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Late Holocene intensification of colds fronts in southern Brazil as indicated by dune development and provenance changes in the São Francisco do Sul coastal barrier

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ABSTRACT

Holocene coastal barriers from southern Brazil present great geomorphological changes during their late stages of development. In this study, we investigate the Holocene evolution of the São Francisco do Sul (SFS) barrier through geomorphological, heavy minerals and grain size analyses constrained by Optically Stimulated Luminescence (OSL) dating. The SFS barrier stands out among the southern Brazilian barriers due to its well preserved morphology with a parabolic dune belt in the seaward portion. The progradation of the SFS barrier started at least 4914 ± 478 years ago and had a pronounced morphodynamic shift around 1891 ± 155 years ago. This shift is characterized by episodic development of parabolic dunes migrating to NNW associated with sand coarsening and a marked variation in sediment provenance represented by the input of sands derived from local coastal watersheds southward from the SFS barrier. This morphodynamic-provenance shift resulted from the strengthening of SSE winds and associated wave systems responsible for the northward alongshore drift, implying intensification of cold fronts coupled with higher precipitation since 1891 ± 155 years ago. OSL dating combined with grain size, heavy minerals and geomorphological analyses allowed assessing the response of coastal barriers to the impacts of centennial to millenial climate events occurred during the Late Holocene. Reconstruction of the Late Holocene climate variability and associated impacts on coastal sedimentation is a key issue to evaluate the sensitivity of coastal barriers to future climate changes.

1. Introduction

Beach ridges with superimposed aeolian dunes are common features of coastal sandy barriers formed by progradation of wave-dominated depositional systems following the Holocene relative sea level rise throughout the world (Clemmensen et al., 1996; Lancaster et al., 2002; Orford et al., 2003; Cooper and Navas, 2004). A great number of coastal barriers on southern Brazil prograded since the Mid-Holocene with superimposed dunes forming at later stage of barrier development (Giannini and Santos, 1994; Martinho et al., 2006; Giannini et al., 2007; Sawakuchi et al., 2008; Giannini et al., 2009; Guedes et al., 2011a, 2011b). However, the factors controlling the generation of these superimposed dunes during the later evolution stages of southern Brazilian barriers and eventual decoupling of sediments from their beach ridges and dunes have not been completely understood. The dynamics of barrier depositional systems is under the influence of climate and sea-level forcings (Cowell and Thom, 1994). Late Holocene climate changes in South America have been documented by several authors under different proxies (Rodbell et al., 1999; Haug et al., 2001; Lamy et al., 2001; Markgraf et al., 2003; Gilli et al., 2005; Wanner et al., 2008; Cruz et al., 2009; Vimeux et al., 2009; Lamy et al., 2010; Fletcher and Moreno, 2012). Despite relative sea-level playing an important role for the evolution of coastal barriers, the great geomorphological diversity of southern Brazilian barriers (Angulo et al., 2009 suggests that coastal physiography and climate are the most important forcings for their Holocene sedimentary dynamics (Sawakuchi et al., 2008; Guedes et al., 2011a); In this context, the northward migration of frontal systems (cold fronts) are particularly important for the sedimentary dynamics of coastal depositional systems in southern Brazil because it shifts and intensifies wind and wave activity (Siqueira and Machado, 2004; Rodrigues et al., 2004; Pezza and Simmonds, 2005). The activity of cold fronts in southern Brazil is sensitive to regional South American climate systems such as the westerlies wind belt (Siqueira and Machado, 2004) and the El Niño Southern Oscillation (Grimm and Doyle, 2000). Changes in the intensity and displacement

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of the westerlies and the onset of the El Niño Southern Oscillation (ENSO) at about 5 ka ago triggered shifts in atmospheric circulation that persist to the present day (Markgraf, 1998; Moreno, 2004; Gilli et al., 2005). The westerlies activity favors the development of frontal systems in southern South America (Stutt and Lamy, 2004; Gilli et al., 2005; Lamy et al., 2010). The northward advance of cold fronts stimulates S to SE winds as well as wave systems responsible for the northward alongshore sediment transport on the southern Brazilian coast. In this context, the São Francisco do Sul (SFS) barrier stands out as a wave-dominated prograded barrier in the southern Brazilian coast presenting well developed parabolic dunes generated by S to SE winds related to the activity of cold fronts.

The aim of this study was to evaluate the relation between aeolian dunes generation during the late stages of development of the SFS barrier and climate changes able to affect winds and waves acting on the southern Brazilian coast. Changes in sediment sources between beach ridges and superimposed dunes sands are also investigated in the SFS barrier. Variation in sediment provenance between beach ridges and adjoining coastal dunes have been reported by several authors (Bauer, 1991; Shulmeister and Kirk, 1993; Orford et al., 2003; Anthony et al., 2010) and have been associated to processes related to sea level or climate changes. Hitherto one hindrance in solving the mechanisms responsible for shifts in barrier geomorphology and sediment provenance was the lack of absolute ages. First absolute ages obtained by Optically Stimulated Luminescence (OSL) with the application of the single-aliquot regenerative-dose (SAR) protocol for beach ridges and dunes in the SFS barrier were attained. Thus, OSL ages provided a detailed chronological for sediment deposition that coupled with grain size, heavy minerals and geomorphological analyses helped to evaluate the climate significance of changes in barrier morphology and sediments provenance through time.

2. Study setting

2.1. Geological aspects

The major portion of the southern Brazilian coast rests against crystalline massifs that forms the Serra do Mar coastal range, stretching from the southern State of Espírito Santo (~20° S) to the southern portion of Santa Catarina State (~28° S, Angulo et al., 2009). Its most prominent geomorphological characteristic is the scarped coastal range that, when intersecting the coastline, creates coastal embayments where strandplains, and less frequently estuarine systems, are found (Angulo et al., 2009). The SFS barrier is located on the northern coast of the Santa Catarina State in Babitonga bay estuary vicinity (Fig. 1). It covers an area of about 280 km^2 with an approximate length of oceanic coastline of 40 km. The facing inner shelf is identified by a low-gradient slope (~0.01%) with the −50 m contour at around 45–75 km away from the shore (Angulo et al., 2009). The Precambrian substrate is composed of granitic-gneissic rocks of the Coastal Granitoid Belt (Basei et al., 1992; Siga et al., 1993). On the northernmost part of the barrier, these rocks reach the shore forming headlands and small islands. Also, they outcrop in the western part and in scattered hills throughout the barrier. Despite the occurrence of granites, low to high grade metamorphic rocks represented by schists, gneisses and migmatites (CPRM, 2004; Fig. 2B) prevail over the landward regions.

In southern Brazil, limited coastal progradation occurred in the first 1000 years after the Mid-Holocene relative sea level maximum from 7000 to 5000 years BP (Angulo et al., 2006), when the estuaries were tidal flood-dominant and sequestered sand from the coastal system (Angulo et al., 2009). Coastal progradation was accelerated first with the halt of flood dominance in the estuaries, that eventually became ebb-dominant (Angulo et al., 2009), and later by the input of abundant sediment supply that coupled with the effects of swell waves from the south and sea-level fall allowed the conditions for the progradational of a wave-dominated system and formation of the SFS barrier.

The SFS barrier is segmented by the Icaraí lagoon (Fig. 1) in western and eastern sectors, which could represent two different barriers. The western sector is up to 10 km wide and is considered by many authors (Martin and Suguio, 1975; Lessa et al., 2000; Horn Filho and Simó, 2008; Angulo et al., 2009; Possamai et al., 2010) to be a Pleistocene age barrier due to sedimentological, paleontological and geomorphological features although no chronological analysis has been undertaken yet. Its formation would be associated with the last Pleistocene relative sea-level highstand at about 120 ka, when relative sea level stood 8 ± 2 m above the present level (Martin et al., 1988). The eastern barrier is supposed to be Holocene in age and is the focus of this study. It covers an area of approximately 65 km^2 and comprises a succession of beach ridges, parabolic dunes, blowouts and established foredunes forming sand ridges with same orientation as the present coastline. All geomorphological units are composed predominantly of quartz dominated well sorted sands.

The passive Brazilian continental margin likely experienced relative tectonic stability throughout the Quaternary (Riccomini and Assumpção, 1999). Thus, it appears unlikely that tectonics have contributed to the development of Brazilian Holocene barriers. Rather, changes in the rate of sea-level variations bringing forth cycles of coastal accretion and erosion (Brunn, 1962), periods of abundant sediment supply related to episodic climatic events that affected the balance between accommodation space and sediment input have contributed to the progradation of the coastal systems and the formation of aeolian dunes in southern Brazilian barriers (Martinho et al., 2008; Sawakuchi et al., 2008; Guedes et al., 2011b). Reliable Holocene relative sea-level analyses in southern Brazil have been established through in situ carbonate vermetid shells (Angulo and Lessa, 1997; Angulo et al., 2005, 2006). Relative sea-level investigations in the Santa Catarina State show a Mid-Holocene maximum highstand of around 2.1 ± 1.0 m above present mean relative sea-level at approximately 5400–5800 cal yr BP (Angulo et al., 2006). Relative sea-level fall combined with high sediment input contribute to coastal progradation and formation of sandy barriers (Carter and Woodroffe, 1997). An overview of sea-level changes on the Brazilian coast is given by Angulo et al. (2006).

2.2. Climate

The SFS barrier climate is subtropical (Cfa, according to Koppen's classification) with wet summers and moderately dry winters. The annual rainfall varies between 1000 and 1500 mm and the mean average temperature is 18 °C. The interactions between tropical and extratropical atmospheric systems control the climate in southern Brazil (Nobre et al., 1986). The northward incursions of extratropical Polar air masses and their related cold fronts are of particular importance for the climate in southern Brazil (Seluchi and Marengo, 2000). Cold fronts migrating northward along the southern Brazilian coast occur throughout the year within 1–2 weeks intervals but they are more intense and faster during the winter (Garreaud, 1999). These cold surges provoke sudden weather changes, influencing winds and waves acting on the SFS barrier. Data collected from 1980 to 1985 indicate an average duration of a cold front from 2 to 3 days in the South Brazil Bight (Fig. 2A) with a mean time interval between successive fronts of 6.5 days (Stech and Lorenzzetti, 1992). An approaching cold front brings initially 5 m/s NE winds which may turn up to 8 m/s SSE winds during the following day. The westerlies wind belt influences the activity of the polar air mass. The position and intensity of the westerlies vary seasonally as a consequence of changes in sea surface temperature in eastern South Pacific Ocean. The westerlies belt expands northward during austral winter favoring more intense cold fronts (Heil, 2006; Lamy et al., 2010). Cold fronts can bring wet conditions to subtropical Brazil. In contrast, the warm-season precipitation (South Atlantic anticyclone) from late September to April is associated with the activity of the South American Summer Monsoon (SASM; Cruz et al., 2006; Fig. 2A). An important feature of the SASM is the South American