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The coastal ridge sequence at Rio Grande do Sul: A new geoarchive for past climate events of the Atlantic coast of southern Brazil since the mid Holocene

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ABSTRACT

We present here the first geochronometric analysis of a large succession of coastal ridges that developed south of Rio Grande do Sul inlet, aided by OSL dating of samples taken in this succession that amounts c. 306 coastal ridges. This succession allows defining epochs of enhanced coastal drift or fluvial transport to the river mouth. Additionally, changes in the preservation of ridges also suggest the additional effect of transverse winds that create blow outs, while changes in the ridge packages planview onlap suggest possible changes in the dominant longshore drift. Four OSL samples located strategically allow defining the age of five main stages of this succession. The first stage comprises 2 substages. The first substage shows ridges #1 to #36 onlapping the boundary coastal scarp northwardly, while the second (ridges #37 to #84) shows an inversion of ridge shape wedging out southwards until coast returns to be quasi parallel to the initial coastal scarp estimated to be c. 6 ka. We estimate this first stage to comprise enhanced coastal drift due to higher and sandier ridges, ending at c. 4.1 ka. The second stage (ridges #85 to #124) ridges is marked by a slight unconformity, and indicates a period of enhanced fluvial progradation and less coastal drift suggesting milder winds up to 3.6 ka. The third stage (ridges #125 to #204) initiates with erosion of ridges near the delta front, being higher and sandier ridges, suggesting enhanced coastal drift due to windier conditions, being the windiest time bracketed between 3.3 and 2.35 ka. The fourth stage (ridges #205 to c. #270) shows again, as second stage, a tendency of wedging out southwards, suggesting enhanced fluvial progradation, estimated between 2.34 and 1.7 ka. The fifth stage is defined by a complete change of coastal plain progradation, due to the rapid recycling of beach ridges into a complex of blow outs and arcuate sand dunes. Ridges are sparsely recognized in cases they developed during short lived events of enhanced longshore drift, with an outstanding group (ridges #288 to #290) that we correlate to a 1.1–0.9 ka cooling event. Future studies, improving the chronostratigraphy of the beach ridges succession at Rio Grande and comparing it with the Paraná river delta ridges, will help understanding the complex environmental history of South America, that include a reversal of the longshore drift, given the fact they are among the most complete upper Holocene geoarchives available.

1. Introduction

Coastal beach ridge successions could be very good geoarchives to understand the recent climatic and environmental evolution of a region (cf. Otvos, 2000; Reimann et al., 2011; Dörschner et al., 2012; Hinojosa et al., 2016; Vespremeanu-Stroe et al., 2016). The southern coast of Brazil, shows extensive development of beach ridge successions but their significance for understanding the climate history of this part of the South American continent is still unexploited. This is partly related to the scarcity of detailed stratigraphic studies of the very last coastal events and the lack of instrumental records that show a short to medium term evolution of coastal parameters, in spite of the thousands of km of coast that is today heavily populated. For instance, a very important aspect on

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coastal evolution is determining the real value of longshore sediment transport (LST) or drift, based on field measurements. Instead, many models are applied to estimate the LST flow (Martinho et al., 2006, 2010; Dillenburg et al., 2006; Dillenburg and Hesp, 2009), but they are based on events of coastal erosion and growth, while no field measurements of longshore coastal currents or LST are shown. Thus, the best way to learn about the coastal dynamics given the lack of instrumental deployed at the coastal or shoreface environments, is to extrapolate the effect of the wave structure during fair weather and storms, on the coast of Rio Grande do Sul state (RGDS). On this sense, the work of Guimarães et al. (2014) is one of the best as it takes all data available offshore, but it still faces the problem that those results cannot be confronted against shore data of similar quality. As a result, longshore drift is still a qualitative issue, instead of being quantified by instrumental records. In this scenario, it is clear for most authors that the present-day dominant longshore drift is northeast directed (cf. Dillenburg and Hesp, 2009), but that is composed by two different modes: A fair weather mode that moves the sand in the southwest direction, and a storm mode that has a dominant effect and moves the sand northeastwards.

The state of RGDS is characterized by an extensive, slightly sinuous and 620 km long and NE–SW orientation (Fig. 1). It includes the Cassino Beach, considered one of the longest sandy beaches worldwide (Dillenburg et al., 2004). All this extension consists of unconsolidated deposits from quaternary rivers and beach deposits, and most authors consider that the modern shore does not receive sand contributions from modern sources (cf. Dillenburg and Hesp, 2009). However, studies of the modern dynamics of the Rio Grande estuary located right at the north end of the Cassino Beach suggest the contrary. The detailed study compiled by Asmus (2007) showed that bottom samples taken across a year showed high contents of sand (January: 42%, June: 26% and October 33%, average of 10 bottom samples). This bottom composition plus the fact measured stream velocities reached 1.5 m/s, with modeled velocities for flood discharge peaks would reach up to 4 m/s, suggest that there should be some active sand transport along the Rio Grande estuary seawards, and therefore it could be considered a potential modern sand source.

On the other hand, the local continental shelf extends more than 150 km from the shore attaining maximum depths between 100 and 140 m and a slope of c. 0.06. The shoreface is very wide and shallow and Toldo et al. (2006) suggest a local boundary at a depth of 10 m, where deposits are dominantly sandy. According to Fachin (1998), the shoreface geomorphology is different to the south or north of the Rio Grande estuary. To the south, and for c. 60 km, it shows gradually decreasing depth seawards, while to the north; he observed a high concentration of sand ridges oriented roughly parallel to the shore. This difference south and north from Rio Grande estuary, creates an important effect on wave attenuation, which seems to be more important south of Rio Grande estuary according to Guimarães et al. (2014), limiting the effects of storm waves. Local storms today considered as the main forcing of longshore drift (directed to the NE, cf. Dillenburg and Hesp, 2009), are

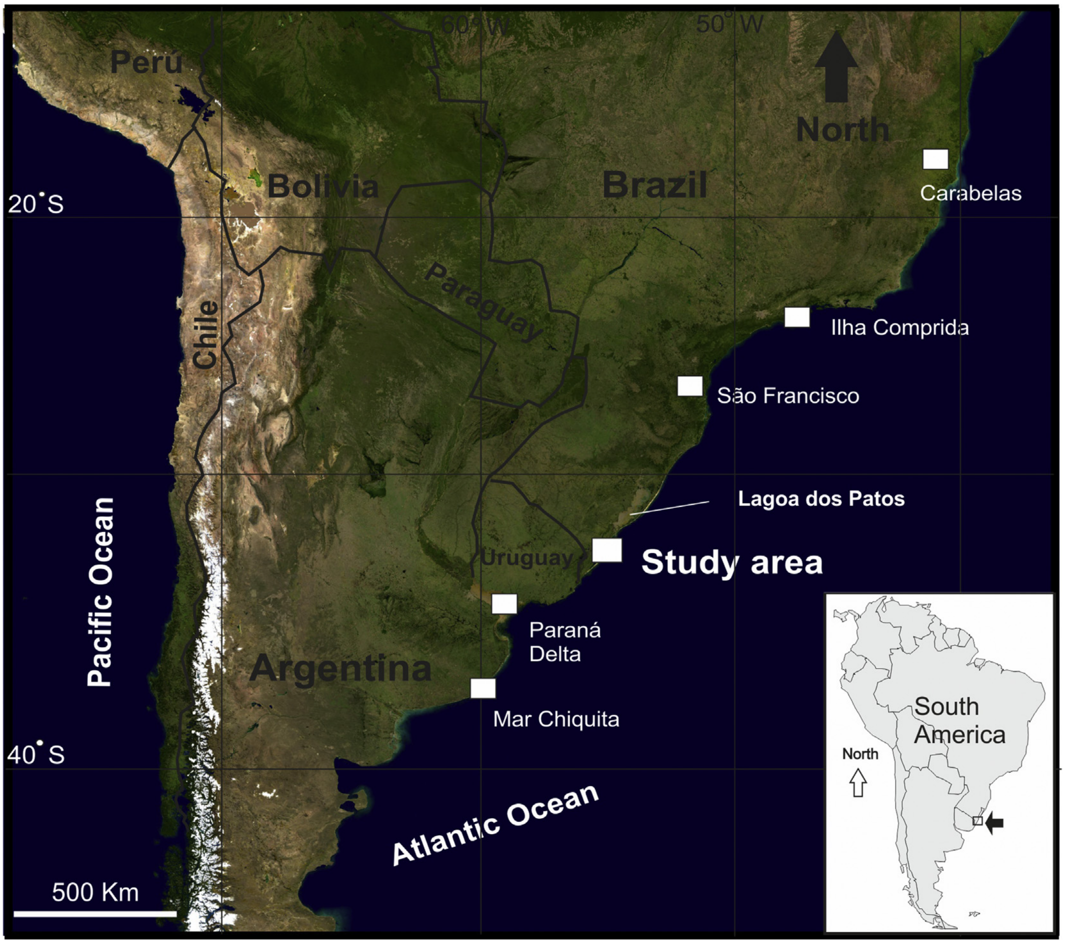

Fig. 1. Location map of the study area and other coastal realms mentioned in the text.

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very turbulent and unstable extra-tropical cyclones, created by synoptic-scale, low-pressure systems usually developing at mid-latitudes (Guimarães et al., 2014).

1.1. Defining the research goal

The problem we would like to tackle in this paper, is how the present day conditions were the same in the recent coastal evolution, because coastal dynamics in southern Brazil is mainly modulated by waves, and hence, it is in a delicate equilibrium with the dominating climate. In this sense, while many studies describe the recent coastal evolution of the southern Brazilian shore (e.g. Dillenburg et al., 2004; Dillenburg and Hesp, 2009; Sawakuchi et al., 2008, 2012; Barboza et al., 2009; Guedes et al., 2011; Zular et al., 2012; Hein et al., 2013, 2016; Mendes et al., 2015), only few of them recognized the presence of significant climatic events affecting the coastal evolution of this aforementioned region (Sawakuchi et al., 2008, 2012; Zular et al., 2012; Hein et al., 2013; Mendes et al., 2015). The timing of those events is still not very well established, but Sawakuchi et al. (2008) and Zular et al. (2012) detected an important change in coastal sand composition that might be related to a pervasive change in LST conditions.

Defining the timing of the coastal events in southern Brazil faces two main problems: a) there was a highstand at c. 6 ka BP (Milne et al., 2005; Angulo et al., 1999, 2006) and therefore during this last rise, many previous coastal landforms were erased by the ravinement surface, and b) there are several extensive strandplains placed along the SE litoral of Brazil (cf. Dillenburg and Hesp, 2009) but there are only a few places where coastal progradation is large enough and reasonably continuous to allow the coast to record most events in this short lapse of few millennia. As a result, only a few places would reach a decadal resolution as would it be possible if a periodic feature is formed during coastal progradation. A recent paper produced out of the Paraná delta (Fig. 1) in Argentina (Milana and Kröhling, 2015), where land is created at the incredible rate of 1.9 km^2/yr, showed this kind of resolution might be possible to achieve only at very particular places. They demonstrated that the last 6000 yrs of coastal evolution were quite heterogeneous and signed by many events suggesting several more climate shifts at the region, on top of those defined near 2 ka BP.

One of the most eloquent studies of the possible coastal changes was done following the coast of the study area to the north. At about 1000 km NNE from Cassino (Fig. 2), an impressive change in coastal sand composition was detected suggesting a complete reversal of the dominant longshore drift at c. 2 ka BP (Zular et al., 2012), while other authors found indirect evidence of a longshore drift change (Sawakuchi et al., 2012). As we all know, longshore drift depends on the dominant winds and a reversal suggests a pervasive and important climate change in very recent years. In fact, curved spits until a complete reversal are present in the coastal areas of Buenos Aires Province of Argentina (37°37′37.30″S, 57°22′27.60″W, cf, Schnack et al., 1982), witnessing that the observed change in coastal drift at the Brazilian coasts, was not local but probably of a continental scale, although probably with own regional characteristics. It is therefore desirable to find new places where the coast progradation has been large enough and the post-progradation reworking enough low, to preserve the original signal of the coastal dynamics, as it is widely recognized that coastal ridge successions are excellent archives for paleoenvironmental and hence paleoclimate changes (cf. Taylor and Stone, 1996; Tamura, 2012).

1.2. The Barrier IV stage at Cassino

With the idea of better understanding the coastal environmental changes recorded since sea level was reaching the last highstand at c. 6-5 ka BP, we revised this youngest stratigraphical unit, with the objective of finding those places where the coast prograded important amounts, without evidences of large erosive surfaces embedded in the sequence. A logical place for enhancing coastal progradation is logically near the river mouths where the supply of sediment is large enough to add material to the prograding coast. However, constructive deltas have the problem of lobe repositioning, creating a sort of “unconformities” in the successive coastal lines, as we observed near the San Francisco river mouth, or at the Caravelas regressive strandplain (Dominguez et al., 2009). The most suitable location we found for our purposes, after this search was the area south of Rio Grande city (RGC), in the RGDS State of Brazil (Fig. 1).

The Holocene coastal construction at this selected place is included in what it has been generically known as Barrier IV (cf. Dillenburg and Hesp, 2009). However, while this denomination could apply to the deposits ascribed to this stratigraphic unit northwards, it does not entirely reflect the way these deposits were formed at this specific location. This is because the beach ridge succession west of Cassino does not initiate nor evolve as a barrier system, i.e. with a lagoon or marsh/tidal plain separating this sand ridge from the mainland. Thus, the respective facies will be absent from this succession. On the other hand, our first stage is a series of successive ridges that are onlapping directly onto the pre-5 ka coastal scarp. It could be more comparable to those regressive strandplains described for the Caravelas area (Andrade et al., 2003; Dominguez et al., 2009). However, in this case as the sea level variations during the last 5 millennia were no higher than 4 m and relatively slow (Angulo et al., 2006), this period could be considered a highstand from a stratigraphic point of view. Therefore we prefer to call these ridge succession as prograding, instead of regressive (although both terms are correct), as the last term implies a sea level forcing of the coast retreat and the coast line movement seawards at Cassino, that implies a 14 km of displacement in 5500 years, was mainly a process allowed by the addition of sediment than to the sea level fall. As we will see, this ridge succession is more affected by other types of forcing than that of sea level. In this case, it is clear that only 4 m of sea level fall since 5 ka BP, would not explain the shore progradation of 14 km in that period, so we believe sedimentary progradation forced by an important local supply of sediment, was the dominant process of the local coast over a regression-forced coastal evolution.

Besides the clear progradational dynamics of this sector of the coast of RGDS, another important fact that we observed in this succession is the absence of evident large erosive surfaces embedded in the sequence. This became not true after the detailed mapping as we will describe later, but the initial analysis of this coastal segment suggested a relatively good concordance between successive ridges. It is also important to note that this study is not dealing in detail with the particular origin of the beach ridges, but only with their organization, structure and evolution. This is why we use the generic name “beach ridges” that as proposed by Otvos (2000) includes linear features formed along the coast by different processes as quoted in the referred work.

1.3. The study site

The group of ridges assigned to Stage IV (Barrier IV) locally attaches directly to the previous unit without any evidence of a lagoon. The units predating Stage IV are well differentiated because of the elaboration of a well-defined relictic coastal scarp produced during the last highstand of c. 6 ka BP. This geomorphological feature, separates Stage IV beach ridge sediments from Pleistocene coastal sediments ascribed to “Barriers I, II, and III”,

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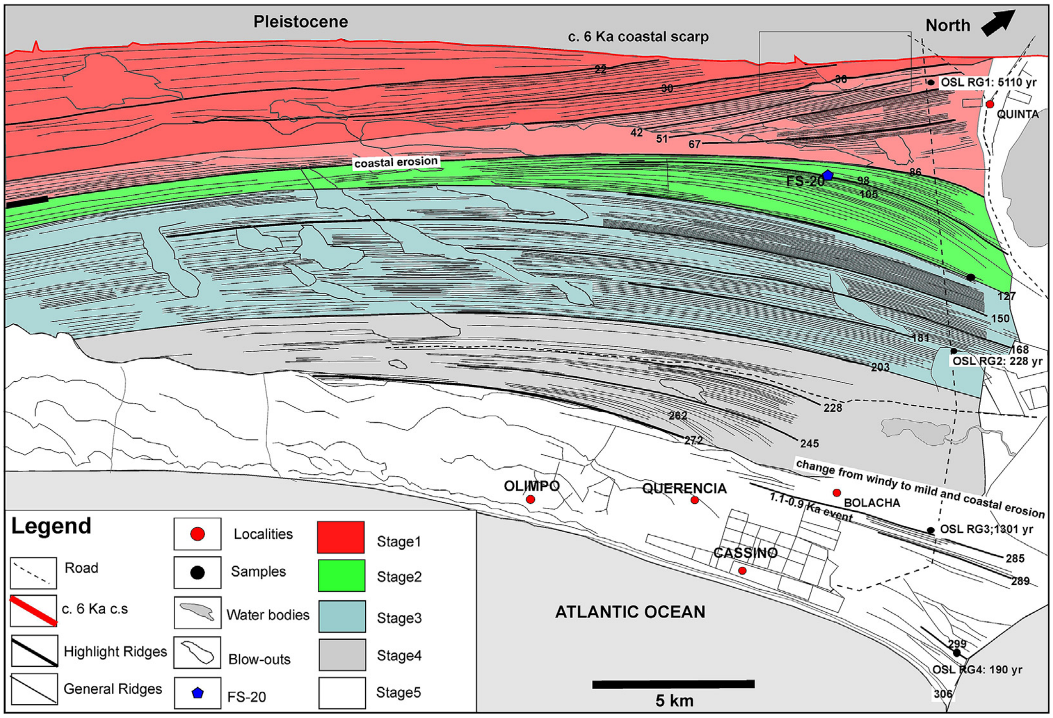

Fig. 2. Detailed mapping and counting of individual ridges of the Holocene RGDS strandplain (Barrier IV), with indication of the five mayor subdivisions discussed in the text. Rectangle indicates location of Fig. 3A.

undifferentiated at the latitude of Cassino (Clerot et al., 2005: Dillenburg and Hesp, 2009). The paleocoastal feature at Cassino latitude is actually showing a minor topographic step between the sandy ridges and the more even surface of Pleistocene Stages I to III. In some cases it is possible to see a dendritic drainage elaborated incising the coastal terrace and forming flat and restricted terminal fans at the exit of these few incised streams (Fig. 3). These fans are built directly onto the linear ridges and not over lagoons, in spite of the different and more depressed topography of the initial ridges of this RGDS succession (Fig. 2).

A very important number of coastal ridges formed between this paleocoastal scarp and the present coast line in a continuous but progressively narrower belt of c. 16 km maximum width, parallel to the present coast for about 55 km; south form that point they become almost completely reworked by aeolian activity. A preliminary count of the ridges suggested c. 300 ridges, formed at open ocean conditions and thus making this succession very well suited to compare the coastal events described at the Paraná delta, depicted out of a succession of continuous c. 330 ridges until the present day coastline (Milana and Kröhling, 2015) but generated under more restricted coastal conditions.

The Stage IV coastal ridge succession at Cassino, shows three characteristic that make the succession attractive for a geochronological study as:

A) *A change of onlap direction*: A striking feature observed in the preliminary survey of the locality was a reversal of ridge onlap or convergence. It can be clearly seen that the initial set of ridges seem to be fed from the south, as the ridges are onlapping the maximum sea level coastal scarp (highstand coastline) from south to north, being the group of ridges where the city of Quinta (Fig. 2), is located. On the other hand, the next package of ridges show a reversal of onlap direction, as the initial ridges show onlap from north to south, while the following ridges tend to be continuous southward but showing a progressive thinning southward and in many times a convergence of smaller ridges in the same direction. This geometrical distribution of ridges suggest therefore, the same phenomenon mentioned previously about a pervasive change of coastal drift along the eastern South American coastline, making this area very well suited to start a dating plan.

B) *Evident presence of environmental changes*: The interest of this succession does not end in this change of onlap direction. In second place, the evident presence of important environmental changes that left their path in the type of ridges formed, could help to unveil the environmental history of middle to late Holocene of South America. We are particularly interested in how these events recorded in this rapidly growing coastline allow us to link marine coastal activity and wind activity with other processes that occur at the interior of the continent as glacier growth episodes. We were interested specifically into finding if there was a record of the Little Ice Age (LIA) in this coast, as suggested by Milana and Kröhling (2015) for the last coastal ridge group surveyed at the Paraná Delta (although without dates), and by Sawakuchi et al. (2008) at Ilha Comprida, São Paulo state. It is worth to mention that the link between glacial growth and wind activity (and hence the strength of longshore drift), was long time suggested by researchers, in particularly by Talbot (1985) who studied the link between Sahara desert cycles of expansions and shrinking and compared them with Pleistocene glacial phases. Although the well-known linkage between desert expansions and glacial growth (cf. Talbot, 1985) is not yet well established in South America, it is widely accepted that the Pampean Sand Sea (Iriondo and Kröhling, 1996, 2007), was active during Pleistocene glacial phases and became inactive near the onset of the Holocene, with a minor period of partial reactivation between 4 and 3.5 and 1,4-1 ka BP during the Holocene (Iriondo, 1999; Kröhling, 1999; Kröhling and Iriondo, 1999), that has been linked recently with colder weather in the Andes including a glacial growth stage starting at c. 5.3 ka BP (Thompson et al., 2006), and coastal ridge formation within the La Plata estuary, at the northeast side of the Paraná delta (Milana and Kröhling, 2015).

C) *A Potential place to evaluate solar cycles*: The third interest of

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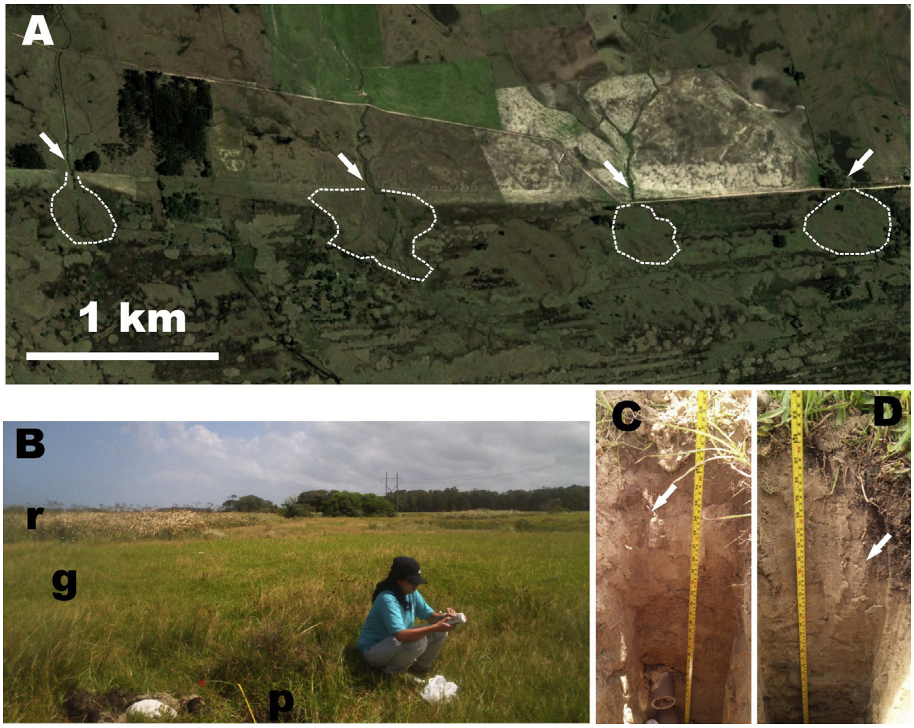

Fig. 3. A) Processed satellite image showing the c. 6.5 ka BP coastal scarp, incised by fluvial streams (arrows) that built terminal fans (white dashed lines) over the beach ridges of Stage 1. B) View of one ridge sampled (RG3) showing the pit (p), the grassland characterizing high grounds (g) and low ground vegetated with reeds (r), C) Sample pit of RG1 with the PVC tubes ready to sample. D) Sample pit of RG4 showing the development of pedogenetic layer mainly at its upper sector (arrow).

this study is to investigate the possibility that ridges at RGDS succession were formed at the same pace as suggested for the Paraná Delta ridge succession. This is particularly important as both successions were formed in different geographical scenarios and therefore this could be a good test to prove the correlativity of ridges independent of their formation setting. This would open the opportunity to test the interhemispheric correlation of these features at places where long and continuous ridge successions could be found. Secondarily, as ridge periodicity at the Paraná delta could be formed by the periodic change of sediment supply the Paraná river shows (cf. Pasquini and Depetris, 2007; Milana and Kröhling, 2015), in concordance with sunspot periodicity (c. 11 yrs), would be challenging to find out what kind of periodicity and what possible environmental control was acting at the RGDS open ocean coastal realm.

2. Methodology

As the starting point of correlation is to have information about the age, the first step was to establish a preliminary sampling of this ridge succession. Therefore, an initial number of samples to be taken out of the succession were first defined, in order to start learning about the time distribution of the ridges. The objective was to further refine the sampling if results suggested this was a prospective area for improving the dating precision. Four OSL samples taken regularly spaced were planned as the first sampling round at this area.

The second step was to define the exact position of environmental changes that could be observed in the overview. Therefore, high-resolution imagery of the studied area available at Google Earth was used with the aid of the open software QGis to map and trace the ridges at its maximum resolution. Imagery included a mixture of Geoeye, Ikonos and Quickbird, as we also used imagery from Bing maps (www.bing.com/maps) for inspection of problematic areas. The mapping included c. 30 km along the north-south direction (ridge strike) in the first third of the ridge succession, while due to a larger level of reworking at the southern area, the younger two thirds of the succession were mapped in a segment of c. 15 km along the ridge strike. This difference is also justified by the fact older ridges are prograding from south to north, and therefore, counting them too close to Rio Grande city eliminates several tens of them out of the complete succession. On the other hand, the c. 2/3 younger ridges show onlap, convergence or wedging southward, and therefore they require more detailed mapping in the northern sectors of the ridge belt. In all cases, the inner boundary of Stage IV ridge belt is quite well defined by a continuous paleo-coastal scarp that runs north-south starting near the town of Quinta, RGDS, and in the field is defined by a minor topographic step of a few meters. This minor scarp, is eroded by an incipient fluvial incision forming dendritic drainage networks of very limited extension upstream. Further than 50 km to the south, the depression eastward from this paleo-coastal scarp has been occupied by lagoons, so ridges there are either submerged under water or reworked by blowouts in the exposed areas.

The third step after mapping was the field sampling. This is locally complicated due to the few roads giving access to places where the original ground is still present and not much affected by human activities, the few places at which there are no deep swamps at the road sides and the fact most terrains are private and there are no indications of where to ask permission. During the field search of sampling sites, notes about relative topography (between groups of ridges) were taken in the field, aided by the fact that lower topography segments show increased development of swamps and ponds (Fig. 3). Difficulties in access caused that many originally targeted sampling places, would become inaccessible in the field, forcing the sampling team to take new decisions with

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Table 1
OSL Sample information and laboratory results.

OSL results													
Sample #	Depth (cm)	Location	Dose (Gy)	Approved/total aliquots	O.D. (%)	K (%)	Th (ppm)	U (ppm)	Gamma (Gy/ka)	Beta (Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Age (kyr)
RG1	90	32° 5′11.08″S, 52°16′30.43″W	3.47 ± 0.04	20/20	4	0.410 ± 0.020	0.92 ± 0.001	0.40 ± 0.001	0.161 ± 0.016	0.324 ± 0.037	0.1944 ± 0.0097	0.679 ± 0.041	5.1 ± 0.3
RG2	90	32° 6′55.49″S, 52°11′46.65″W	0.130 ± 0.002	12/14	1	0.351 ± 0.019	0.52 ± 0.001	0.32 ± 0.001	0.119 ± 0.012	0.256 ± 0.028	0.1944 ± 0.0097	0.569 ± 0.032	0.23 ± 0.01
RG3	90	32° 8′33.30″S, 52° 8′55.52″W	0.96 ± 0.018	16/20	5	0.535 ± 0.025	0.87 ± 0.001	0.32 ± 0.001	0.169 ± 0.016	0.375 ± 0.041	0.1960 ± 0.0097	0.738 ± 0.045	1.30 ± 0.08
RG4	90	32° 9′5.62″S, 52° 6′28.96″W	0.196 ± 0.009	17/20	11	0.786 ± 0.033	1.41 ± 0.001	0.42 ± 0.001	0.261 ± 0.026	0.577 ± 0.064	0.1958 ± 0.0097	1.032 ± 0.070	0.190 ± 0.016

limited information available. Although sampling was conduced with a GPS, the quality of the satellite image in the field was not good, and in some cases the sampling places were not as optimal as originally planned. Sampling OSL was done using PVC tubes to avoid light incidence (Fig. 3c). The soil horizon was quite superficial, and organic soil was present in the upper 40–50 cm of the sampling hole (Fig. 3d). In general we could sample sand at a depth of c. 90 cm in average avoiding soil forming processes and a persistent effect of the water table.

Optically Stimulated Luminescence (OSL) dating was performed in an automated Risø DA-20 TL/OSL system at Federal University of São Paulo. Equivalent radiation doses for OSL ages calculation were determined using the single aliquot regenerative-dose (SAR) method (Murray and Wintle, 2000; Wintle and Murray, 2006) applied to multigrains aliquots of quartz sand grains. The preparation of quartz aliquots was performed under red light and consisted of: separation of 120–150 m sand grains through wet sieving; treatment with H_2O_2 27%, HCl 3.75%, HF 48–51% for 40 min, in order to remove organic carbon, $CaCO_3$ and feldspars, respectively; density separation with lithium polytungstate solution (at densities of 2.75 g/cm^3 and 2.62 g/cm^3). Radiation dose rate were obtained through concentrations of U, Th and K measured in a gamma spectrometry system (HPGe detector) at São Paulo University. The contribution of cosmic radiation to dose rate was calculated through the model presented in Prescott and Stephan (1982).

The fourth step comprised the reanalysis of age data with respect to the expected age calculated from geological evidences, once geochronological data was available. In this case, the age of the highstand scarp is widely accepted to be near 6 ka BP and we calculated an approximated constant progradation of the coast. In this process we discover that the second sample gave data not coherent with our expectation and when we check the sampling position we could see that it was taken just at the edge of a sand blow out, which was the product of the need of relocating sample places due to the problems to access the originally selected sampling places.

3. Results

The sample location coordinates and age, plus the laboratory procedure data are summarized in Table 1, and samples are also located in the geological map of Fig. 2. The samples RG1, RG3, and RG4 yielded reasonably ages while the sample RG2 showed incoherent dates to be a coastal ridge sampled. However, its age is useful also telling us about the episode of ridge sand reworking that was not modern. Unfortunately, that sample was key to define the approximate age of the longshore drift reversal, so we will have to hypothesize about the age of this event, using the ridge counting and a selected age model. Before doing so, it is important to emphasize that our ridge counting could be modified in the future by improved mapping tools (as for instance using LiDAR topographic maps or other high resolution tools), and thus it has to be considered a transient solution for the local age model. Besides, as a map is an interpretation of the ground, it involves a degree of subjectivity that could change or improve as well. In this sense, we used cross-controls of mapping between the authors to try to diminish misinterpretations of geomorphological features.

In this section a particular description of each stage will be made, and preliminary interpretations of observed features are given, while in the next section of discussion, preliminary interpretations (as the age model) will be compared with the existing knowledge of similar features.

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3.1. First stage

The oldest sample is useful to define the age of the first stage we defined according to the ridge geometry. This first stage is basically defined by ridges that seem to be fed from a longshore drift moving northwards due to the fact they onlap the highstand coastal scarp from south to north. This geometry would be quite difficult to explain calling a northward longshore drift due to the fact sedimentary ridges tend to be thinner and disappear in the direction of the drift, except in cases of sharp obstructions which seems to be not the case. Additionally, in this case it could be observed onlap to the north. This allows dividing this first stage into two substages: the oldest substage that includes ridges from #1 to c. #36, shows ridges onlapping the highstand coastal scarp northwardly. The ridges onlapping start to occur about 52 km south from Quinta and therefore the first ridges were not included in the detailed map of Fig. 2, that start showing from ridge #16, given it start showing ridges half way from they start to be visible and prograding northwards. The second substage is gradationally formed after ridge #36 (from ridges #37 to c. #84), and shows a gradational change into a more equilibrated situation in which the coastline tends to recover its linearity. As this set of ridges to the south show a parallel tendency, it is suggested this stage comprises a period in which longshore drift is still northward, but the sediment supply from the south progressively diminished and the coast tends to acquire its previous shape.

The age of this first stage could be preliminary estimated by the OSL local sampling. For reasons of space and simplicity we will write ages as years BP, without including errors, although they are quoted in Table 1, and should be translated to final results. The oldest sample was finally falling into ridge #49, while the following one falls in ridge #285. Respective central ages found were 5110 and 1301 yrs BP, respectively. An intermediate age would be desirable, but as indicated above, that sample (RG2) was misplaced in the field (at the edge of a blowout). Assuming a roughly constant pace of coastal progradation (it is a simplification, but it is a first approach to the preferred age), the 236 ridges took 3809 years to form, meaning an average rate of formation of 16.1 years each. It is important to notice that there are unconformities in the succession and belts without ridge formation, so this age model is only the first approach. With this rough approach, the first stage would start forming near $5110 + (49 \times 16.1)$, that is 5899 yrs BP Surprisingly, this age is quite close to the central age indicated for the Holocene highstand in this region (Milne et al., 2005; Angulo et al., 2006). On the other hand, the end of the first stage would have occurred 4546 yrs ago.

3.2. Second stage

The beginning of this stage is marked by a slight unconformity and a clear change of ridge geometry. In our ridge counting, this stage is spanning from ridges #85 to #124. Another clear feature that indicates an environmental change is the “stratigraphic” alignment of blowouts just in coincidence with the coast line defining the initiation of this stage. Therefore, the boundary between the first and the second stage could imply a period of coastal erosion, and hence a sort of hiatus or unconformity. This would suggest that the selected way to assign ages is wrong, but as stated above it is a first approach. This second stage is also characterized by a lower topography which could be the result of two different external causes; it could be the result of a lower sea level (there is a minimum of sea level at c. 4.0 ka, Angulo et al., 2006) or that wave action or wind action were not so strong to shape a higher ridge.

In this second stage is located the FS-20 drilling of Clerot et al. (2005), in which they found a shell of the gastropod Olivanicillária sp. at c. 23 m deep that gave an age of 4940 ± 80 C14 yrs BP, estimated to be 5245 cal yrs BP. It is clear this date has to be older than that of the surface, and therefore depends on the original topography of the shoreface. Today, the 20 m isobath, is located at c. 15 km offshore, thus it is difficult to establish the shape of the stratigraphic surface that connects this dating with coeval coastline. However, this sample given its location would correspond to a coastline formed during the First Stage, instead of this particular one. It is not surprising therefore that our sub-surface sample and that obtained by Clerot et al. (2005) shows almost the same age, reinforcing the fact the age of the first stage, would range from 5.1 to 4.5 ka BP.

Besides the inversion of the ridge onlap in planview, the most distinctive feature of this stage is the strong convergence of ridges to the south making it completely opposite to the geometry that characterized the first stage, particularly, the older substage. The best explanation for this geometry is the combination of two controls, the first is a change of the longshore drift dynamics, comprising a reversal of dominant drift direction and a strength decrease of this process and the second is a possible interval of increased sediment supply from the Rio Grande, to the coastline. This curved geometry and stronger convergence, in combination with the lower topography of these ridges suggest that this stage was formed under mild wind conditions, explaining the growing curvature of the coast and the low relief of the foredunes during this stage. According to our preliminary age model, this stage would be spanning from 4546 to 3918 yrs BP.

3.3. Third stage

This stage, as the previous one is initiated by a slight unconformity between ridges, but with a different geometry: while at the start of Stage 2 ridges were eroded at their medium and distal positions with respect to the Rio Grande mouth, at the start of Stage 3, ridges show erosion at their proximal position, that is, near the Rio Grande mouth. This means that at Stage 3, there was a clear reactivation of the coastal transport system from north to south, indicating the longshore drift reversal was complete and fully active at Stage 3. After this event of erosion, the ridge succession of Stage 3 is characterized by its remarkable parallelism, linearity, good development and also by the fact the entire stage tends to form a higher topographic unit. This is almost the similar situation observed at the Paraná Delta (PD) by Milana and Kröhling (2015) in quite correlative age. At RGDS as at the PD, the well developed, higher topography and good parallelism between ridges may indicate a period of stronger winds creating more wave action that causes successive coast lines to be parallel but also enhance the formation of higher relief ridges.

Stage 3 includes ridges from the #125 to the #204, thus according to our rough age model this stage would be spanning from 3918 to 2646 yrs BP. When compared with the other stages, it is clear the Stage 3 was formed under the stronger and more sustained winds due to the resulting wave effect on beach ridge linearity. This stage could again be subdivided in at least three substages. The Substage 3.1, spans from one #125 to #150 and is characterized by the lowest topographic expression that is more evident when the succession is traced southwards. The Substage 3.2 is characterized by an intermediate topographic expression in average, and spans from #150 to #180, while the youngest Substage 3.3 spans from #180 to #204 and shows the highest topographic development. This subdivision is a generalization of ridge aspects, as internally it could be seen that there were times at which ridge reworking as by small blowouts was enhanced, but it serves to indicate that environmental conditions were increasingly windy from the beginning to the end of this stage.

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3.4. Fourth stage

This stage is characterized by an initial almost complete disappearance of the ridge morphology together with an increase of topography with respect to the last substage of Stage 3. Ridges reappear after an initial 500 m wide gap showing good linearity and several low-topographic gaps. This Stage 4 spans from ridge #204 to #273, and could be subdivided into four substages. According to our age model, this stage would be spanning from 2646 to 1494 yrs BP.

Substage 4.1 comprises an initial high ground without evident ridges found just eastward of the end of Stage 3, making a highland belt of c. 500 m constant wide extending up to 18 km south from the Rio Grande. Due to its topography many farms have their houses along this belt. It looks depleted of ridges, but when inspected in detail along strike, two ridges are still recognizable and perhaps there were more, but their higher topography seems favored their reworking into low-relief blowouts and flat dunes. In some cases, it is possible to see these dunes and blowouts were actually advancing westwards and including ridges of Stage 3 into the reworking process.

Substage 4.2 comprises a very heterogeneous succession of ridges (some are thin, other thick, some with low topography and others with higher topography), but they tend to be reasonably parallel along strike, although start to show a slight divergence to the north and conversely, some convergence to the south until they become parallel at about 12 km south of Rio Grande inlet but they soon disappear due to the reworking by blow out activity. This substage spans from ridges #206 to #241.

Substage 4.3 tends to be again forming slightly elevated ground as the first substage, but in this case ridges are visible, although quite affected by wind reworking. The most particular feature of this substage is the higher curvature of ridges near the Rio Grande inlet, creating a very divergent pattern northwards. Another feature that makes these ridges particular is the apparent change in topography and sand proportion of ridges along strike: they start quite wide in the north and they narrow rapidly northwards, sometimes disappearing or merging with others. This substage spans from ridges #242 to #259.

Substage 4.4 is similar to the 4.2 in the basic design of the ridges, but differing from the previous ones. It shows ridges that tend to thin, and/or to wedge out to the north, that is, in the opposite direction than the previous substages. Some few well preserved ridges in this stage, also show thinning to the south, which makes some ridges to be thickest at about 11 km south of the Rio Grande inlet. This shape seems to be produced by the tendency to compensate the excessive curvature created during the previous substage by a strongly constructive phase of the Rio Grande inlet, and probably as a result of the migration of the main river channel c. 9 km northwards to its present location. This substage spans from ridges #242 to #259.

As suggested by the description, Stage 4 seems to be formed during very variable environmental conditions than before, alternating from windy to low wind conditions.

3.5. Fifth stage

This stage is completely different from all the previous ones, as in this case it is possible to recognize long moments of coastal erosion and then progradation without the formation of coastal ridges. This time of no-ridge formation has the exception of two groups of ridges that will be described separately. As indicated above, the Stage 5 initiates by a clear event of erosion of previous ridges with an apparent rectification of the coast. Probably it is the result of the interaction of a lower amount of sediment entering to the coast out from the Rio Grande inlet, the effect of a potential channel migration to the north (5 km) and a change of the dominant coastal longshore drift. Subdivisions of Stage 5 are only visible in the first 5 km southward from the Rio Grande inlet, as further south this segment is completely recycled into parabolic dunes and blowouts. This recycling together with the erosive contact between Stages 4 and 5, causes the entire Stage 4 to disappear southward by the activity involved in Stage 5 development. This uneven erosion of Stage 4, suggest clearly that dominant longshore drift for Stage 5 was towards north, as it is observed in the present day, indicating a reversal of longshore drift and explaining the important coastal erosion, progressively deeper southward as it was the place providing sediment for the coastal drift.

Substage 5.1 (no ridge): It is unclear if this could be considered a constructional stage, but it clearly represents a time of ridge truncation. Although the proximal terminations of ridges of Substage 4.4 are in general reworked by blowouts, about 2 km southwest from Bolacha town (RGDS) it is possible to see that these ridges are well unconformable with respect to ridges of Stage 5, in this case belonging to Substage 5.2. In general, this substage formed mainly by blowouts, which could be formed afterwards as suggested by the age of our second sample.

Substage 5.2 (older ridge group of this stage, from #282 to #291): this is the most outstanding group of ridges found in Stage 5, and actually the third sample that gave 1301 yrs BP it was taken just at the boundary between substages at a reasonably low place to avoid the effect of sand reworking that is evident at higher topographic places. Therefore, this sample suggest the oldest age of the Substage 5.2. Like in the Substage 4.4, ridges tend to fade away from the Rio Grande inlet and only 6 km they are completely reworked by wind in blowouts and parabolic dunes.

Substage 5.3 is actually a low topographic area separating the older and the younger ridge group. There are no typical beach ridges visible, although several curved lines are present suggesting low-relief dunes or the alignment of blow out tips that formed after coast progradation. In spite of their different nature from the other ridges, we counted ridges these highly curved and discontinuous ridges from #292 to #298.

Substage 5.4 (younger ridge group of this stage, from #299 to #303) is the last evidence of genuine coastal ridges in the succession. Ridges are slightly more curved than the older ridge group (Substage 5.2) near the Rio Grande inlet suggesting some influence of sediment provision from this source. These ridges fade away southward rapidly into reworked ridges, and eastward they turn into the present-day coastline formed by ridges #304 to #306, with slightly more curved trajectory near the Rio Grande inlet, probably resulting from the construction of artificial breakwaters along both margins of the Rio Grande estuary to facilitate navigation. Last OSL sample (RG4: 190 ± 16 years BP) was taken just at the boundary between Substage 5.3 and 5.4. The resulting Stage stratigraphy, unconformities and potential subsurface development of the entire Barrier IV unit, is shown in Fig. 4, in which subsurface data of Clerot et al. (2005) has been integrated.

4. Discussion

In this section the geomorphological evidence, their possible environmental significance and the best correlation to some other known processes in the region will be discussed, in order to tune the age of the stages and if possible, the substages described above.

4.1. The highstand

It is clear that the Holocene maximum sea level was creating the inner coastal feature in this region as it has been observed in most

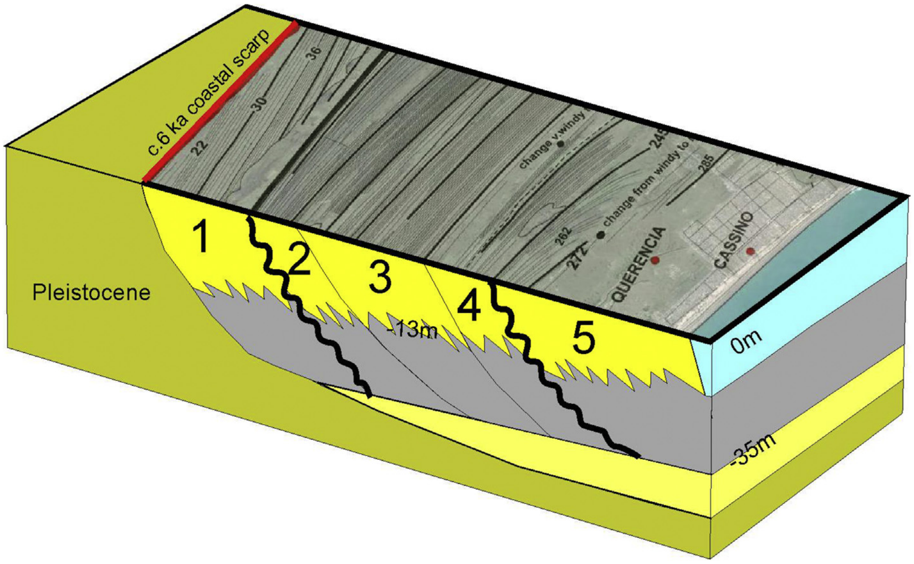

Fig. 4. Block diagram composed using the surface geomorphological mapping and subsurface sedimentary data obtained from Clerot et al. (2005) from wells and geophysical exploration, showing the expected depth development of this strandplain according to the available information of the Holocene "Barrier IV" unit (cf. Dillenburg et al., 2004) at the study site, the Cassino Beach strandplain.

coastal realms of South America and the world. Particularly, many authors coincide that this sea level peaked close to the 6–5.5 ka BP, along the South American Atlantic coast (Milne et al., 2005; Angulo et al., 2006) as well as from the South American Pacific coast (Ota and Paskoff, 1993; Paskoff, 1999). The preliminary age calculation made here of c. 5.9 ka BP based in a constant period of time falls quite close to that age. If calculated with the periodicity suggested for ridges in the Paraná Delta (11.5 yrs, cf. Milana and Kröhling, 2015) this would be c. 5.65 ka BP, but in any case it is clear that the coastal scarp took some time to be elaborated, and therefore it is difficult to use this feature for timing the event of sea level peaking. Besides, it could seen that during the time span of Sub-stage 1.1, the northern part of the studied segment of the coast remained depleted of any added sediment, probably working as sediment bypass or having sediment starvation. Once the ridges growing from the source started to onlap the coastal scarp, they deactivated this scarp as the coastal feature and a true beach started to replace it. It is also unclear if this coastal scarp was pre-existing before the 6 ka highstand, but scarp incision is still evolving today as there are minor fan shaped deposits formed at the mouth of the incisions that spread out over the Holocene ridges (Fig. 3a).

4.2. Stage 1 and first reversal of LST

According to the observations made, this stage is the only one suggesting north directed longshore drift. This process would end near 4.5 ka BP. However, at the end of Stage 1, there seems to exist a time of erosion due to the truncation of the younger ridges and some period of erosion due to the stratigraphic alignment of blowouts just at this boundary. On the other hand, a pervasive reversal of the longshore drift long way to the north. A reversal of longshore drift was identified by Zular et al. (2012) at São Francisco do Sul Island (740 km straight line), while at Ilha Comprida (950 km straight line) Sawakuchi et al. (2012) inferred a record of a change of dominant processes, by increased of cold fronts/storms. Both studies suggest this change occurred near the 2 ka BP which cannot be correlative to this change. On the other hand, at the Caravelas strandplain, Dominguez et al. (2009) record two important changes in the dominant LST. The first change is defined between Stage III and IV of the study of Andrade (2000) and Andrade et al. (2003). Stage III is related to northward LST, and spans from 5.6 to 5.2 ka BP, while Stage IV is related to dominant southward LST. We therefore interpret that the change in longshore drift observed between our Stage 1 and 2, might be correlative to the change observed at Caravelas strandplain some time earlier, and that is rarely preserved along the coast due to the fact it would be only preserved at places with high rates of shore progradation which is only possible where sediment supply is available from both directions along the coast.

4.3. Stages 2, 3 and 4

It is clear that for certain reason during Stage 2, three phenomena interacted in order to promote the characteristics observed in this stage: 1) a phase Rio Grande inlet progradation, 2) a period of sustained but regularly episodic longshore drift southward implying the reversal respect to Stage 1, and 3) an intermediate wind-forced wave activity producing the lower relief of ridges. According to our initial estimation, this stage would span from 4.5 to 3.9 ka BP, but as the base is eroded, the initial sedimentation could be started later. In this case, a correlation with similar coastal evolution observed at the Paraná Delta (PD) is suggested: both RGDS and PD successions show two intervals of higher topography and well preserved linear ridges, ascribed to windier periods, followed by two periods with moderate winds, with ridges developed at lower topographic levels, until at PD they disappear at. 1.7 ka BP. Correlating stages in this scheme, the pass at RGDS from Stage 1 to the lower topographic level of Stage 2, defined by Ridge #85, is also observed in the PD, to occur between ridges PD#98 to PD#120. According to the suggested chronometry for the PD ridges (Milana and Kröhling, 2015), the change between Stages 1 and 2, would be around 4.0 ka BP.

The younger limit could be also compared with a similar evolution observed in the PD, where a windier epoch is marked after ridge #185, although an interesting erosion and truncation of ridges was mapped a few ridges before, near ridge #175. This change at PD has been dated as close to 3.6 ka BP which is not quite far from the 3.9 ka BP, initial estimation at RGDS. The differences in numbering

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(Ridge #124 vs #175) between successions could indicate that at RGDS there was a time of no-progradation or coastal erosion that is expectable for an open ocean position as this, in comparison to the PD estuarine ridges.

Stage 3 would be the easiest to correlate with the PD as there is only one stage in both successions when ridges show their best developments so we could be quite certain that Stage 3 at RGDS (particularly Substages 3.2 and 3.3) could be confidently correlated to the stage formed by the windiest conditions at PD, bracketed between 3.3 and 2.35 ka. As noted before, the preferred age of Stage 2 end would be 3.6 ka BP, so these 300 yrs at the beginning of Stage 3, would represent the time when the first substage was deposited, that as mentioned for the older substage spanning from ridge #125 to #150, shows the lowest topographic expression and hence a less wind action with respect to the following two substages (from #150 to #180, and from #180 to #204) that show increasingly stronger wind activity. Another fact to take into account is that most authors suggest a sea level fall centered at 3.9 ka BP (cf.Angulo et al., 2006), and Substage 3.1 with its lower topography, may just indicate it was formed during a period of lower sea level than the previous and following substages. On the other hand, if we correlate RGDS ridges with those following similar succession the timing of this Stage 3 would be between 3.6 and 2.35 ka BP, which is younger than our estimate between 3.9 and 2.65 ka BP. Another element to take into account is the fact, a second sea level fall is described in most sea level reconstructions and is dated at c. 2.7 ka BP, and the following low-topography interval is Substage 4.2. Thus, the age of this Stage 3 could be ambiguous, but central age would be from 3.6 to 2.6 ka BP.

Stage 4 shows the same tendency of less linearity observed in the PD for the last ridges of the continuous succession. At RGDS it is clear coastal drift and hence longshore currents were not so active. As a result RG inlet progradation was enhanced, causing ridges to show more curvature towards a progressively basinward river mouth as well as a faster decrease of width and sand content as the ridges becomes further from the river mouth. Again this period of progressive decay of wind activity, could be well correlated to a similar period of the PD that was dated between 2.35 and 1.7 ka BP. If we consider the low topography of Substage 4.2, the age model should be older, as that substage would fit with the 2.7 ka BP sea level low. Our age model would suggest this stage spans from 2.6 to 1.4 ka BP. Also, there were important events of reactivation of the longshore drift at 2338–2153 cal yrs BP and 2353–2331 cal yrs BP respectively at the Caravelas strandplain (Andrade et al., 2003). These events of important southward reactivation of the LST may coincide with the last Substage 4.3 that composed high ground and indicates that the coast was receiving much more sand than before. Therefore, the timing for Stage 4 would be between 2.6 and 2.0 ka BP.

4.4. Stage 5 and a new drift reversal

Stage 5 implies a divorce with respect to the evolution of the PD, as while ridge succession at PD ends naturally, at RGDS ridge succession is truncated by a period of coastal erosion. Another element that makes this boundary so important is the return to the conditions of Substage 1.1, with net LST to the north, defining a complete reversal of longshore drift. This reversal causes erosion and cannibalization of almost the entire Stage 4 to the south.

This change in dynamics causes that places that were growing offshore by receiving sediment, started to act as supplier to the Cassino embayment. It is thus possible that most of Stage 5 sands would be supplied by recycling Stage 4 ridges that were protruding too much from the coast under this new scenario, which is maintained until present. Thus, the pass from Stage 4–5 marks the entrance to present day dynamics, in which the wind regime prevailing is the fair-weather system that creates southward longshore drift. But the time-averaged northward LST results from the final dominating interannual term produced by the enhanced sediment transport created by the few storm events generated from a special arrangement of a transient low pressure winter centre that is generated offshore Argentina, Uruguay and South Brazil coasts, and that is called Sudestada (Bischoff, 2006). The *Sudestada* is a generic term used for storms produced as a side-effect of polar fronts advancing over tropical warm waters, creating synoptic extra-tropical cyclonic centers whose location depends on the seasonal development of them. These storm events show a dynamics that is today studied and their effect on the coast depends largely on how storm energy is dissipated by the shape of the coast, but also the submarine topography. Submarine topography and particularly the shallow and extensive shoreface is the main forcing for wave energy dissipation before they hit the shore: storms generating 8.3 m high waves only 200 km offshore RGDS turn into 0.9 m high waves at the coast as quoted by Guimarães et al. (2014). A resulting effect of these storms generated so close to the coast (and sometimes advancing over the continent) is the impressive effect on coastal dynamics, and are today one of the major problems of some populated places of the shore of RGDS as Hermenegildo that are subjected to coastal erosion by this LST dynamics (cf. Calliari et al., 1998; Esteves et al., 2002, 2003; Dillenburg et al., 2004).

As indicated above, a reversal of longshore drift or at least on the dominant vectors of it along the same shore was identified to occur near 2 ka BP (cf. Zular et al., 2012; Sawakuchi et al., 2012), suggesting as potential cause the enhanced activity of the storm events described by Guimarães et al. (2014). Thus, while both north and south directed LST exist, the today dominating process is the one forced by storms and not the one created by permanent winds that do not release enough energy. If progressing to the north, at Caravelas strandplain, Andrade (2000) and Andrade et al. (2003), define also a change in the dominating longshore drift, and in this case the previous southward dominating LST is replaced by a northward prevailing one, at the pass from their Stage VI to VII. The events making the boundary between these stages are defined by shells dated in 1310 and 1273 cal yrs BP (Andrade, 2000).

Finally, the erosion and LST reversal event suggested by the boundary between our Stages 4 and 5, could also be compared to two similar events observed in Argentina. The first and better dated event is the clear change in coastal dynamics observed at PD: at 1.7 ka BP, the continuous ridge succession observed since the c. 5.3 ka BP, ends quite abruptly. In this embayment (La Plata River estuary), an internal dynamics would prevail over the open ocean dynamics. In the RGDS system, the ridges start becoming more curved before being eroded, while in the PD, they passed from continuous sandy ridges, into a segmented ridges separated by channels just before disappearing. The change of ridge structure in the PD could well be explained by increasing activity of the Sudestada storm phenomenon; it reduced internal longshore drift, as waves entering the estuary create a surge (reaching up to 4 m as measured in the last 50 years, Bischoff, 2006) during storm events and the shore was redesigned to allow entering water into the delta plain, and then letting it drain out. Increase of the Sudestada storm effect might be related to a strengthening of tropical conditions offshore southeastern South American (Bischoff, 2006) and could well be linked to the change of LST dynamics observed at RGDS, as it is this phenomenon the one well described and modeled by Guimarães et al. (2014) as forcing a northward directed LST along the RGDS coasts. Interesting to mention here, is that the end of the long beach ridge sucession at PD coincides with the observed end of intramontane loess deposition at the Taiwan island (Wenske et al., 2011) at 1.72 ka BP, and hence, it could be a potential marker for

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wind activity at tropical latitudes.

Reversals of net LST along the South American southern Atlantic coast would be not so uncommon. Moving southward from the PD along the shore, Schnack et al. (1982) and Isla (1997) reported that the Mar Chiquita spits and beach barrier were formed by dominant LST to the south, while present day LST is to the north, suggesting also a reversal in the dominant LST direction. Although the timing of that reversal event is not well dated, 8 different datings from shelly debris recovered from 5 different locations along this stratigraphic unit, suggest this barrier was formed from 3850 to 1340 C14 yrs BP (Schnack et al., 1982).

The timing of the reversal at RGDS is also not clear. The suggested time span for Stage 4 would be 2.6 to 2.0 ka BP, but this does not need to coincide with the initiation of Stage 5 as there is evidence of erosion at this boundary, that 50 km south from the Rio Grande estuary causes recycling of all ridges of Stage 4, 3, 2 and the younger ridges of Stage 1. This boundary is therefore pointing to a significant environmental change. Ages BP of correlative events of this boundary range from 2 ka (Ilha Comprida, Sao Francisco barrier), 1.7 ka (PD) and 1.3 ka (Caravelas, Mar Chiquita); so in this case we prefer to leave a question mark on the specific age of this change, that would range from 2 to 1.3 ka BP.

4.5. The Medieval Ice Age (MIA) and the Little Ice Age (LIA)

After this seemingly important change involving erosion, two episodes of beach ridge construction and hence a returning to the environmental conditions observed in the previous stages involving apparently colder and windy weather were detected. These are substages 5.2 and 5.4, separated by a sustained period of strandplain progradation without any evidence of beach ridge formation but instead some sinuous and discontinuous linear features that seem more connected to wind action alone than to a wave dominated coast.

The first ridge group, nominated here as Substage 5.2 could have its counterpart in the PD, as Milana and Kröhling (2015) observed a group of ridges that were detached from the main succession. This separated ridge group forms a slightly higher topography over which actually is founded the Villa Paranacito town, as the topographically higher ground was favoring settlement of the early nucleus of the town, as the location is seasonally flooded as most of the lower delta plain. The Villa Paranacito ridges are not dated but the mentioned authors suggested their connection to the Little Ice Age (LIA) as an epoch of increased bad weather. However, in RGDS, the sample RG3, taken in this work from Substage 5.2 just at the oldest side of this ridge group yields an age of 1.30 ± 0.08 ka BP. Thus, Substage 5.2 ridges do not correlate to the LIA as preliminarily deduced, but to another event.

We introduce here the name of Medieval Ice Age (MIA), for naming the environmental interval that could have been formed the Substage 5.2 ridges, referring to a long-time recognized glacial advance that predates both the LIA and the MWP (Medieval Warm Period), and that is not quite formally included in the late Holocene literature of events. In fact, Grove and Switsur (1994) indicate that there is a good amount of evidence of a glacial advance that may started close to 1.3 ka ending at 0.95 ka BP, with a possible readvance in the middle of the MWP, close to the 0.7 ka BP. Due to the fact, dating morraines is quite imprecise, dating this event is complicated. In South America, several datings of morraines fall near the 1 ka, as at Ventisquero Negro or Manso Glacier in Argentina, Ventisquero Torres and O'Higgins in Chile (Röthlisberger, 1986). These glacier advances correlate well with other evidence that suggest cool summer periods in northern Patagonia as reconstructed from tree-rings (Villalba, 1990). The MIA would coincide in this case with the cold phase recognized from 900 to 1080 yr AD (Villalba, 1994), while as mentioned above there might be another short cold period between the MIA and LIA, just at the middle of the MWP, between 1300 and 1450 AD. However, the most interesting statement about this cold phase comes also from the Southern Hemisphere, when Cook et al. (2002) state after discussing the significance of the MWP in New Zealand, as; "*Of equal interest in the reconstruction is the sharp and sustained cold period in the A.D. 993–1091 interval. This cold event is easily the most extreme to have occurred over the past 1100 years*". They also correlate this cold event with a regional glacier advance in the Mount Cook area around the period 1100–950 BP described by Gellataly et al. (1988) and coinciding with observations worldwide according to their study.

The main problem of the MIA is that, due to its almost similar development of the LIA at many places, re-advances usually erase, recycle or cannibalize the previously deposited morraines, explaining why the LIA is worldwide known, while not many references exist to the MIA. In general, it is clear that around the 1 ka, there was a time of altered weather conditions and some coastal records in the Northern Hemisphere show important peaks of longshore drift around 1000 yrs BP (Toomey et al., 2013; Forman, 2015). Other facts that may correlate are the increase in wind activity recorded at north American sand seas centered at 0.7 ka BP (Halfen et al., 2016), and increased debris flow activity at the Tatras mountains (Kłapyta et al., 2016), a glacial advance mentioned in the Altai region by Agatova et al. (2014) around 1.4 ka BP, and the well known Göschenen II glacial advance that is associated to the Dark Ages Cool Phase (Zoller et al., 1966; Le Roy et al., 2015) although it may occur slightly earlier than the locally recognized MIA. It is therefore suggested that the ridge group of Substage 5.2 may correspond to the cold phase identified in many regions of the world and centered at 1 ka (950–1100 AD, or c. 1000–850 BP).

The last ridge group (Substage 5.4) shows less morphological evidence than the Substage 5.2 and would be actually formed in the time of the LIA, as the sample RG4, took just at its beginning of this ridge group yielded 190 yrs BP. This age is quite coincident with the age of the blowout dated by mistake (RG2) that reworked ridges of Stage 3 (228 yrs BP), suggesting a generalized increased aeolian activity near the expected time of the LIA development that locally is indicated to end near 1850 AD (Araneda et al., 2009). Thus, we expect that ridges of Substage 5.4 may indicate a climate change that could be linked to the LIA.

In general, this minor geomorphological expression of the LIA when compared to the MIA, suggests that a reappraisal of climate episodes of South America should be done. As we showed above, many authors indicate that the MIA could be a more notorious cool phase in the Southern Hemisphere, and the coastal record at RGDS seems to suggest this, placing an attention mark to future interpretations and age assignations of the last glacial events. A summary diagram of the preferred ages for each stage boundary and their correlation to the PD stratigraphy is shown in Fig. 5.

5. Conclusions

The first geochronometric data obtained for the Rio Grande do Sul (RGDS) ridge succession shows it has a very good fit with a comparable succession described for the Paraná Delta (PD) in a different setting, making these types of successions excellent geoarchives to unravel the Holocene coastal history after the 6 ka highstand. The different environments of the RGDS coastal ridge succession with respect to the PD (in this case open ocean conditions) created a couple of intervals at which erosion occurred, making this succession partially incomplete as seems to occur at the boundary between Stages 1 and 2, and between Stages 4 and 5. With these exceptions, the sequence is quite continuous and future

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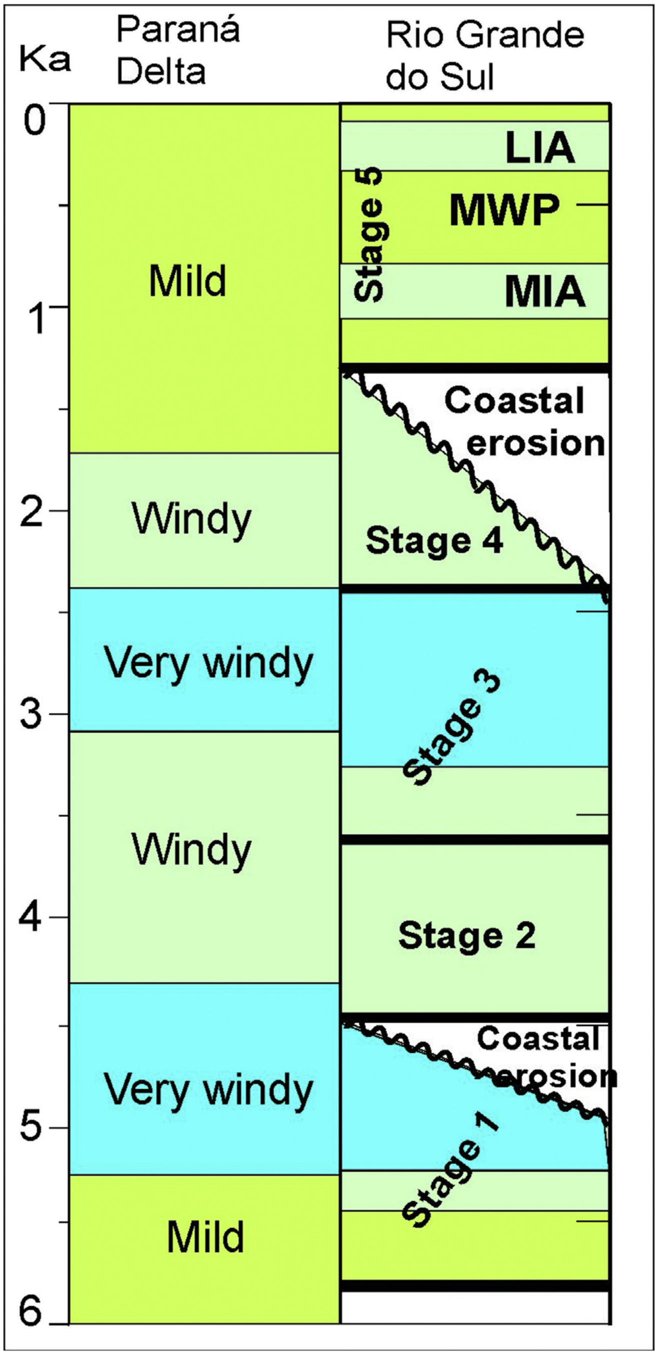

Fig. 5. Possible correlation between environmental changes observed at the Paraná Delta (modif. from Milana and Kröhling, 2015) with those observed at the Holocene of RGDS.

improvements of this preliminary chronology may improve the age constraining of the important environmental changes here analyzed.

We recognized two intervals of important wind activity and ridge formation related to Stage 1 and Stage 3 (Substages 3.2 and 3.3), and a sudden termination of the ridge succession formation at the end of Stage 4, which is also very well correlated to what was observed at the PD. However, at RGDS this change means a change in longshore drift and a progressive cannibalization of the previously deposited ridges due to new coastal dynamic conditions. Our initial timing calculation based on only three successfully located samples coincides quite well, although not exactly with the correlation of the similar evolution depicted for the Paraná delta ridge succession. The initial stage (windy) could be started soon after the highstand c. 5.6 ka BP, ending close to 4 ka BP, time when both a reversal of the longshore drift occurred and a decrease of wind activity and increase of sediment transport along the Rio Grande estuary is recorded.

The second stage of less windy conditions spans from 4 to 3.6 ka BP, while the third stage of highest wind effects constructing foredunes spans from 3.9 to 2.6 BP, although the strongest winds seem to be bracketed between 3.9 and 2.6 ka BP, time that would probably coincide with the maximum extent of the Holocene Pampean sand seas (Iriondo and Kröhling, 1996; Kröhling, 1999) and the concomitant glacial growth in the Andes (Thompson et al., 2006). Stage 4 (2.6–2.0 ka BP) would indicate a slow decrease of the strength of climate conditions peaking in Stage 3.

The onset of late Holocene and conditions comparable to those of today occur at the start of Stage 5, that initiates with an important event of coastal erosion that becomes minimal near Rio Grande estuary. The change could be occurred near the 1.7 ka, but probably first deposits of Stage 5 took place at 1.3 ka BP according to our preferred correlation. In Stage 5 two episodes of climate deterioration were detected. The first, termed here as Medieval Ice Age (MIA) is dated to be c. 1.1–1.0 ka BP, and seems to be the effect of a glaciation that has not properly weighted in South America. The MIA might have been more important than the LIA locally, as some other authors suggested for other regions. In the RGDS succession, the LIA would be represented by ridges of Substage 4.4 and by an extensive period of wind reworking of previous ridges, as the dating of Substage 4.4 is concordant with the date of a sample located in a blowout in Stage 3. Future research is recommended in order to improve the age control of the many environmental events recorded at this coastal realm.

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