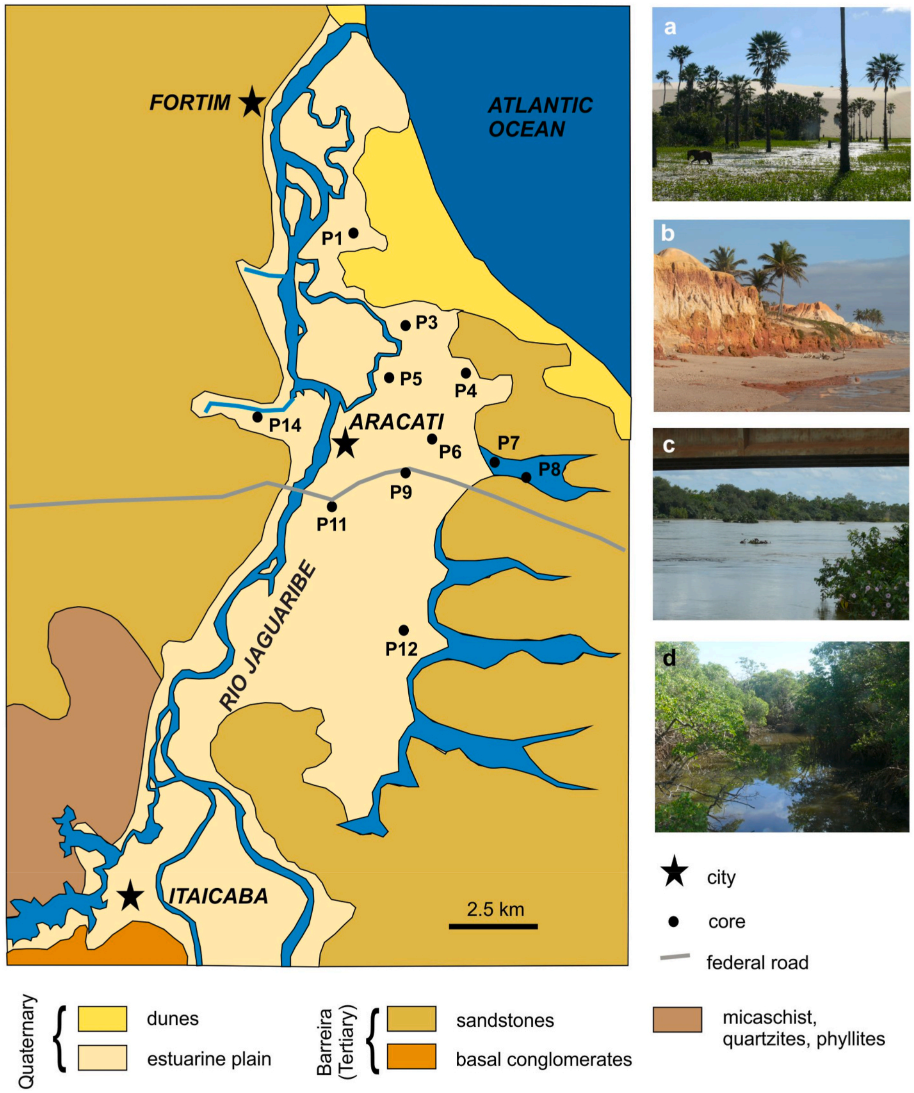

Fig. 2. The location of the 11 cores taken in the estuarine plain of the Jaguaribe. The clay mineralogical results of the cores are plotted in Table 1 and in Fig. 3. a: view from the estuarine plain to the dune east of the estuary mouth, b: sandstone of the Barreira formation cropping out at the coast about 10 km southeast of the estuary mouth, c: high water in the Jaguaribe during annual floods at Aracati, d: estuarine plain of the Rio Jaguaribe south of the dunal area.

Rio Jaguaribe and of 1.16 from the surface sediments at the river mouth of Rio Jaguaribe (Tintelnot, 1995: Appendix page 276) taken during the MAR 15/2 cruise with the research vessel 'VICTOR HENSEN' in 1990.

Along the coastline the Barreiras Formation, a feldspar rich Tertiary sandstone crops out. Actively retreating cliffs are carved into the weathered Barreiras formation (Dominguez and Bittencourt, 1996). Consequently, the marine sediments supplied from the coast are characterised by a relatively higher kaolinite content. Samples taken from surface sediments of the inner shelf up to 25 km in front of the river mouth of Jaguaribe between 10 and 20 m water depth have illite/kaolinite peak area ratios between 0.73 and 0.97. Samples taken from the inner shelf around 100 km south-eastwards show higher kaolinite contents with illite/kaolinite peak area ratios between 0.48 and 0.88 (Tintelnot, 1995: Appendix page 280).

3. Methods

The methods were selected on the basis of the assumption that the sediments originating from the hinterland and transported by the river can be differentiated from sediments originating from the sea and transported by the incoming tide into the estuary. The main method applied was clay mineral analysis. Samples were selected from sediment cores every 100 cm. In some samples, not enough clay fraction could be extracted for the clay mineral analysis. Exemplary, grain size analysis was applied for cores P3 and P5, and sediment analysis for detecting marine versus fluvial/terrestrial indicators was applied for cores P3, P5 and P12.

3.1. Coring

11 sediment cores were taken in the estuarine plain of the Rio Jaguaribe from the coast to approximately 20 km upstream (Fig. 2) with a piston corer (Merkt and Streif, 1970) of 5 cm diameter and sampled every 100 cm for faunal and floral determination and clay mineralogical analysis. The sediment cores vary in length between 3 m and 23 m.

3.2. Clay mineralogy

A total of 65 samples was taken from 11 cores.

The samples were treated with hydrogen peroxide (30%) to remove organic matter, the salt was removed by centrifugation. Afterwards, the sediments were suspended in de-ionised water in an Atterberg cylinder, from which the clay fraction (<2 μm) was separated through settling (Atterberg, 1912) for further treatment (Müller, 1967). From each sample, 3 smear slides were prepared and treated with Mg-Acetate, K-Acetate or Ethylene glycol to exchange cations and thereby obtain standardized conditions for the measurement. The Mg-acetate treated specimens were run from 2 to 32°2Θ in the X-ray diffractometer (XRD), the K-Acetate and Ethylene glycol treated specimen were run from 2 to 17°2Θ.

Results of XRD analyses are plotted as XRD diagrams. In this study we focus on the illite peak, representative for the bedrock of the hinterland, and the kaolinite peak, representative for the weathered Tertiary sandstone of the coast. Therefore, the final results of the XRD analysis are expressed as illite/kaolinite peak area ratio.

If not enough clay fraction could be extracted, no XRD data could be generated.

3.3. Particle size analyses

Samples for particle size analysis were collected in a sampling interval of 100 cm in core P3 and P5.

Particle-size distributions of grain size samples were measured using a Beckman-Coulter LS 13320 laser diffraction particle size analyzer at both, the Bentley University Particle Size Laboratory (Waltham, USA) and the Particle Size Laboratory at the Lower Saxony Institute for Historical Coastal Research (Wilhelmshaven, Germany) following the method described in Machalett et al. (2008). An auto-prep station was used to measure each sample (2–3 aliquots per sample, 5 measurements per aliquot) under equal conditions using the standard operating method Bentley-BM-v13 (Machalett, 2011). Prior to laser diffraction analysis an effective, but gentle procedure of dispersion has been applied by spiking each sample with 1% ammonium hydroxide and treating them for at least 24 h in overhead tube rotators.

3.4. Sediment analysis

For core P3, P5 and P12 samples were additionally treated with HCL to test the carbonate content, generally assumed to originate from marine shell fragments. Provided that sufficient sample material was still available after the XRD analysis samples were analysed with a binocular to detect marine indicators such as mollusc shells and foraminifera. Additionally, smear slides were prepared for microscope analysis in order to identify diatoms.

3.5. Palynological analyses

A selection of 17 samples from sediment cores P4 and P7 have been subjected to preparative treatment for the extraction and concentration of botanical microfossils (pollen, spores and non-pollen palynomorphs). The samples were prepared for microscopical analysis according to the standard procedures outlined by Moore et al. (1991) and investigated using a light microscope (Nikon Eclipse Ni–U) at 400-600x magnification. The sieving residue >200 μm retained at the early stages of the preparation were scanned for botanical macrofossils using a stereo microscope (Nikon SMZ800) at 10-50x magnification.

3.6. Radiocarbon datings

The cores did not contain organic material in situ and in sufficient quantity. Therefore, no age constraints are provided for the study area.

4. Results

4.1. Clay mineralogy and sediment analyses of the sediment cores

From the 62 samples collected, 52 contained sufficient clay to be analysed.

The sediments of the Holocne estuary infill recovered in the cores show a distinct change in clay mineral composition in the vertical profile and, therefore, through time (Table 1). Regardless of the core position the illite/kaolinite peak area ratios vary between 0.3 at the bottom of the cores (P4, P8 and P14) and up to 1.8 (P1 and P14) at the top of the cores (Table 1).

In each core, the illite/kaolinite peak area ratios show a transition, in some cases even a jump (P5, P11 andP14) from very low values in the lower part of the core (0.3–0.5) to relatively high values in the upper part of the core (1.1–1.8). In most cores, the change from lower to highe ratios is gradual (P1, P3, P4, P6, P7, P8, P9 and P12).

Macroscopically, all core segments appeared to be similar with no change in color and sediment structure. Samples from core P3, P5 and P12 cores showed reaction to HCl in the lower meters. Foraminifers, including their chitinous tests, dinoflagellate cysts, marine diatoms and shell detritus were rarely found. HCl reaction and marine microfossil content were summarised to 'marine indicator' and plotted together with the XRD results in Fig. 3.

4.2. Results of particle size analyses

For most samples, the clay content is 20%–30%. Only in the Ria lake on the eastern side of the estuary the clay content reaches up to 60%. The sandiest samples were found in the north, where the mangrove plain meets the dune ridge, for example the upper 5 m in core P4 exhibit a sand contribution of more than 70%.

Particle-size distributions show multimodal patterns with varying and discernible subpopulations on a log scale around 1 μm, 6 μm, 20 μm and 400 μm (Fig. 4). In the cores sampled here, the coarser subpopulations, which are narrowly distributed around 400 μm (Fig. 4), can be assigned to aeolian activity of dune sediments (cf. Kudrass et al., 2018), as the sediment load of river sediments would normally show a much wider distribution with significantly coarser particle size fractions. However, no regular pattern and no vertical succession is observable within the cores as shown for core P3 and P5 representatively (Fig. 4). For example, in core P5 the samples from metres 4 and 7 show a very similar distribution with two peaks, one around 6 μm and one around 50 μm. The samples 2 and 6 both show a peak around 15 μm. The samples with peaks in coarser parts of the diagram, between 400 and 500 μm are from metres 2, 5, 9 and 10.

4.3. Results of pollen palynological analyses

The samples selected proved to be largely unsuitable for palynological analyses. The high minerogenic content of the samples exacerbated by an indispensable multiple treatment with hydrofluoric acid yielded in an overall very low concentration of pollen and spores combined with a generally bad preservation, which did not enable a meaningful pollen analysis. However, few remains more resistant to the taphonomic conditions described could be identified as foraminifera tests and dinoflagellate cysts, see paragraph 4.1.

5. Discussion

5.1. Interpretation of the illite/kaolinite peak area values

Based on the clay mineralogical data from the MAR 15/2 cruise as reported by Tintelnot (1995), values between 1.1 and 1.3 are typical for the surface sediments of river Jaguaribe diminishing from the upper river to the river mouth, whereas values from 0.4 to 1.0 are documented from the offshore area. The higher values of the offshore sediments, between 0.7 and 1.0, are documented offshore the Jaguaribe estuary. The lower values down to 0.4 are measured around 100 km south-eastward of the Jaguaribe coast, the source direction of the North Brazil longshore current. The analysis of the marine indicators as carbonate content and marine organisms for P3, P5 and P12 supports a marine influence for the illite/kaolinite peak area ratios from 0.3 to 0.5. For the ratios from 0.6 upwards no marine indicators could be

Table 1
Illite/kaolinite peak area ratios of the cores as depicted in Fig. 2. Depth relates to the core depth from the surface. P11 was taken next to a federal road, therefore we expect landfill in the top part, what explains the unusual illite/kaolinite ratio in the first metre of P11.

Depth/Core	P1	P3	P4	P5	P6	P7	P8	P9	P11	P12	P14
- 1 m	1.8				0.8		1.0		0.5		1.8
- 2 m	0.8		1.1	1.1	1.0		0.7		1.1	0.8	
- 3 m	0.9	1.6		1.4	0.6	0.6	0.3			0.5	0.4
- 4 m				1.4			0.3		0.3	0.4	0.3
- 5 m		1.2	0.9		1.0		0.3	0.5			
- 6 m	0.7		0.4	0.5	0.6						
- 7 m						0.2	0.3			0.4	
- 8 m		0.8		0.5	0.8					0.4	
- 9 m			0.3		0.6	0.2	0.3				
- 10 m		0.6						0.4			
- 11 m			0.3	0.5	0.4						
- 20 m								0.4			
- 23 m		0.4									

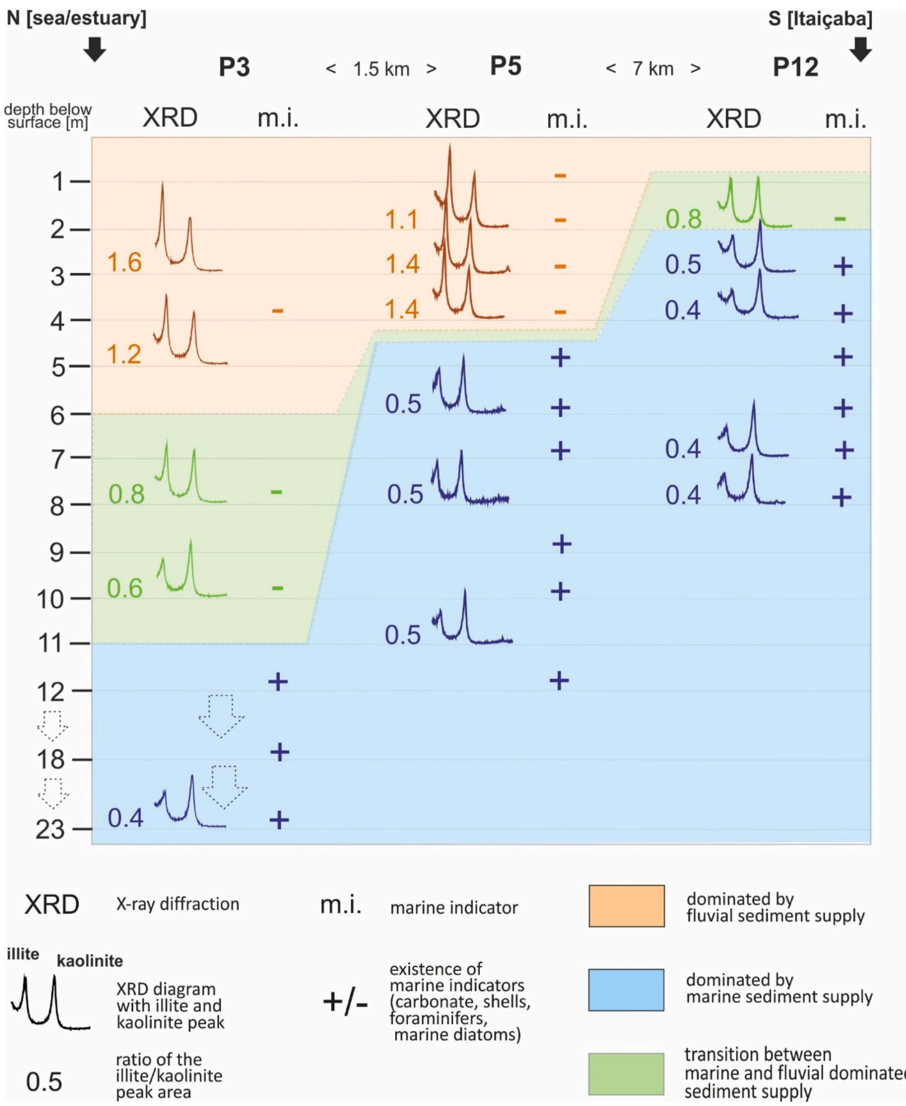

Fig. 3. XRD diagram, illite/kaolinite peak area ratios and existence of any marine indicators in core P3, P5 and P12. The distance between the cores is given in the upper line of the figure. For the exact positions of core P3, P5 and P12 see Fig. 2.

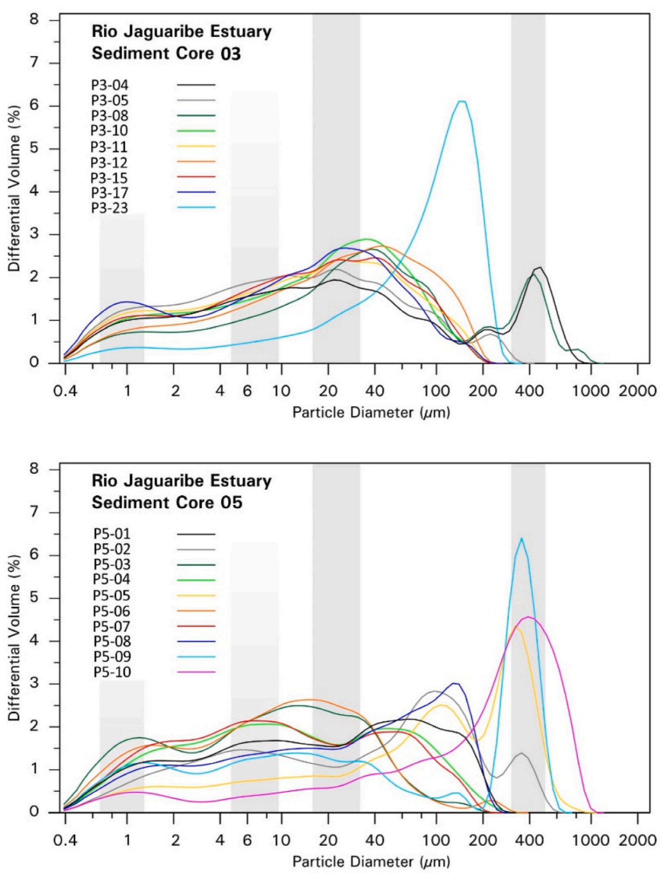

Fig. 4. Particle size distribution in core P3 and P5 displayed on semi-log scale. The shaded areas show the main accumulation of subpopulations. Samples were measured for every metre, in case enough sample material was available.

documented. We therefore interpret the sediments with low values up to 0.5 as marine dominated. Following the clay mineralogical results from the surface sediments by Tintelnot (1995) we interpret the values higher than 1.1 as dominated by terrestrial sediment sources, whereas the values from 0.6 to 1.0 we mark as a transition zone with high mixing not showing a dominance of fluvial or marine source sediment sources. Naturally, in an estuary, all kind of deposits are supposed to be mixed, but in parts dominated by marine or fluvial sources.

The differences of the illite/kaolinite ratios in the sediments are easily explained by the two sources of sediment. The hinterland is characterised by magmatic and metamorphic Precambrian rocks. This results in the high illite content of the fluvial sediment load. At the coast of the Jaguaribe estuary the highly weathered Barreira Formation (Tertiary sandstone) outcrops, resulting in high kaolinite contents in the marine sediments.

It is also noticeable, that in the areas, where the two large rivers of Céara, the Rio Parnaiba and the Rio Jaguaribe originating in the crystalline bedrock area far back in the hinterland, discharge into the sea, the illite content rises in the respective shelf sediments (Morais de et al., 2006; Tintelnot et al., 1994; Tintelnot, 1995).

For reasons of plausibility, we therefore assume, that the clay mineral associations in the lower core sections with a relatively high proportion of kaolinite similar to the today's offshore sediments refer to a marine origin. Consequently, it can be concluded that the sediments deposited in the deeper sequences of the estuary deposits were transported into the estuary from the sea and are mixed with fluvial sediments within the estuary.

The clay mineral composition in the cores recovered shows a clear succession and a distinct change in the Holocene geological record through time (Fig. 3). The sediments in the lowest parts of the cores have an illite/kaolinite peak area ratio of about 0.3–0.5, which rises up to a ratio of 1.8 in the first metre of the cores. This implies an increasing mixing of marine sediments with fluvial sediments at the top of the sedimentary succession of the estuary. For the vertical sedimentological record within the 11 cores taken from the Rio Jaguaribe estuary, distinct differences in the illite/kaolinite peak area ratios are documented representatively in Fig. 3 and show higher kaolinite contents in the lower parts of the deposits indicating a marine dominance and higher illite contents in the upper part of the deposits indicating a fluvial dominance.

The sedimentological and microfossil parameters support these findings. The grain size measurements, however, only document a mixture of sediments and transport mechanisms that are characteristic for an estuarine environment. However, in the vertical succession no clear tendency can be documented from the grain size analysis (Fig. 4), which could be further tested by higher sampling resolutions in future studies.

According to these observations, the sediments in the cores can be classified to marine or fluvial dominated origin (Fig. 3). The change from the illite poor marine clay mineral associations to the illite rich fluvial clay mineral associations is particularly well defined in all cores and lies between 2 and 11 m below surface (Table 1). This shows the potential of clay mineral analysis for the reconstruction of transport ways of sediments in estuary or coastal settings.

5.2. *Stacking pattern of the Holocene sedimentological record within the estuary and development of the estuary over time*

The geological record along the 12 km long core transect from the inner estuary to the coast shows a thickening sequence of fluvial dominated sediments towards the sea (Figs. 3 and 5).

The stacking pattern of the Holocene sediments of the Jaguaribe estuary is a consequence of the hydrodynamics of sediment supply, which in turn is controlled by the RSL history. For a better understanding of this stacking pattern a RSL curve is needed. Along the north-eastern Brazilian coast, there is a data gap of sea level data. No RSL curve for the coast of Ceará has been published so far. Irion et al. (2012) describe beach rock deposits as sea level indicators at the coast of Jericoacoara in Ceará (Fig. 6). As they could not find any beachrock higher than present spring tide level, Irion et al. (2012) conclude that sea level has not been higher than the present level during the Holocene. The study by Peltier et al. (2015) and Peltier (2015) based on earth rotational models show a RSL curve for Natal, which is located 310 km south-eastwards and 150 km south of the coast of Jaguaribe. The RSL curve shows a rise until 7000 BP to 2 m above modern sea level (Fig. 6). From 7000 BP onwards sea level is continuously falling to the recent level (Peltier, 2015).

The clay mineralogical results shown in Fig. 5 imply a stratigraphic architecture with a seaward shoreline migration and an offlapping character as depicted in Fig. 5. Without any seismic profiles it cannot be defined whether the late Holocene sequence shows a normal regression, which is typical for a RSL stillstand, or a forced regression, typical for a RSL fall (e.g. Posamentier and Allen, 1999; Catuneanu, 2002; Catuneanu et al., 2011). Additionally, the mean tidal high water values are generally higher in the inner estuary than directly at the coast (Ebener et al., 2021). Furthermore, no age constraints are given for the studied deposits in the estuary.

However, since about 7000 BP a change of RSL development is documented in several studies, which results in a change of A/S ratio. Thus, a prograding system can be assumed since 7000 BP, which is supported by the seaward thickening sediment sequence of fluvial dominated sediments in the study area.

For the landscape development this means that the river valley, that had been formed during sea level lowstand by erosion of the river, was continuously filled by inland prograding marine dominated sediments during early Holocene steep sea level rise until 7000 BP. During this time

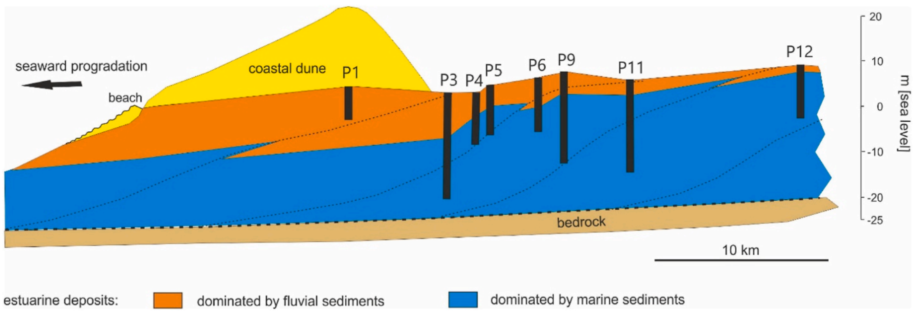

Fig. 5. Hypothetical geological profile section from the coast upstream the Jaguaribe estuary with its stratigraphic architecture as deduced from the core data shown in Fig. 3. The cores are projected on the profile section, besides P14 as it is positioned northwards the river, and P7 and P8, which are located in greater distance in a Ria lake. The base of the Holocene sediments on top of the bedrock is hypothetical and therefore depicted with a dashed line. From the data we just know that the bedrock must be deeper than core P3. The dotted lines within the estuary infill are potential isochrones to give an idea of the stacking pattern of the prograding system.

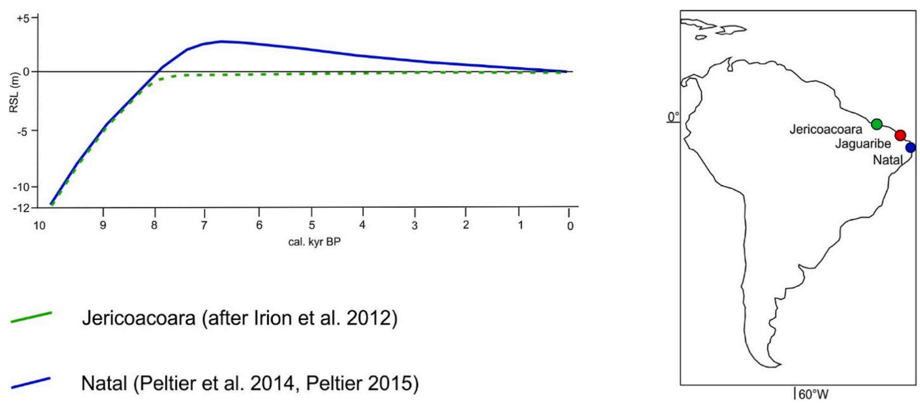

Fig. 6. RSL history for Jericoacoara following the assumptions of Irion et al. (2012) and RSL predictions based upon the model variant ICE-6G (VM5a) with rotational feedback as published by Peltier et al. (2015) and Peltier (2015). Locations of the respective studies including the Jaguaribe estuary are marked in the map.

a shallow mangrove basin with a large tidal channel system may have formed. When sea level rise stagnated or started to fall, the filling of the estuary reached a point when discharge of sea water into the estuary decreased and the system started to prograde seawards finally reaching the recent coastline. Today, the dam in Itaiçaiba stops the upstream tidal currents.

6. Conclusions

We have analysed the Holocene sedimentological record of the Jaguaribe estuary for a better understanding of transport dynamics over time. The obtained dataset allows two major conclusions.

- To define the sources of sediment supply of the Holocene sediments within the Jaguaribe estuary we state that the clay mineral analysis is a reliable approach giving consistent results in all cores. While the grain size analysis shows a general mixture of grain size classes through the vertical profile, microfossils and shell debris are very sparse and mainly the carbonate content shows a reliable continuity in the geological record of estuary. However, from the peak area ratio of illite and kaolinite in the XRD diagrams it can be concluded that two sediment sources exist. Based on data from surface sediments of the river and offshore plus supporting sediment analysis, these were differentiated into sediments with a low illite/kaolinite peak area ratio between 0.3 and 0.5 and sediments with higher illite/kaolinite peak area ratios of 1.1 up to 1.8. The sediments with the lower values are dominated by marine sediments from the kaolinite rich weathered Barreira formation cropping out along the north-eastern Brazilian coast. The higher values result from the domination of fluvial sediments from the inland crystalline rocks.
- Based on a distinct change of the Holocene clay mineral distribution in the geological record of the Jaguaribe estuary, a change in the main transport processes from marine to river-dominated could be identified.

These conclusions may add to the knowledge on regional Holocene sea level development and coastal reaction: For the coast of Ceará no RSL curve has been published so far. Field data from Jericoacoara, 350 km northwest of the study area, show a rising sea level during the first part of the Holocene and suggest a stagnating if not decelerating RSL curve since the mid-Holocene high. Model predictions from Natal, which is 310 km southeast of the study area, suggest a mid-Holocene high and a falling RSL curve since then. The stacking pattern of the deposition within the Jaguaribe estuary suggests a seaward prograding coast, which could be the consequence of a stagnating or falling RSL since the mid-Holocene high. As there are no age constraints so far, this can be only stated as a tentative hypothesis.

CRediT authorship contribution statement

Friederike Bungenstock: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Georg Irion:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Björn Machalett:** Writing – original draft, Formal analysis. **Lidriana de Souza Pinheiro:** Writing – original draft, Project administration, Funding acquisition. **Steffen Wolters:** Writing – original draft, Methodology, Formal analysis. **Jader Onofre de Morais:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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