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Process Control in The Geneses and Evolution of A Lagoon-Barrier System inside of The Patos Lagoon, South of Brazil

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ABSTRACT

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The origin and geological evolution of a complex of a beach ridgeplain in the Feitoria lagoon-barrier, located on the western margin of the southern cell Patos lagoon, Brazil was influenced by the interactions between the alocyclic (climate change and relative sea level) and autocyclic (sediment supply, waves, longshore drift and storm surges) forcing. The study of this regressive beach ridgeplain included the analysis of orthophotos; topographic detail (PRO-XRS Trimble® – post-processed); and shallow geophysical data with Ground Penetrating Radar (GPR), 150, 200 and 400 MHz antennae, combined with facies analysis and radiocarbon dating (AMS) and Optically Stimulated Luminescence (OSL) from shallow borehole samples. The analysis of orthophotos allowed for the definition of at least nine morphologically distinct series of progradation, marked by truncations of progressive orientation changes. The integration of topographically corrected GPR data, sedimentary records, and geochronological data determined the beginning of the progradation occurred at 7.2 kaBP. At the beginning of progradation, the low tide terrace was at the height of 1.9m (EGM96) Above the Sea Current Level (ASCL). The swash zone was in the 2.5m, and the crest reached 4.3m ASCL. Currently, the low tide terrace quota is -0.4m, the swash zone to 0.3m and the crest reaches 2.1m ASCL. Among other factors, the fall of the lagoon base levels was associated with sea level fall during the Holocene regression. However, crest construction control is dependent on the lagoon base level oscillation, which in turn is controlled by the precipitation regime and storms surges. Moreover, these results suggest that the orientation of the ridges was controlled by changes in the internal lagoon hydrodynamics, due to the progressive narrowing of the lagoon connection with the open ocean.

ADDITIONAL INDEX WORDS: *Barrier-Lagoon system into lagoon, GPR, beach-ridge plain, coastal evolution.*

INTRODUCTION

During the late Quaternary, sediments stored in the continental shelf and the shoreface migrated landward as the sea-level rise developing coastal barriers. In some places this process isolated wetlands from the sea creating coastal lagoons simultaneously or after barrier attachment. At the Coastal Plain of the Rio Grande do Sul (CPRS), four barrier systems designated I, II, III (Pleistocene) and IV (Holocene) were formed in association with sea level (Villwock *et al.*, 1986).

The geomorphology of the Feitoria lagoon-barrier system resembles some extent the Barrier III system and chronologically to the Barrier IV system (Villwock and Tomazelli, 1995). The genesis of the Feitoria lagoon-barrier and the Pequena lagoon is correlated with the previous topography, marked by the existence of a high topographic remnant among the fluvial paleo-valleys of the Turuçu and Corrientes rivers, where this high served as a substrate for the beginning of the development of this barrier (Manzolli, 2016). Also, it is evidenced that the geomorphological evolution of the Feitoria lagoon-barrier was associated with sea level variations from the medium Holocene (8 – 7 ka) and was also influenced directly by the high frequency fluctuations of the basal level of the Patos lagoon, caused by the interaction of three main factors: variability in the volume of the drainage basin; wind tides; and geomorphological changes at the mouth of the Patos lagoon.

The study area (Fig 1) is located in the Pelotas Basin, a marginal sedimentary basin with approximately 40,000 km² emerged area, covering the southern portion of the continental margin of Brazil. On land, a low-relief coastal plain was formed during the Quaternary by the juxtaposition of sedimentary deposits of four barrier/lagoon systems that were designated I (oldest) to IV

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(youngest) by Villwock *et al.* (1986). Each barrier/lagoon system corresponds to a high-frequency depositional sequence (Rosa *et al.*, 2011). The youngest system began its formation about 7 kaBP in consequence of the PMT. At that time, the sea level reached approximately 3 m above the present level (Angulo *et al.*, 2006) and enabled the formation of a barrier that consists essentially of sand that has been transported by longshore drift (Dillenburg and Barboza, 2014).

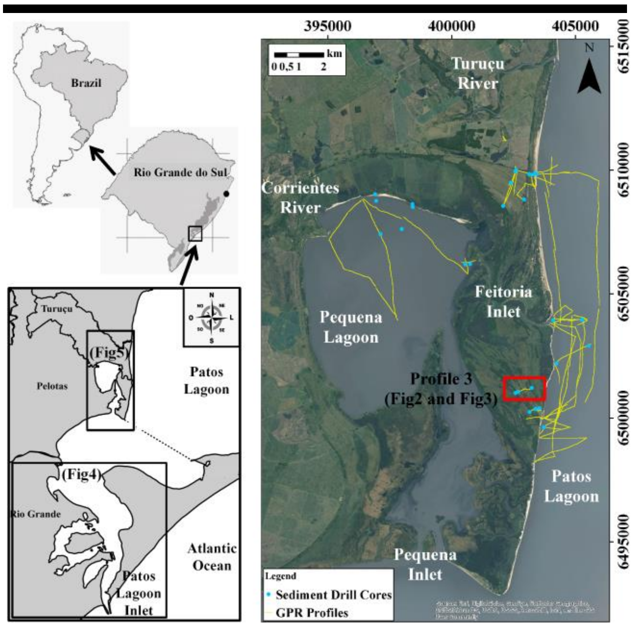

Fig 1.Study area with sampling plan (UTM-22J-WGS1984).

The Patos lagoon has a length of 240 km, an average width of 40 km, and is considered the largest choked coastal lagoon in the world (Kjerfve, 1986). The climate is humid temperate, with generally warm to hot temperatures in summer and cool temperatures in winter (Cfa – Köppen). The average annual temperature ranges between 16 and 18ºC. Rainfall ranges from 1,000 to 1,500 mm and is evenly distributed throughout the year (Alvares *et al.*, 2014). NE winds predominate along the entire coast but vary considerably in intensity depending on location. The wind drives the subtidal lagoon circulation in time intervals of 3–16 days, coincident with the passage of frontal systems over the area. The local wind produces a water level setup (set-down) in the southern part of the lagoon and a depression (rise) in elevation in the northern part during NE (SW) wind events, and the long period oscillations generated offshore by non-local winds are attenuated as they propagate into the lagoon (Moller *et al.*, 2001).

During the Holocene the deposits of systems I, II and III were partly reworked by waves and currents within the lagoon, the construction of the extensive spits being the most important product of the reworking of these sediments (Toldo Jr. *et al.*, 2006). One of this spit is the Feitoria lagoon-barrier, which is formed of a complex of a beach ridgeplain, located on the western margin of the southern cell Patos lagoon (Fig 2).

This paper presents evidence that the genesis of the Feitoria lagoon-barrier and the Pequena lagoon is correlated with the previous topography, marked by the existence of a high topographic remnant among the fluvial paleo-valleys of the Turuçu and Corrientes rivers, where this high served as a substrate for the beginning of the development of this barrier.

METHODS

This study is essentially based on the geological and geomorphological mapping, GPR records, lithofacies analysis (sediment drill cores), and radiocarbon (Accelerator Mass Spectrometry - AMS) and OSL dating.

The superficial geology and geomorphology of the Feitoria lagoon-barrier system were mapped using aerial photographs from 1948, 1953 and 1975 (1:25,000) and high-resolution satellite imagery (Google™ Earth) in a Geographic Information System (GIS) software (ArcMap™). Furthermore, GPR profiles (162 km) were performedto show the stratigraphy of depositional systems. The equipment used for data acquisition was a SIR-3000 model from GSSI™ (Geophysical Survey Systems, Inc.), with contact antennas (150, 200 and 400 MHz). Topographic corrections were made by the coupling of the GPR system to the high precision differential positioning system (PRO-XRS Trimble® – post-processed). The processing of the profiles was performed in software Prism® and Radan™. The data interpretation followed the method of sismoestratigraphy (Payton, 1977) adapted to GPR (Neal, 2004) which consisted in the terminations (onlap, toplap, downlap,and truncation), geometry and the pattern of reflectors.

The lithofacies analysis was based on sedimentary records from 27 boreholes obtained using a percussion drilling system. Sediment color and texture were analyzed, along with sedimentary structures (which are not commonly preserved) and degree of compaction. The radiocarbon dating (AMS) was performed by Beta Analytic Inc., and OSL ages were performed by LeGAL/USP. Equivalent doses were determined using the single-aliquot regenerative dose (SAR) protocol applied to multigrain aliquots of quartz (Murray and Wintle, 2003).

RESULTSAND DISCUSSION

Integrating satellite image data with geoprocessing techniques products has allowed a detailed mapping of the Feitoria lagoon-barrier sequences of Holocene sand ridges. These sedimentary units were divided into at least nine distinct sets, showing a varying pattern of progradation, marked by erosional truncations of progressive orientation shoreline shifts and elevation difference. Many processes and factors are known for this reorientation alignment such as shifts in river courses, wave regime, wind patterns, sediment supply, base level changes, and accommodation space, for example (Taylor and Stone, 1996; Tamura, 2012; Costas, 2016). Erosional truncations are recognized in others sand ridge plains (Biancini *et al.*, 2014; Bitencourt *et al.*, 2016; Leal *et al.*, 2016; Dillenburg *et al.*, 2017).

Regarding sequence stratigraphy, each ridge set corresponds to zones of relatively uniform shoreline trajectory, and the entire strandplain correspond to parasequences (Hampson *et al.*, 2008).

A total of 162 km of high-resolution GPR data were acquired on the regressive Feitoria lagoon-barrier strand plain. Following interpretations of other GPR studies (Neal, 2004; Barboza *et al.*, 2011 and 2013; Dillenburg *et al.*, 2017; Rosa *et al.*, 2017), a series of 12 radarfacies were identified based on internal characteristics, stacking patterns, external bounding surfaces, and spatial relationships. To corroborate the results of different GPR signatures, 27 shallow boreholes (up to 5.5 m deep) were collected. The internal structure revealed by the GPR survey (Fig 2) in association with sedimentary faciesfrom the boreholes (Fig 3) shows a complex stratigraphic architecture for the study area. The internal stratigraphy suggests that progradation occurred in the form of shoreface successions with occasional aeolian capping (foredunes) over the preserved ridges (Fig 2). Base level fluctuations at Patos lagoon favored by high sediment supply and beach characteristics has probably played a major role in the development of this plain.Also, the antecedent topography, marked by numerous paleochannels, played an important role in the basin-marginarchitecture, facies distribution and accommodation during the Quaternary sea-level fluctuations (Weschenfelder *et al.*, 2010).

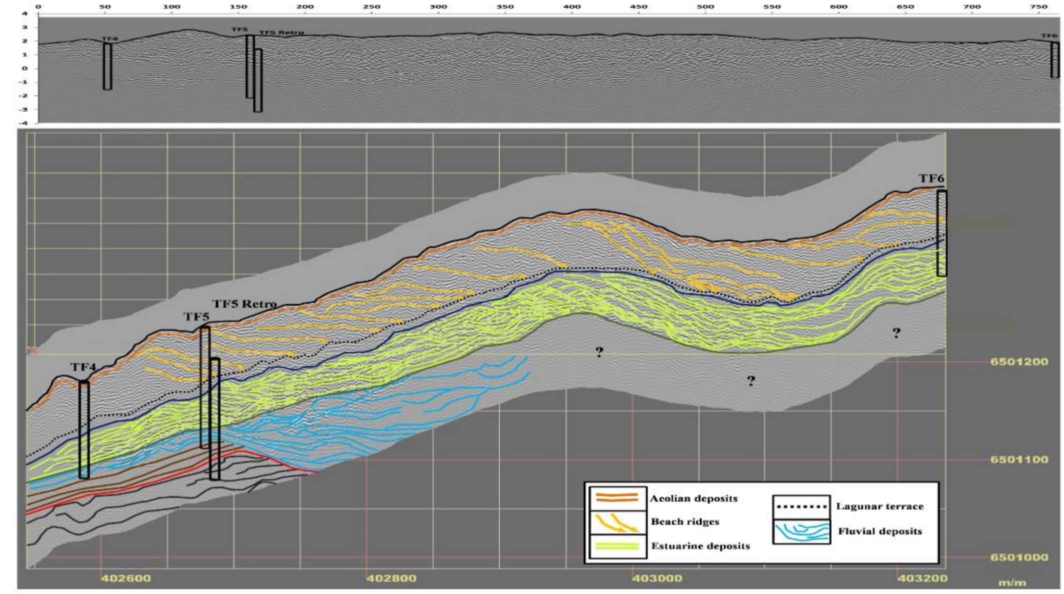

Fig 2.A) Profile 3 -Above presented in the 2D plane and below the interpretation of the profile presented in 3D perspective. In the 2D plane radargram, the X-axis corresponds to the profile length (m) and the Y-axis corresponds to the altitude about sea level (m) (EGM96). In the 3D perspective radar, the coordinates are shown in UTM (WGS84-22S).

The ages obtained by OSL (19 samples) and ^{14}C (seven samples) for the ridge crests indicate that progradation started during the slowing sea-level rise (7.2ka) of the Postglacial Marine Transgression (PMT).

This age has good agreement with previous studies for the CPRS. The data obtained indicate that sea level was about 3 m above the current level. According to Barboza and Tomazelli (2003) and Dillenburg *et al.*(2017) have found the sameorder of sea level in the CPRS.At the beginning of progradation, the low tideterrace was at the height of 1.9 m (EGM96) above the ACSL. The swash zone was in the 2.5 m,and the ridge crest reached 4.3 m above the ASCL. Currently, the low tide terrace quota is -0.4 m, the swash zone to 0.3 m and newly formed ridge crests are at 2.1 m ASCL (Fig 1).

Among others factors, the fall of the lagoon base levels was associated with sea level fall during the late Holocene regression, after the PMT. Most simply, two processes can contribute to the formation of beach ridges: wind and/or waves, and they can act alone or in combination (Nott, 2010). However, for the Patos lagoon, the crest construction control is dependent on the lagoon base level oscillation, which in turn is controlled by the precipitation regime and storms surges similar to the model proposed by Psuty (1965). Besides, the actual elevation of a beach ridge may also include the effect of winds.

The lagoon beach is typically inundated by the storm surge and waves during extreme events, typically with the passage of a cold front. Moreover, as stated by Bendixen *et al.* (2013), the base level originated from storm floods is the sum of five components: (1) storm surge, (2) windset-up surge, (3) wave set-up, (4) wave run-up and (5) swash. Thus, quantifying precisely just one factor is a difficult task. The correspondence between base-level fluctuations and sand ridge formation is relatively well-known around the world (Tanner, 1995).

Thompson and Baedke (1995), proposed a theoretical model explaining beach ridge development as a product of changing rates of sediment supply and water level change for Lake Michigan. Similarities could be found in the Patos lagoon. The orientation of the ridges was controlled by changes in the internal lagoon hydrodynamics, due to the progressive narrowing of the lagoon connection with the open ocean, according to the model proposed (Fig 2) by Godolphim, (1985).This bottleneck of the mouth of the Patos lagoon was probably the most important factor for the changes in the internal hydrodynamics of the lagoon, which was responsible for the evolution of the complex system barrier-lagoon inside the Patos lagoon. Besides that, from this period, the control over the morphology and orientation of the coastal strandplainswill have a greater influence associated with the variations in lagoon base level (volume of precipitation and wind tides) the highest frequency is responsible for the making coastal beach ridges.

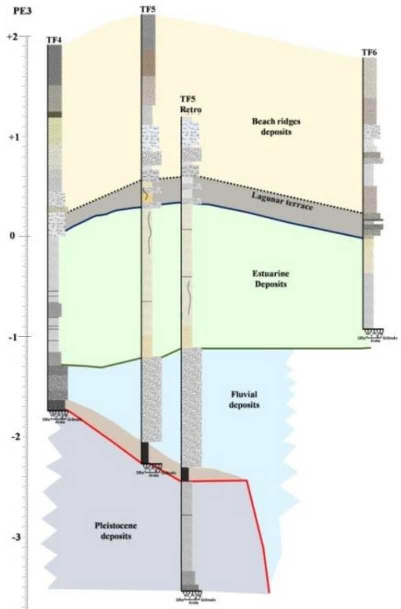

Fig 1. Profile 3 - with TF4, TF5, TF5 Retro and TF6 in the Feitoria lagoon-barrier. The TF5 and TF5Retro were carried out in the same place, and the second was carried out in a trench with a depth of 1.30m. The Y-axis corresponds to altitude relative to sea level (m) (EGM96). The X-axis of the cores corresponds to the granulometric scale.

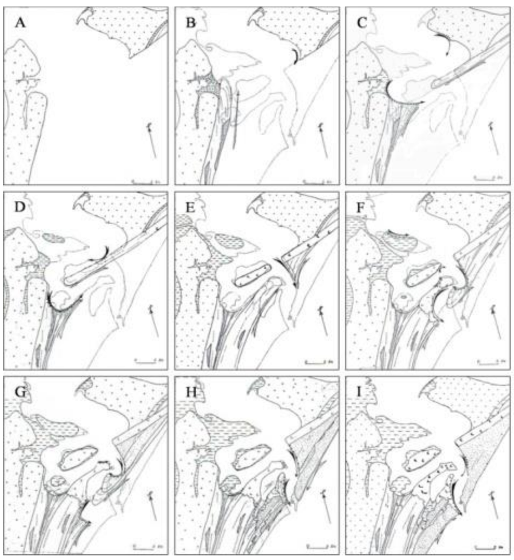

Fig 2.An evolutionary model of the mouth of the Patos lagoon (adapted from Godolphim, 1985).

Thus, the association of these two factors, the bottleneck of the mouth and the high-frequency variations of the base level of the Patos lagoon (Autogenic Factor), in addition to the drop of the sea level (Allogenic factor) controlled the nine sets sedimentary units (Fig 3).

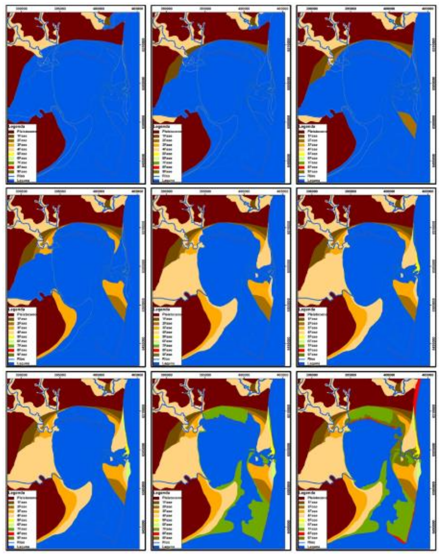

Fig 3.An evolutionary model of thelagoon-barrier system of the Feitoria lagoon-barrier (adapted from Manzolli, 2016).

CONCLUSIONS

The results of this work suggest that the Feitoria lagoon-barrier system began approximately 7.2 ka BP associated with the end of the sea-level rise period. With the decline of sea level and, consequently, decline of the lagoon base level, the outcrop of the high topography gave subsidy to the Feitoria lagoon-barrier to develop.

At the beginning of progradation, the low tide terrace was at the height of 1.9m (EGM96) above the ASCL. The swash zone was in the 2.5m, and the crest reached 4.3m ASCL. Currently, the low tide terrace quota is -0.4m, the swash zone to 0.3m and the crest reaches 2.1m ASCL. Among other factors, the fall of the lagoon base levels was associated with sea level fall during the Holocene regression. However, crest construction control is dependent on the lagoon base level oscillation, which in turn is controlled by the precipitation regime and storms surges. Moreover, these results suggest that the orientation of the ridges was controlled by changes in the internal lagoon hydrodynamics, due to the progressive narrowing of the lagoon connection with the open ocean.

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