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Paleoenvironmental insights into the Quaternary evolution of the southern Brazilian coast based on fossil and modern diatom assemblages

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ABSTRACT

Diatom assemblages provide a strong basis for detailed interpretations of paleoceanography and diatom paleoecology of the southern Brazilian coast. Nine cores obtained in the coastal plain, shelf and continental slope and thirteen surface sediment samples of the Patos Lagoon, provide an excellent opportunity to use a paleoecological approach to study detailed Quaternary environmental changes in the southern coasts. In the interval studied, the basin sedimentation occurred in a marine-dominated environment related to humid periods prior to 43,500 year BP. Abundant diatom taxa are highlighted as excellent indicators of environmental changes, including salinity, sediment composition and transport by incised-valleys, providing additional insights into coastal evolution. *Paralia sulcata* is dominant in all analyzed cores, occurring continuously from Late Pleistocene to Holocene, but is rare in the modern sediments. Non-marine diatom assemblages occurred continuously, but in very low densities in periods before and after the Last Glacial Maximum. Abrupt changes in sedimentation have been recorded related to shifts from marine-dominated to shallow-estuarine deposition. During the Holocene, sea-level rose rapidly which is responsible for the progressive coastal flooding prior to 8420–7930 year BP. The Holocene barrier system became more continuous and Patos Lagoon developed. Consequently, the secondary former inlets from the Jacuí and Camaquã rivers are closed and only one single inlet (Rio Grande channel) remains active. The spatial distribution of modern assemblages is controlled by salinity gradient, wind action, and climate forcing. The bottom sediments of Patos Lagoon are dominated by freshwater diatom *Aulacoseira veraluciae*, *Aulacoseira* sp. 2 and marine-estuarine species of *Cyclotella litoralis*.

1. Introduction

Sedimentary systems occurring along the southern Brazilian coast are consequence of Quaternary high-frequency, glacio-eustatic sea-level oscillations (Corrêa, 1986, 1996; Villwock et al., 1986; Villwock and Tomazelli, 1995; Tomazelli and Villwock, 2000) consistent with global sea-level changes (Shackleton and Opdyke, 1973; Clark et al., 1978, 1996; Chappell, 1983; Imbrie et al., 1984; Chappell and Polach, 1991; Berger, 2013). The postglacial sea-level history of the southern Brazilian coast started at around 17,500 year BP when the sea-level was positioned at about 120–130 m below the present level. After that, sea level rose rapidly at a rate of 2.0–1.2 cm/year until the Middle Holocene Highstand, when it started to slow down until it reaches the current position (Corrêa, 1996).

This classic wave-dominated coast has a huge subtropical lagoon that is partially enclosed by a broad and active sand barrier. The Patos Lagoon is strongly influenced by wind action and fluvial discharge (Möller et al., 2001; Möller and Fernandes, 2010; Marques, 2012; Marques et al., 2014). During El Niño events the NE winds are dominant; they enhance precipitation which increases the freshwater influence by flushing the estuarine area (Garcia, 1997; Marques, 2012; Barros et al., 2014) and affects the spatial distribution and composition of organisms into the lagoon (Odebrecht and Abre, 1998; Garcia et al., 2001, 2003; Odebrecht et al., 2005, 2010).

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Despite the previous knowledge regarding the Quaternary high-frequency sea-level oscillations, little is known about the late Pleistocene and Holocene paleoenvironments developed in the Brazilian coast. Preliminary microfossil investigations, including observations of fossil diatoms analyzed a distinct area of the southern Brazilian coastal plain and shelf (Medeanic et al. 2008; Weschenfelder et al. 2008a, 2014; Lima et al. 2013; Corrêa et al. 2013, 2014a, b). Most studies addressing this issue are associated with palynomorph and other microfossil records, which were used to infer changes in salinity along incised-valley systems and barrier stratigraphy. Paleoecological studies based on diatom-inferred environmental changes are considered rare in this region (Medeanic et al. 2009; Santos, 2011, 2015; Hermany et al. 2013) compared to diatom analysis of modern sediments. The study of modern diatom assemblages recorded in surface sediments of the distinct environments of the coastal plain is restricted to the taxonomic composition and distribution of diatom taxa (Garcia-Baptista, 1993; Garcia-Baptista and Baptista, 1992; Garcia, 2006, 2010; Garcia and Souza, 2008; Garcia and Talgatti, 2008, 2011; Medeanic et al. 2008; Bergesch et al. 2009; Garcia and Odebrecht, 2008; Silva et al. 2010; Talgatti et al. 2014). However, the information provided by these ecological studies was not applied to interpret the fossil sequences and they did not attempt to produce detailed paleoecological information about environmental shifts in a dynamic scenario linked to sea-level changes.

Quaternary sea-level oscillations and its impact on coastal environments provide an excellent framework to explore fluvial and marine inputs interacting in transitional environments. Considering that there are no reliable data on sea level changes during the Holocene along the southern Brazilian coast (Dillenburg et al., 2004; Dillenburg and Barboza, 2009), fossil and modern diatom records can provide important outcomes about paleoenvironmental insights into the Quaternary evolution of the southern Brazilian coast. The goal is to provide simple and consistent outcomes and insights about the lagoon-environment hydrodynamic conditions during the Late Pleistocene and Holocene, and contrast them against the modern coastal configuration.

2. Geologic and oceanographic outline

The coastal plain of Rio Grande do Sul (RS), the southernmost state of Brazil, is a passive margin coast situated in the upper part of the Pelotas Basin. This sedimentary basin was developed in the Early Cretaceous associated with geotectonic events related with opening of South Atlantic Ocean (Fontana, 1990). The southern Brazilian continental shelf is characterized by a low gradient (1.3–1.4 m/km) and an average width of 125 km, gradually increasing southward, with a break zone around the 170 m isobath (Martins, 1984). The gradient of declivity is quite soft (1:1000), increasing towards the continental slope. The slope has a convex form with declivities between 1:40 a 1:60. It is wide and irregular in relief, with several canyons and submarine channels that appear related to fluvial drainage (Martins et al. 1972). Also, both the shelf and continental slope are considered stable, subject to epirogenic movements and shaped by sea-level oscillations and local hydrodynamic conditions (Corrêa, 1987).

The southern Brazilian coastal plain is wave dominated and characterized by wide lowlands spanning ~33,000 km^2. According to Villwock and Tomazelli (1995) the coastal plain deposits are mainly formed by both alluvial and barrier-lagoon sedimentary deposits that were developed in response to sea level changes controlled by glacioeustasy during the Quaternary. Four barrier-lagoon depositional systems were identified and classified based on geomorphological and lithological patterns. The oldest systems designated as systems I, II, III and the youngest barrier-lagoon as system IV. A correlation between the sea level highstands and major peaks of the oxygen isotope curves of Shackleton and Opdyke (1973) and Imbrie et al. (1984) has been established by Villwock and Tomazelli (1995). Consequently, the formation of each depositional system is related to Marine Isotope Stages-MIS 11, 9, 5e and 1 with 400,000 year BP (I), 325,000 year BP (II), 120,000 year BP (III) and the system IV is related to the LGM and the next interglacial cycle (MIS1), confirming the correlation between sea level oscillations and climate changes (Berger, 2013).

A large warm-temperate lagoon and a broad active sand barrier system are the most remarkable physiographic features preserved on the modern coastal plain. According to Kjerfve (1994) the Patos Lagoon is considered the world largest choked lagoon (10,000 km^2; 240 km long), representing one of the main water sources in South America. The main axis of the lagoonal system extends over 180 km in a NE–SW direction, including an estuarine area that is 60 km long (Calliari et al. 2008), (Fig. 1a). Both the bottom and margins of the lagoon are influenced by medium- to high-energy waves up to 1.6 m (Toldo Jr. et al. 2000). Longshore current direction is bidirectional and highly regular towards both SW and NE (Jung and Toldo Jr., 2012). The astronomical tide is semi-diurnal; near the channel entrance, the mean amplitude is 0.47 m (Garcia, 1997). Patos Lagoon has a huge surface area, but only a single inlet, the Rio Grande channel, which exchanges water with the Atlantic Ocean. However a geomorphologic feature preserved on the southeast margin of the lagoon, located at 87 km north of the present Rio Grande channel (Barra Falsa paleochannel) acted as an inlet that connected the Patos Lagoon and the Atlantic Ocean during the Holocene (Toldo Jr. et al., 1991; Weschenfelder et al., 2008a, 2008b, 2010a, 2010b, 2014; Santos, 2015).

The Patos Lagoon receives freshwater from the Guaíba Hydrographic Basin (GHB), which has an area of ~200,000 km^2. The main contributing rivers are the Jacuí and Taquari, which flow through the GHB, and the Camaquã River, which flows into the southern region of the lagoon. The Jacuí River basin is 710 km long, draining an area of 71,600 km^2. This basin is characterized by intense land use for agriculture and energy generation (FEPAM, 2010). The Camaquã River basin has a surface of 24,000 km^2 and is currently creating a delta system in the central portion of the western margin of the lagoon. According to Vaz et al. (2006) the mean annual water discharge from the Jacuí River is 801 m^3/s, followed by the Taquari River (452 m^3/s) and the Camaquã River (307 m^3/s). However, the mean annual discharge of freshwater into the Patos Lagoon is 2400 m^3/s (Marques and Möller, 2009). According to Marques (2012) freshwater discharge contributes to the circulation pattern, the mixing and exchange process, and the transport of suspended sediments along the coastal zone varying from monthly, seasonal, and longer time scales (Marques et al. 2010, 2011). Also, a recent study performed in the Guaíba fluvial system suggests that the mean annual suspended solids discharge from GHB towards the lagoon corresponds to 1.1×10^6 t/year, of about 400,000 m^3 (2650 kg/m^3) of sediments, with a yearly sediment supply rate of 0.11 kg/m^2 (Andrade Neto et al. 2012).

The climate conditions in the southern Brazilian coast, including Patos Lagoon and adjacent areas, are strongly influenced by ENSO activity (Grimm et al. 1998, 2000; Fernandes et al. 2002) and the South Atlantic Convergence Zone (SACZ). Interannual variability of rainfall is also related to anomalies in sea surface temperature (SST). According to Möller et al. (2001) the seasonal averages of water discharge are variables with low values (700 m^3/s) recorded during summer and high values (up to 3000 m^3/s) recorded during spring. Peak values of 8000 and 12,000 m^3/s can be observed during El Niño events (Möller et al. 1996). In addition, both fluvial discharge and the wind action are responsible by affecting the hydrodynamic regime of the lagoon (Möller and Fernandes, 2010) actuating in the salinization and desalination processes (Möller and Castaing, 1999). Wind action is in the primary control of estuarine circulation. Also, marine intrusions are favored during periods of higher temperatures, lower precipitation, and SW wind action, while that freshwater input is associated with lower salinity ranges related to high precipitation and winds from the NE (Möller and Castaing, 1999). Northeast winds are typically dominated in the region, while SW winds increase during fall and winter as frontal systems become frequent (Möller et al. 2001).