Coastal geology of the Holocene progradant plains of sandy beach ridges in Santa Catarina state, Southeastern Brazil

Geologia costeira das planícies progradantes holocênicas de cordões litorâneos arenosos no estado de Santa Catarina, sul do Brasil

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Abstract

Beach ridges are indicators of supratidal and intertidal depositional environments built by waves. The major factors that influence on the ridge's formation is related to antecedent topography, sediment supply, sedimentary balance, and substrate gradient. They consist of siliciclastic and/or bioclastic sediments whose grain size varies from very coarse sand to very fine sand. At Santa Catarina state, progradant plains are related to Pleistocene and Holocene regressive marine processes. The Holocene marine terraces, object of this study, predominate in the coastal plains of Passo de Torres, Pinheira, Jurerê, Tijucas and Navegantes, presenting heights from 3 to 6 m in elevations and 1 to 2 m in depressions. The ridge deposits are constituted by sandy sediments, medium to very fine, composed by quartz, opaque and heavy minerals and shell fragments. The runnel deposits comprehend silt-sand-clayey sediments enriched by organic matter. The evolution of Holocene Santa Catarina beach ridges is connected to the regressive events occurred after 5,1 ky BP that indicate the position of paleo coastlines and mean sea level of the Holocene.

Key words: Geomorphology; Sedimentology; Coastal evolution.

Resumo

Os cordões regressivos são indicadores de ambientes deposicionais formados por ondas sob regime de supra e intermarés. Os fatores mais relevantes que influenciam na formação dos cordões estão relacionados à topografia antecedente, suprimento sedimentar, balanço sedimentar e gradiente do substrato. Os cordões consistem em sedimentos siliciclásticos e bioclásticos, cujo tamanho de grão varia desde areia muito grossa à areia muito fina. No estado de Santa Catarina, as planícies progradantes estão relacionadas aos processos regressivos marinhos ocorridos durante o Pleistoceno e Holoceno. Os terraços marinhos holocênicos, objeto desse estudo, predominam nas planícies costeiras de Passo de Torres, Pinheira, Jurerê, Tijucas e Navegantes, apresentando altitudes que variam de 3 a 6 m nas elevações e 1 a 2 m nas depressões. As cristas dos depósitos são constituídas por sedimentos arenosos, médios à muito finos, compostos de quartzo, minerais opacos e pesados e fragmentos de conchas. As depressões dos depósitos compreendem sedimentos síltico areno argilosos enriquecidos em matéria orgânica. A evolução dos cordões litorâneos holocênicos de Santa Catarina está correlacionada aos eventos regressivos ocorridos pós 5,1 ka que indicam a posição das paleolinhas de costa e o nível médio do mar do Holoceno.

Palavras-chave: Geomorfologia; Sedimentologia; Evolução costeira.

1. Introduction

In Brazil, coastal zones are distributed along of 7.367 km of coastline, enclosing an area of 442.000 km², corresponding to nearly 4% of the Brazilian territory. This coastal zone presents a diversity of ecosystems, including sand dunes, beaches, inlets, mangroves, estuaries, *restingas*, reefs and beach ridge plains. Quaternary deposits (Pleistocene and Holocene) are founded on this area, and its origin is linked to marine and eolic processes, generating deposits of different shapes, ages, and textures.

Brazilian Quaternary coastal plains stretch out from Amapá to Rio Grande do Sul states. Geomorphologically, these plains are constituted by marine terraces, ridges, beaches, dunes, cliffs, spits, tidal plains, besides of submersed features, like lagoon terraces. Transgressive and regressive marine processes evidenced along of Holocene are important to explain the evolution of the coastal plains, shaped mainly in the last 7 ky BP.

The coastal deposits located between marine and continental areas are extremely fragile; hence practical actions are important to conservation and management of these systems (Lacerda et al.1984).

The objective of this study is to characterize the morphology, texture, and paleogeography of progradant plains of Quaternary sandy beach ridges in Santa Catarina state, focusing mainly on Holocene terraces.

The methodology applied to this study consisted in bibliographic revision, interpretation of aerial photos (1:25.000) and satellite images (several scales), field works and textural analyses.

2. Background

Beach ridge is a term frequently used on coastal literature, but with different meanings. Redman (1852, 1864) introduced the term beach ridge in the classical work of changes of South and West England shoreline, being originally associated to storm waves of high energy.

In other hand, Johnson (1919) presented this term to describe features built from storm waves of low energy.

Davies (1968) defined beach ridges as ridges parallels or sub parallels, which oscillate from two or more of 100 unities built of sands, shells, and gravels, located on the emerged portion of actual beaches, each ridge corresponding to the position of a paleo shoreline. Bates & Jackson (1980) described beach ridges as an accumulation of beach and/or eolic sediments, deposited on the high beach zone by waves that break beyond backshore because of storms or ordinary tides. Suguio (1992) described and named beach ridges as typical elongated deposits, generally composed by sand, and less frequently constituted by gravel or bioclastic (shells), disposed parallel to the paleo coastlines and separated by depressions. Each ridge is a component of progradant zone and formed by action of storm waves, coastal currents, and tides.

Several theories have been proposed to explain the genesis of the beach ridges. The theories are not conclusive once there is not a mechanism able to explain the genesis of all types.

According to Schwarz (1971), the polygenetic origin should be accepted as one of the possible explanations for sandy beach ridges formation. Based on the traditional school, most of the researchers claim the marine origin for beach ridges and exclude the origin from foredune (Short 1984, Taylor & Stone 1996).

The genesis of the regressive beach ridge plains suggests formation by marine processes, which sediments are deposited slowly as it occurs in an upswing beach (Figure 1).

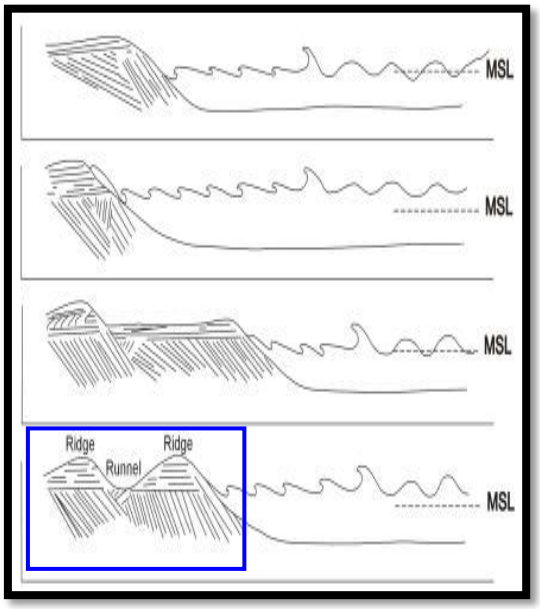

Figure 1: Origin of the regressive beach ridges proceeding from high beach ridge (MSL = mean sea level).

According Hesp et al. (2005), many progradant barriers and some dune fields in the world have been termed “beach ridge”' plains, but the actual genesis of the “'ridges” is often unknown. Use of the terms, berms, beach ridges and foredunes is also confusing in the literature because their definitions are highly variable and are commonly used interchangeably. Beach ridges are re-defined as entirely wave formed deposits which are most formed during high wave conditions and/or elevated water levels. Foredunes are formed by eolic sand deposition rear the backshore.

The fluctuation of sea level is an important parameter to control the orientation and morphology of ridges and runnels, with few other changes regarding to the energy conditions. In a study about the genesis of Australian sandy beaches, Hesp (1984) followed the proposed models of Davies (1958), Bird (1960) and Thom (1964), confirming that the growth of ridges are related to eolic deposition through analysis of the internal structures. In this case, genesis, and growth by one group of regressive sandy beach ridges was anchored in basement rocks or preexistent sedimentary deposits.

Carter (1986) classified two types of progradant beach ridges: (i) beach ridges formed for gradual attachment and coalescent of swash bars by the normal coastline sedimentary transport and, (ii) beach ridges formed by sedimentary transport along the shore, from one side to the other of submersed bars, resulting in an addition of sediment to the emerged beach profile by dominant waves.

Beach ridges were classified by Stapor (1988) and Stapor et al. (1988) as linear sandy deposits constituted by a succession of ridges and runnels, parallel to the coast, where the ridges are situated in elevations above of mean high water level, while the bottom of the depressions (swales) are in altitudes near to the low tide medium level.

Tanner (1987, 1992) and Tanner & Demirpolat (1988) recognized tree types of sandy-gravel beach ridges: (i) swash ridges and storm ridges, related to the marine genetic processes; (ii) very shallow water ridges, typical of lagoons; and (iii) foredune ridges areas, originated from eolic mechanisms.

Otvos (2000) classified the beach ridges deposits, based on geologic agents in two categories: (i) beach ridges built from waves, subdivided in storm ridges, barrier ridges and chenier ridges (Buynevich et al. 2005); and (ii) beach ridges built from winds. Storm ridges occur in glacial coasts or in erosive coasts, produced by high energy events that allow accumulation of lithoclastic and bioclastic sediments.

Lastly, Adams & Wesnousky (1998) used barrier ridge and beach barrier terms to the sandy-gravel ridges formed in the Pleistocene tide plains. The chenier ridges develop along of the coast receives clay and sandy sediments, alternately. Remnant foredunes are considered eolic beach ridges, parallel to the coast, developing from the shore face zone and might be integrant of a progradant sequence. These ridges plunge in direction to the continent and are constituted by fine to medium sand.

3. The study area

The study area corresponds to the Santa Catarina coast, located in Southern Brazil, limited by the Saí-Guaçu river (25º57'41"S.) and Mampituba river (29º23'55"S.) (Figure 2). The coastal zone of the state is divided in three sectors: Northern, Central and Southern (Horn Filho et al. 1994), which coastline is subject to action of oceanographic dynamic of Atlantic ocean under influence of waves, alongshore and rip currents and tides.

The location of the Holocene sandy beach ridges listed in this research appears on Figure 2, being called Passo de Torres ❶ in the Southern sector and Pinheira ❷, Jurerê ❸, Tijucas ❹ and Navegantes ❺, all in the Central sector of the coast.

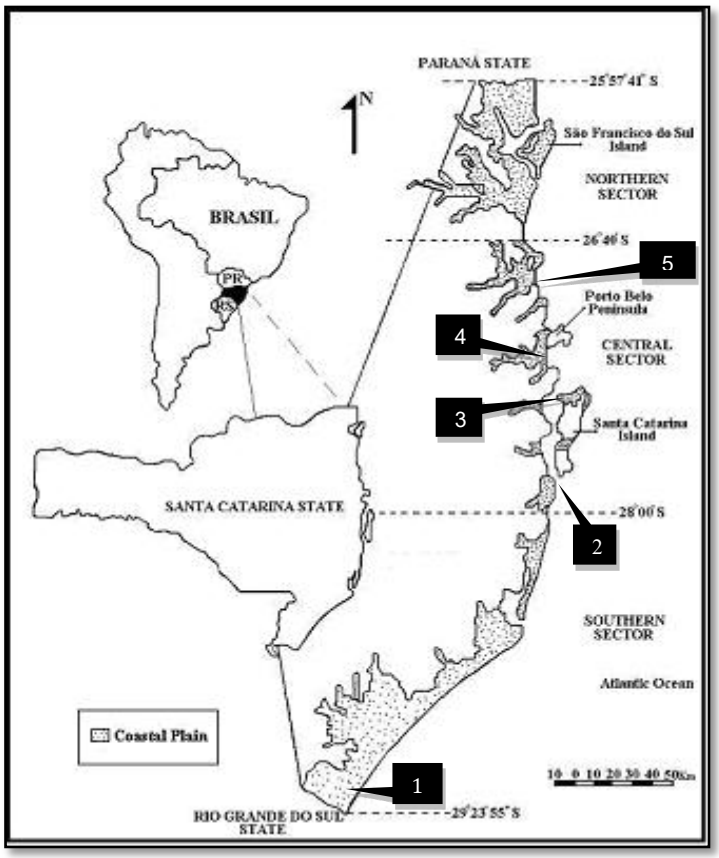

Figure 2: Location of the state of Santa Catarina in Southern Brazil, its three coastal compartments and five expositions of Holocene sandy beach ridges.

The deposits of the coastal plain of Santa Catarina have been reshaped by Quaternary relative sea level oscillations. These deposits are related to those listed in Paraná coastal plain (Angulo 1992) and Rio Grande do Sul coastal plain (Villwock et al. 1986). Transgressive and regressive events during upper Pleistocene and Holocene generated the depositional systems barrier lagoon III and IV, on the Southeastern coastal plains of Brazil.

The winds influence on the regime, energy, and incidence of waves on the coast. The more frequent directions of the waves in the region are from N-NE and S-SE directions (Horn Filho et al. 2020).

Micro tide predominates in Santa Catarina coast (< 2 m) classifying it as a shoreline dominated by waves according to Davies & Hayes (1984).

The Northern sector extends from Saí-Guaçú river (25°57'41"S.) to Barra Velha (26º40'S.), characterized by a wide coastal plain where detach São Francisco do

Sul island, Babitonga bay and presence of the *Serra* do Mar.

The Central sector situated between Barra Velha (26º40'S.) and Garopaba (28º00'S.) is characterized by the proximity of the crystalline basement narrowing the coastal plain, where detach Porto Belo peninsula and Santa Catarina island.

The Southern sector located between Garobapa (28ºS.) and Mampituba river (29°23'55"S.) is distinguished by an extensive coastal plain, shows several large and elongated paleolagoons and lagoons typical of the barrier lagoon depositional system. In this sector detach the lagoon complex of the Santo Antônio, Imaruí and Mirim lagoons.

4. Holocene sandy beach ridges in Santa Catarina coastal plain

Coastal plain is considered the emerged sector of the coastal province, that also includes the submerged continental shelf. The coastal plain is described as a lowland (till 50-60 m of altitude), composed mainly by sedimentary terrains and crystalline rocks, while the continental shelf is described as a shallow region (till 150-200 m of depth) (Villwock 1972)

Santa Catarina coastal province is constituted by two main unities: the basement and Pelotas and Santos oceanic marginal basins, located southward and northward of the coastal province, respectively. The Southern basement comprehends sedimentary and basaltic rocks; Central basement is dominantly granitic, and the Northern basement consists of granitic and metamorphic lithotypes, as gneiss, migmatite, granulite and schist. Pelotas and Santos basins are constituted by two interdigitated sectors: emerged sector, above mean sea level; and submerged sector, below mean sea level; represented, respectively, by coastal plain and continental shelf.

The coastal plain includes deposits of two depositional systems: continental system and transitional or coastal system (Horn Filho & Diehl 1994, Horn Filho 2003), according to Figure 3.

The Holocene sandy beach ridges in Santa Catarina coastal plain are related to morphological features lagoon terraces; dunes and littoral terraces; beach ridges, viewed on the Figure 3, associated to lagoonal, beach marine and eolic deposits.

Continental system is associated to the hillside of highlands, holding colluvial, alluvial fan and fluvial deposits of undifferentiated Quaternary.

Coastal system, in majority barrier lagoon type, associated to sea level changes, includes Quaternary (Pleistocene and Holocene; 120-18 ky BP and 5,1 ky BP, respectively).

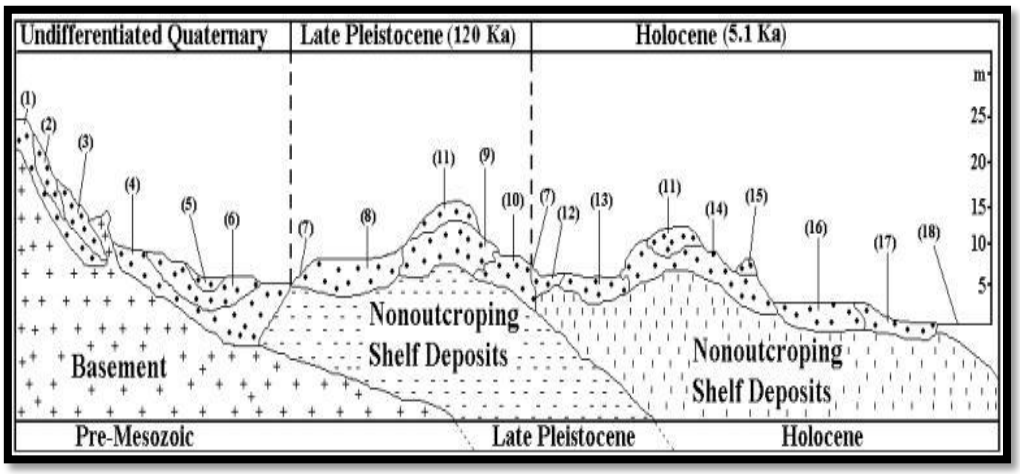

Figure 3: Geological sketch of the Santa Catarina coastal province, showing main morphological features and associated deposits: (1) elluviums; (2) colluviums; (3) alluvial fans; (4) flood plains; (5) and (12) fluvial terrace; (6) levees; (7) cliffs; (8) and (13) lagoon terraces; (9) and (11) dunes; (10) and (14) littoral terraces and beach ridges; (15) shell-middens; (16) tidal plains; (17) beaches; (18) mean sea level (Horn Filho et al. 1996).

There are also sediments constructed by anthropogenic influence, including prototechnogenic Deposit (shell-middens) and technogenic Deposit (embankments and mineral residue wastes).

The Holocene and recent deposits reach altitudes till 10 m; the upper Pleistocene deposits till 18 m and, hillside deposits close to the basement shows heights between 30 and 40 m. Exceptionally, sand dunes are higher than 30 m.

Beach sediments located between coastal plain and continental shelf, along of 538 km of Santa Catarina coast, are composed of sandy sediments that exhibit different texture. The beaches of the Southern coast are dominated by fine sands; while the beaches of the Central and Northern areas are composed of very coarse to fine sands.

Santa Catarina progradant plains related to Quaternary transgressive and regressive marine processes are classified as Pleistocene and Holocene ridges.

The Pleistocene ridges take place in São Francisco do Sul island, Rio Vermelho (Santa Catarina island), Paulo Lopes and Araranguá regions.

The main Holocene ridges, object of this study, are situated in Passo de Torres (❶), Pinheira (❷), Jurerê (❸), Tijucas (❹) and Navegantes (❺) coastal plains, whose location can be seen in Figure 2.

There are still other expositions of Holocene progradant plains in Santa Catarina, such as in the coastal plains of Sombrio, Laguna and Itapoá, however,

they were not selected for their representation in this research.

In the following, the five main exposures of progradant plains from coastal regressive ridges in the state of Santa Catarina, from south to north, will be described one by one.

Coastal areas have been occupied indiscriminately in recent years, due to the use of coastal space, landscape, and tourist vocation. Butler (1980), Smith (1991) and Polette (1993) proposed development stages for coastal balnearies. Thus, the coastal area of Passo de Torres would be framed in the initial stage (exploration, original community, and pre-tourism), while the coastal areas of Tijucas, Navegantes, Jurerê and Pinheira, would be inserted in the main stage (development and urbanization).

Passo de Torres coastal plain (❶), located in the Southern coast of Santa Catarina state (UTM_x 6760686,12; UTM_y 625996,61), in the municipality of Passo de Torres, is constituted by retilineous and flat ridges presenting 10 km of length, 6 km of width and altitudes ranging between 6 and 24 m. Fine sandy sediments over ridges and silt-sandy sediments in runnels characterize a typical barrier lagoon system, whose crests are oriented NE-SW with azimuth 40°.

Except for the eolic and marine deposits towards Bellatorres beach, the deposits of the progradant plains are still uncharacterized by urbanization, being only covered by exotic vegetation (Figure 4 and Figure 5).

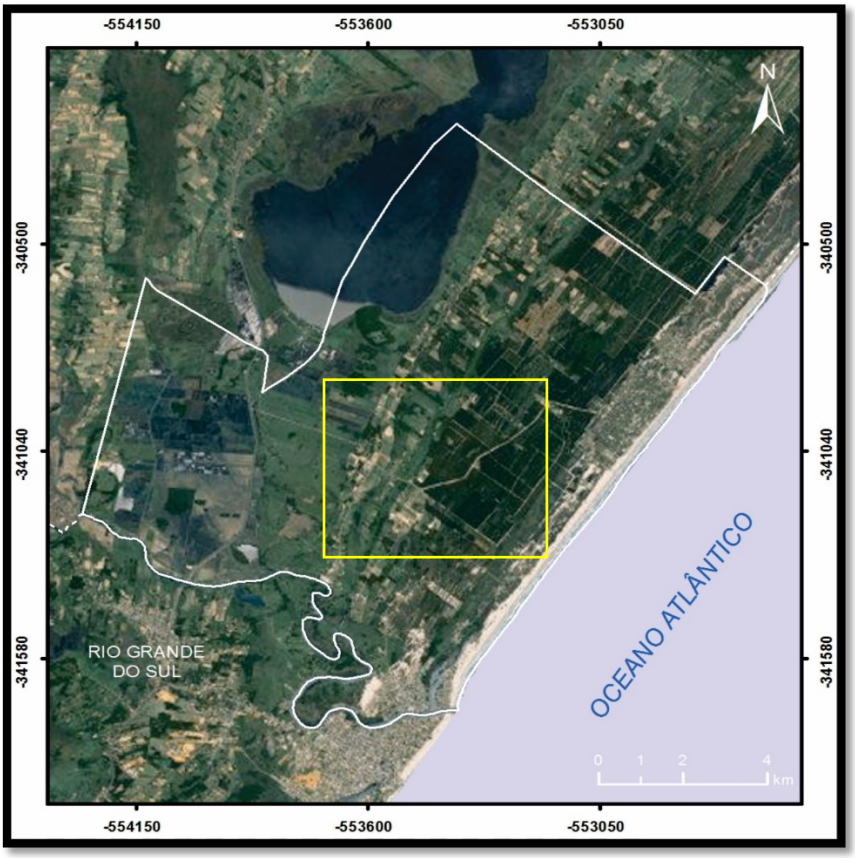

Figure 4. Image showing the approximate limits of the Holocene progradant coastal sandy ridges of Passo de Torres in the municipality of Passo de Torres on the Southern coast of Santa Catarina. The white polygon represents the territorial limits of the municipality of Passo de Torres. The yellow polygon represents the area of the regressive ridges as shown in Figure 5.

Bellatorres beach behaves like an exposed, straight, and dissipative, low slope of the beach face and composed of fine well sorted sand (Horn Filho et al. 2020).

Mudat et al. (2006) studied the beach marine sediments of the Sombrio region, located northeast of the Passo de Torres coastal plain, inferring an average altitude of 4 m and an average width of 2.5 km. It represents the plain of coastal regressive ridges formed during the progradation of the lagoon barrier IV system, of Holocene age. They show a succession of ridges and runnels, arranged in the NE-SW direction, and aligned parallel to the current coastline. The composition is light sandy sediments with the presence of organic matter in the runnels, which indicates darker colors.

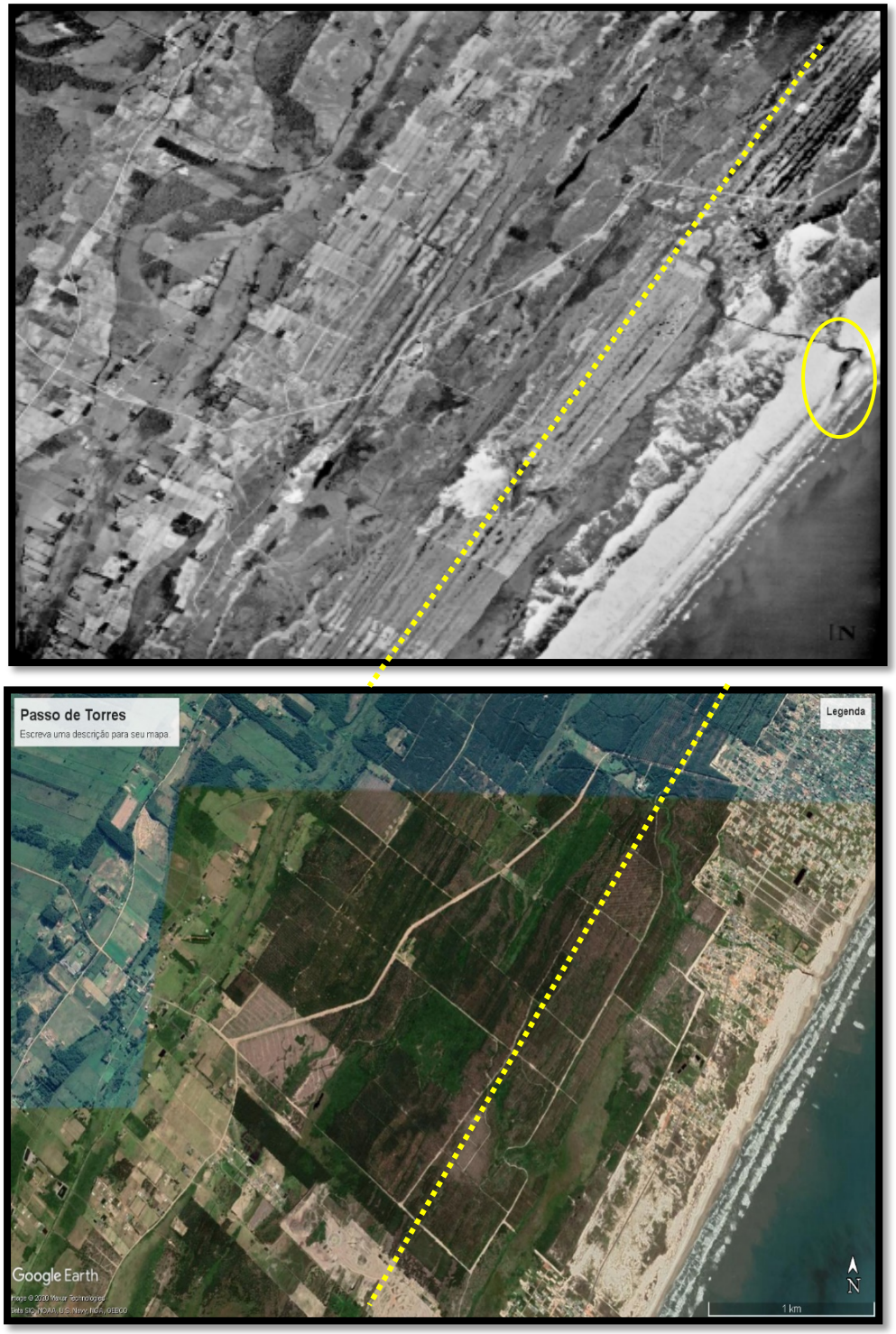

Figure 5: Images showing the coastal plain of Passo de Torres on the Southern coast of Santa Catarina. The upper image refers to the monochromatic aerial photograph of the year 1978, scale 1: 25,000 and the lower image of 17/5/2019 from Google Earth. In both images, the ridges aligned parallel to the coastline of Belatorres beach are evident near the Atlantic ocean. In 1978 photo, a *sangradouro* is well seen at the northeast end of the area (yellow circle) drifting to south. In the image of 2019, the ridges are covered with exotic vegetation, greatly increasing the altitudes of the coastal plain. The yellow dotted line in both images represents the coastal ridges.

Pinheira coastal plain (❷), located in the Central coast of Santa Catarina state (UTM_x 6914785,14; UTM_y 734592,34), in the municipality of Palhoça, is constituted by arched and flat ridges presenting 9 km of length, 4 km of width and altitudes ranging between 1 and 6 m. Fine sandy sediments over ridges and silt-sandy sediments in runnels characterize a typical swash-ridge and foredune ridges, whose orientation of the crests are variable (N-S; NE-SW; SE-NW). The coastal plain displays on the Southern sector Holocene fine sandy eolic sediments covering the ridges (Figure 6 and Figure 7).

Pinheira beach behaves like an exposed, parabolic, intermediate, low slope of the beach face and composed of fine very well sorted sand (Horn Filho et al. 2020).

In the coastal plain of Pinheira, Hein et al. (2013) mapped sands deposited in the intertidal zone, forming successive ridges of beach and dune, and welding the migration of bars towards the continent.

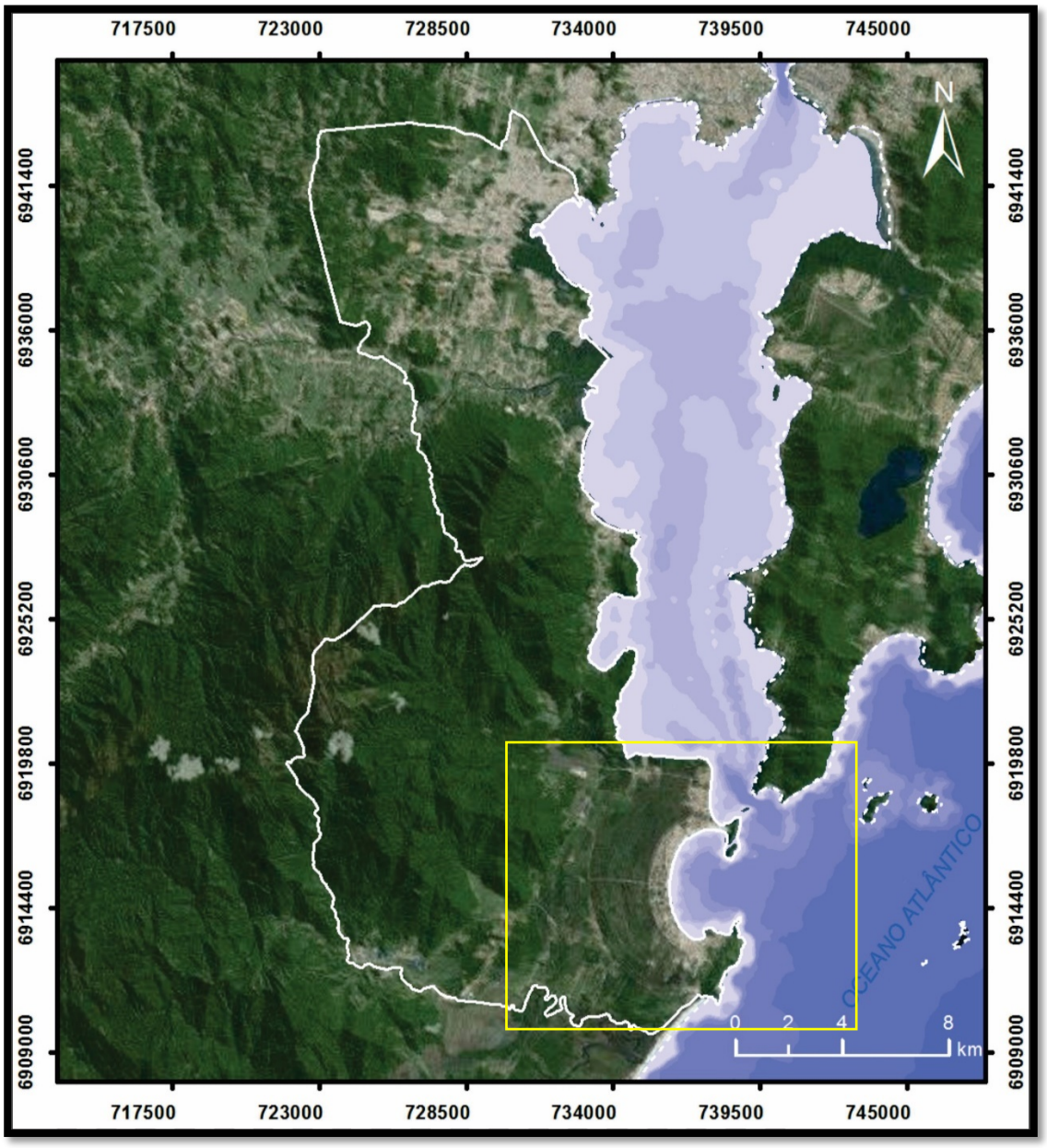

Figure 6: Image showing the approximate limits of the Holocene progradant coastal sandy ridges of Pinheira in the municipality of Palhoça, on the Central coast of Santa Catarina.

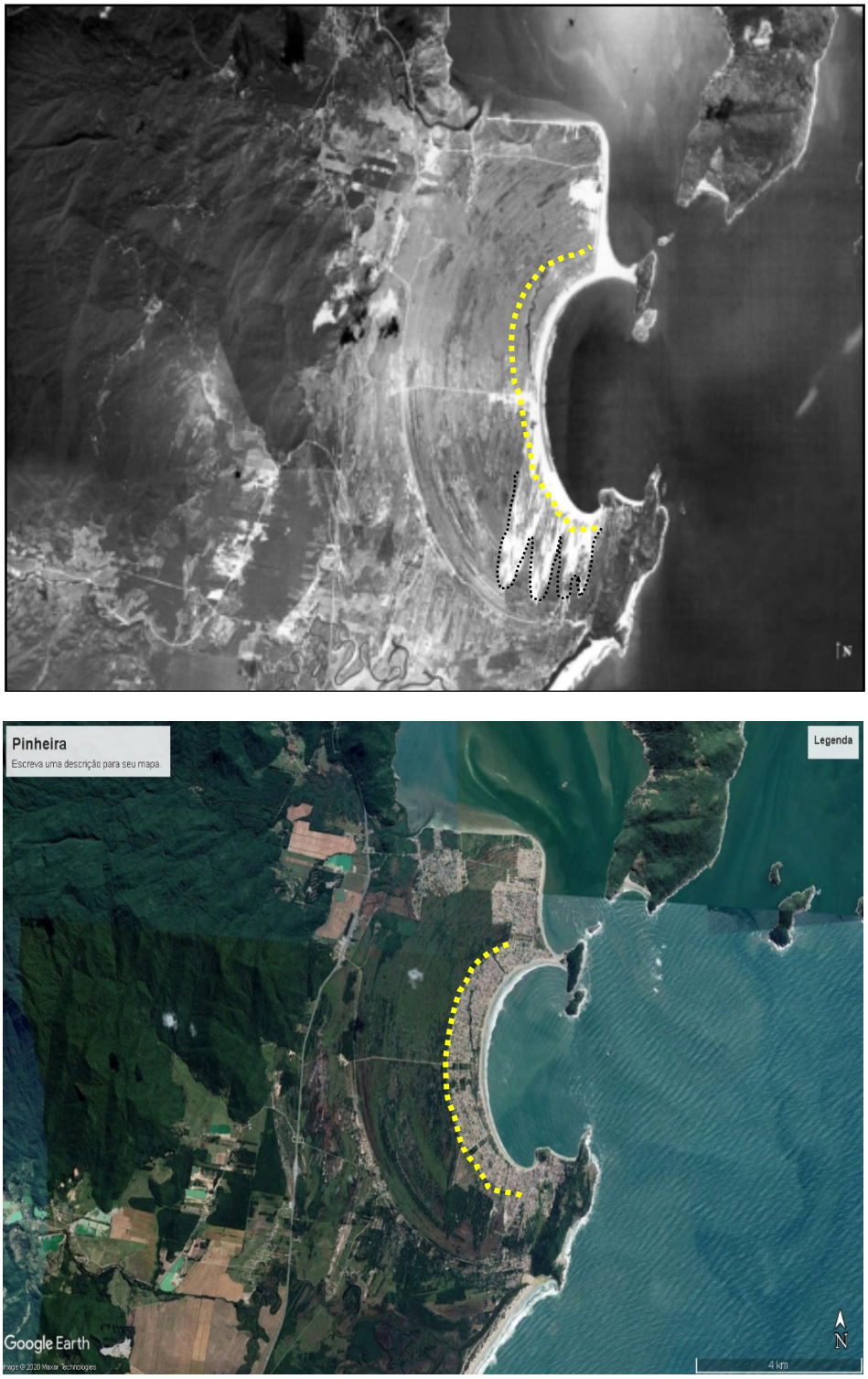

Figure 7: Images showing the ridges of the coastal plain of Pinheira on the Central coast of Santa Catarina. The upper image refers to the monochromatic aerial photograph of the year 1978, scale 1: 25,000 and the lower image of 17/5/2019 from Google Earth. In both images, the ridges and runnels aligned parallel to the current coastline of Pinheira beach adjacent Pinheira cove are evident. In the 1978 photo, the dunes (black dotted line) covering the ridges and oriented NE-SW are visible at the Southern end of the area. In the image of 2019, the entire frontal region of the plain is already anthropized. The dotted yellow lines represent the exposure of arched ridges arranged parallel to the current coastline.

Jurerê coastal plain (❸), located in the Central coast of Santa Catarina state (UTM_x 6961480,36; UTM_y 746676,28), in the Santa Catarina island, municipality of Florianópolis, is constituted by retilineous (slightly curved) and flat ridges presenting 6 km of length, 3 km of width and altitudes ranging between 2 and 6 m. Fine sandy sediments over ridges characterize a typical swash-ridge built by waves, whose orientation of the crests is virtually E-W. The ridge sandy sediments of the coastal plain are occupied at the present time by an intensive land development adjacent to Jurerê beach, only an undeveloped part remains south of the coastline (Figure 8 and Figure 9).

The Jurerê beach arch can be subdivided into Jurerê and Jurerê Internacional beaches, behaves like a semi-exposed, parabolic, intermediate to reflective system, medium slope of the beach face and composed of fine very well sorted sand (Horn Filho et al. 2020).

According to Felix (2020), the ridge sandy sediments of the Jurerê coastal plain represents a typical progradant barrier facies, characterized by the succession of coastal ridges formed by crests (predominantly sandy) and runnels (sand-silty), deposited in environments of medium high hydrodynamic energy, with a positive sedimentary balance regime over the upper Holocene.

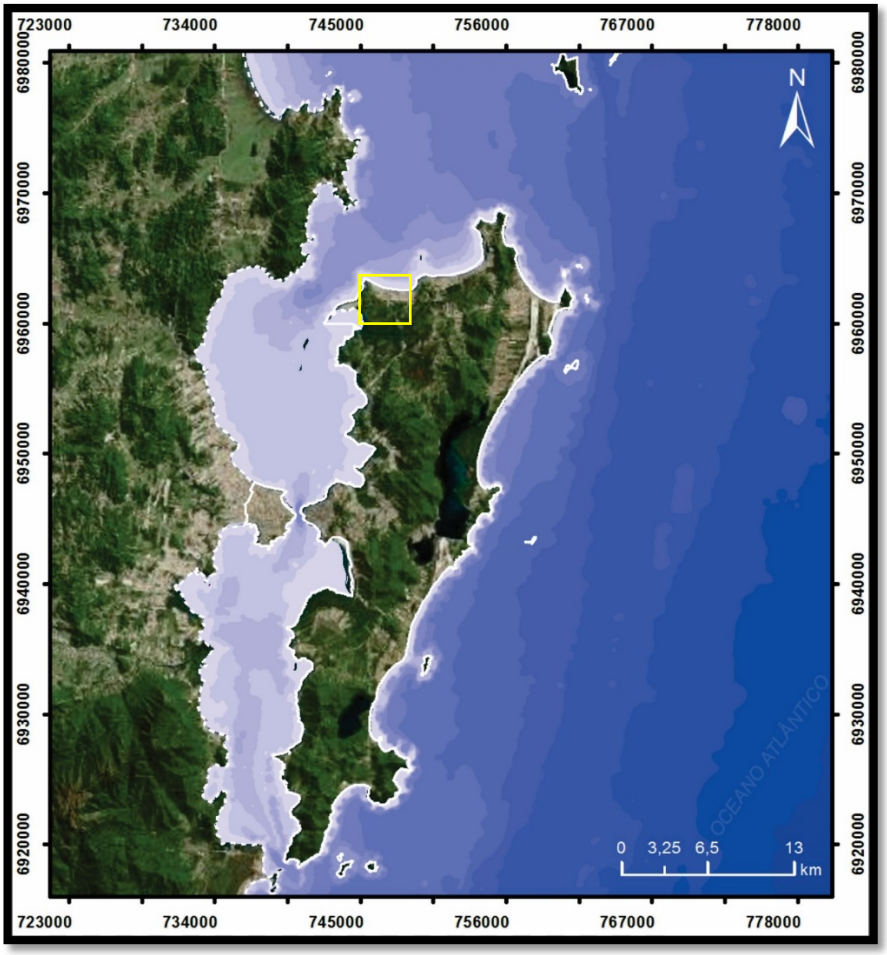

Figure 8: Image showing the approximate limits of the Holocene progradant coastal sandy ridges of Jurerê in the Santa Catarina island, municipality of Florianópolis on the Central coast of Santa Catarina.

Figure 9: Images showing the coastal strands of Jurerê on the Central coast of Santa Catarina. The upper image refers to the monochromatic aerial photograph of the year 1978, scale 1: 25,000 and the lower image of 8/5/2020 from Google Earth. In both images, the ridges aligned parallel to the current coastline of the Jurerê bay on the island of Santa Catarina (yellow dotted lines) are evident, however, there are still few exposures of these ridges that have not yet been occupied by urbanization, except south of the area in question.

Tijucas coastal plain (❹), located in the Central coast of Santa Catarina state (UTM_x 6985002,93; UTM_y 733735,00), municipality of Tijucas, is constituted by retilineous (slightly curved) and flat ridges presenting 10 km of length, 5 km of width and altitudes ranging between 1 and 6 m. Coarse sandy sediments over ridges with concentration of bioclast and siliciclastic and muddy sediments in runnels characterize a typical swash-ridges and chenier ridges, whose orientation of the crests is virtually N-S. The ridges and runnels of the

coastal plain are occupied at the present time by an intensive urbanization adjacent to Tijucas bay, Tijucas beach and municipality of Tijucas, only an undeveloped part remains south of the Tijucas river (Figure 10 and Figure 11). The Tijucas beach behaves like a semi-exposed, parabolic, dissipative, low slope of the beach face and composed of fine coarse moderately sorted sand and mud. *Ficus sp* is founded over sandy ridges parallel to the coastline (Horn Filho et al. 2020).

Regarding the Tijucas coastal plain, Asp et al. (2005) and Fitzgerald et al. (2007), Fitzgerald e al. (2011) identified the domain of the sandy plain, alternated by chenier deposits with a considerable increase in muddy sedimentation in the most recent portions of the coastal plain.

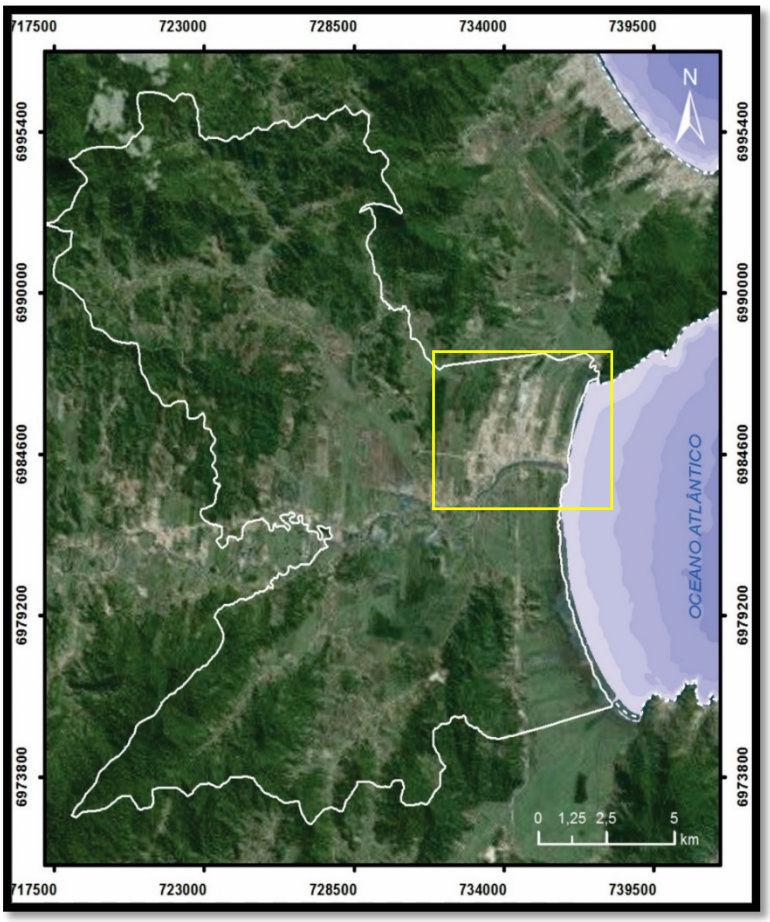

Figure 10: Image showing the approximate limits of the Holocene progradant coastal sandy ridges of Tijucas in the municipality of Tijucas on the Central coast of Santa Catarina.

Figure 11: Images showing the plain of coastal regressive ridges (cheniers) of Tijucas on the Central coast of Santa Catarina. The upper image refers to the monochromatic aerial photograph of the year 1978, scale 1: 25,000 and the lower image of 27/5/2020 from Google Earth. In both images, the ridges aligned parallel to the current coastline of the Tijucas bay are evident, with the first, closer to the coastline, undergoing inflection due to the presence of a small rocky basement island (circle yellow) and, the second, is intercepted by a current sedimentation of the Tijucas river floodplain deposit (blue circle). The dotted yellow lines represent the coastal ridges.

Navegantes coastal plain (❺), located in the Central coast of Santa Catarina state (UTM_x 7025636,09; UTM_y 732949,90), municipality of Navegantes, is constituted by retilineous and flat ridges presenting 6 km of length, 2 km of width and altitudes ranging between 1 and 6 m. Fine sandy sediments over ridges characterize a typical swash-ridges, whose crests are oriented NE-SW with azimuth 20°. The ridges and runnels of the coastal plain are occupied at the present time by an intensive urbanization adjacent to Navegantes beach, Itajaí-Açú river and Navegantes municipality, only an undeveloped part remains to the center of the coastal plain (Figure 12 and Figure 13).

The Navegantes beach currently behaves like an exposed, retilineous, intermediate to dissipative beach, low slope of the beach face and composed of medium coarse well sorted sand (Horn Filho et al. 2020).

On the coastal plain of Navegantes, Fitzgerald et al. (2007) stated that it is composed of fine sandy sediments directly exposed to waves of the open sea, being expressed by the succession of beach ridges interspersed by relatively runnels (10 to 30 m) filled by muddy sedimentation and eolic deposits closest to the current coastline.

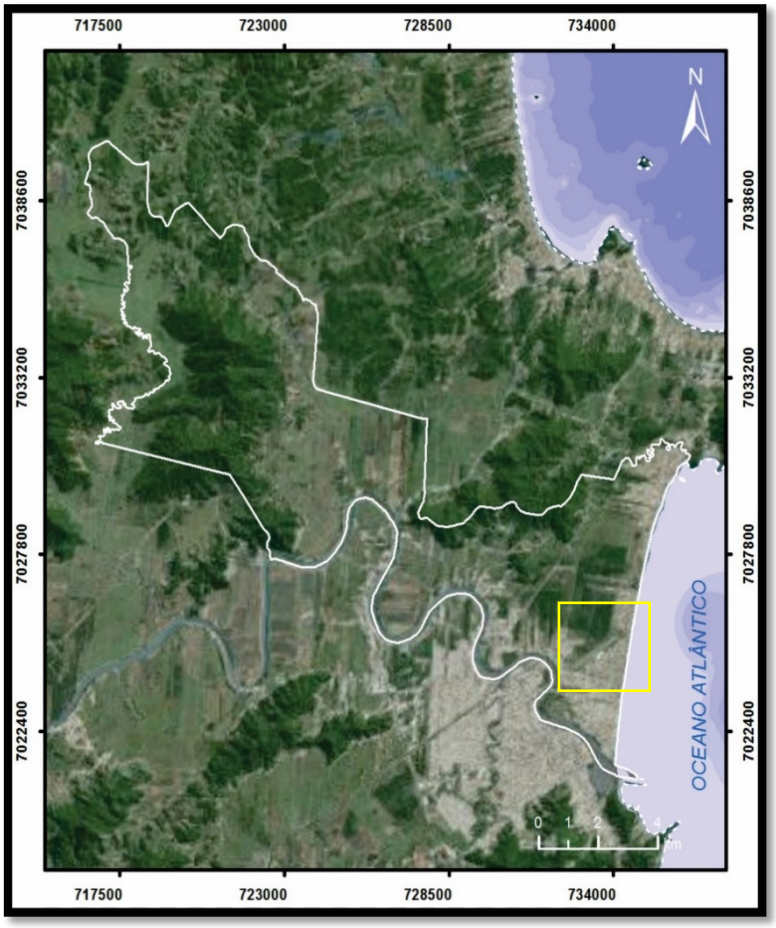

Figure 12: Image showing the approximate limits of the Holocene progradant coastal sandy ridges of Navegantes in the municipality of Navegantes on the Central coast of Santa Catarina.

Figure 13: Images showing the plain of coastal regressive ridges of Navegantes on the Central coast of Santa Catarina. The upper image refers to image of 20/4/2004 and the lower image of 27/5/2020, from Google Earth. In both images, the ridges aligned parallel to the current coastline of the Navegantes beach are evident, represented by dotted yellow lines. The landing and takeoff track of Navegantes International Airport cuts across the ridges in the south of the area (double dotted line in white color).

The Holocene beach ridges are constituted by a succession of crests and runnels, elongated and narrow, continuous and/or interrupted, orientated parallel to the actual coastline, exhibiting right-lined and curve-lined shape. The maximum heights are 3 to 6 m in ridges and 1 to 2 m in runnels. The medium interval between ridges varies between 25 and 50 m.

Horizontal and slightly inclined cross bedding are commonly found in these marine deposits. They are composed by sandy sediments, fine to very fine, sorted to well-sorted, mature to well-mature, with quartz and heavy minerals, sub-rounded to rounded, besides of bioclastics. Due to the humidity, silt-sand-clay sediments, enriched in organic matter are observed in the runnels.

Negative skewness and leptokurtic predominate among the sediments. When covered by eolic sediments on the crest, they are constituted by fine and medium sands, with predominant positive skewness and platicurtic. The shallow origin of the marine deposits is established by the presence of *Callichirus sp* that lives in the sub tidal zone buried on the sand attesting shallow marine environment typical of foreshore and backshore sectors.

According to the paleogeographical point of view, older coastlines located in higher levels are characterized by geological evidences (sedimentologic and geomorphologic), biological and archaeological (shell-middens) (Martin & Suguio 1986).

Martin et al. (1988) stated that the different sea level fluctuations associated with paleoclimatic modifications are the main environmental factors that led to the creation of Brazilian coastal plains, including the construction of Holocene marine terraces and eventual progradation of the coastline, during the lowering of the relative sea level after the maximum transgressive of 5,1 y BP, situation that fits for the formation of the progradant coastal ridges in the state of Santa Catarina (Figure 14, stage h).

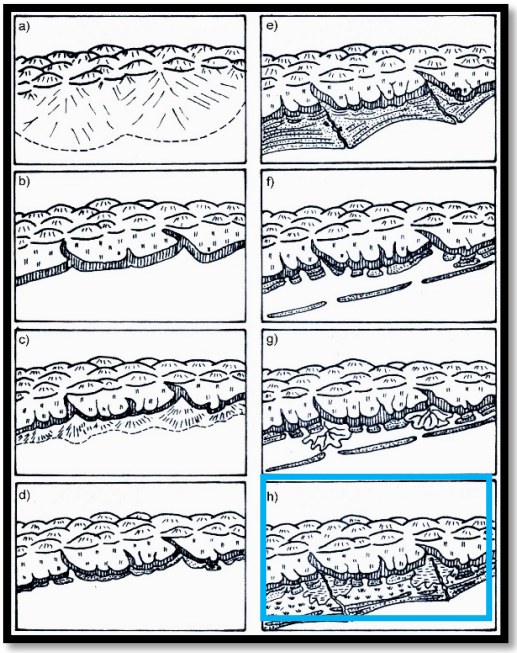

Figure 14: Evolutionary formation model of the Brazilian coastal plains during the Neo-Cenozoic, divided into the following stages: a) Sedimentation of the Barreiras Formation; b) Maximum of the old transgression; c) Sedimentation after the Barreiras Formation; d) Maximum of the penultimate transgression; e) Construction of Pleistocene marine terraces; f) Maximum Holocene transgression; g) Construction of intralagoon deltas and h) Construction of Holocene marine terraces (modified by Martin & Suguio 1989).

The deposits of the Holocene ridges of Santa Catarina coast are associated to regressive phases of Flandrian transgression, formed during three regressive phases: (i) first transgressive-regressive pair, between 5,1 and 3,8 ky BP, reaching the maximum regressive in 4 ky BP with sea level of (–) 2,5 m; (ii) second transgressive-regressive pair, between 3,6 and 3,1 ky BP, reaching the maximum regressive in 3,1 ky BP with sea level of (–) 2 m and, (iii) third transgressive-regressive pair, between 2,7 ky BP to present, reaching actual sea level (0 m) (Figure 15).

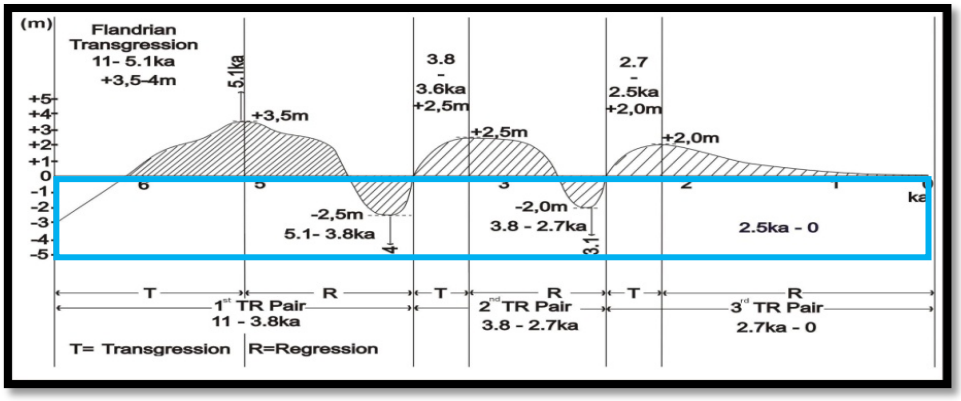

Figure 15: Relative sea level Holocene curve to the Santa Catarina coast.

Conclusions

Beach ridges are indicators of clastic transitional depositional areas and maybe utilized by studies of waves regime, climatic conditions, sedimentary supply, sedimentary provenience, sedimentary source, and sea level changes.

The present interpretation of beach ridge description applies to supra tidal and intertidal coastal ridges, built by waves, stabilized and remnants, consisting of

siliciclastic or bioclastic sediments in a broad range, from fine to coarse sand.

Before beach ridges get stabilized, transgressive ridges have a regressive history (progradational) or transgressive. In the same way, before they can become stabilized and inactive beach ridges, sub tidal transgressive bioclastic and sandy ridges, frequently displace themselves to the inner continent shelf above the tide high level.

The history of the evolution of the majority of the Holocene beach ridges including those on the coast of Santa Catarina have connection to the events of the last 7 ky BP, depending particularly on the surface gradient which suffered the transgressions, on their relative stability, on the intensity of the oceanography agents that trigger the sediments dispersion, and on the supply rate of sediments.

The progradation of the beach ridges in Santa Catarina state is associated with sedimentation arising from marine and aeolian processes. The factors for their origin and stability comprehend constant sediment supply, stable sea level or slow dropping, geological inheritance, substrate gradient, sediment source and fixation by coastal vegetation.

Sequences of beach ridges are frequent components of Holocene coastal plains. Specific beach ridges may be reasonable indicators of paleo shorelines position and sea levels, and even of climate stages and rates of isostatic rising (Mason 1990).

There is not a clear consensus at the literature about beach ridge definition. However, the range of terms frequently used to beach ridges include marine deposits built by waves (intertidal, supra tidal and sub tidal) and winds. Small ridges are normally present in lakes, lagoons, and bight beaches (Fouch & Dean 1982) originated by the progradation of the lagoon and oceanic margins.

Sustainable development will allow the progradant plains preservation on the distinct coastal plains of Santa Catarina state. Continuity of this study should include sub-surface stratigraphy (coastal coring and C^{14}) and detailed geological comparative studies.

References

Adams, K.D. & Wesnousky, S.G. 1998. Shoreline processes and the age of the lake Lahontan highstand in the Jessup embayment, Nevada. GSA Bulletin, 110:1318-1332.

Angulo, R.J. 1992. Geologia da planície costeira do estado do Paraná. São Paulo. 334p. Tese de doutorado. Programa de Pós-graduação em Geociências. Universidade de São Paulo.

Asp, N.E.; Buynevich, I.V.; Siegle, E.; Fitzgerald, D.M.; Klein, A.H.F.; Cleary, W.C.; Angulo, R.J. Coastal geomorphology of the Tijucas plain - Brazil: preliminar evolutionary model. *In*: CONGRESSO DA ASSOCIAÇÃO BRASILEIRA DE ESTUDOS DO QUATERNÁRIO, X, Guarapari, Anais..., 6p.

Bates, R.L. & Jackson, J.A. 1980. Glossary of geology. 2ª Ed. American Geological Institute. 751p.

Bird, E.C.F. 1960. The formation of sand beach ridges. Aust. Jour. Sci., 22:349-350.

Butler, R.W. 1980. The concept a tourist area cycle of evolution: implications for management of resources. University of Western Ontario Canadian Geographer, XXIV, 1:5-12.

Buynevich, I.V.; Asp, N.E.; Fitzgerald, D.; Cleary, W.J.; Klein, A.H.F.; Siegle, E.; Angulo, R. 2005. Mud in the surf: nature at work in a Brazilian bay. EOS Trans., 86(33):301-304.

Carter, R.W.G. 1986. The morphodynamics of beach-ridge formation: Maglligan, Northern Ireland. Mar. Geol., 73:191-214.

Davies, J. L. 1958. The importance of cut and fill in the development of sand beach-ridges. Aust. Jour. Sci., 20:105-111.

Davies, J.L.1968. Beach ridges. *In*: Fairbridge, R. W., (Ed.). Pennsylvania: The Encyclopedia of geomorphology, p.70-71.

Davies, R.A. & Hayes, M.O. 1984. What is a wave-dominate coast? Mar. Geol., 60:313-329.

Felix, A. 2020. Ambientes de sedimentação e sistemas deposicionais do Holoceno costeiro na ilha de Santa Catarina - SC/Brasil. Florianópolis. 570p. Tese de doutorado. Programa de Pós-graduação em Geografia. Universidade Federal de Santa Catarina (no prelo).

Fitzgerald, D.M.; Cleary, W.J.; Buynevich, I.V.; Hein, C J.; Klein, A.H.F.; Asp, N.E.; Angulo, R.J. 2007. Strandplain evolution along the southern coast of Santa Catarina, Brazil. Journal of Coastal Research, 50:152-156.

Fitzgerald, D.M.; Hein, C.J.; Cleary, W.; Menezes, J.T.; Klein, A.H. F.; Scolaro, T.; Buynevich, I.V.; Petsch, S.T. 2011. Climatic and sedimentological forcing of strandplain progradation at Tijucas, central Santa Catarina, Brazil. *In*: INTERNATIONAL UNION FOR QUATERNARY RESEARCH CONGRESS, XVIII, Berna, Proceedings…, Abstract 2791.

Fouch, T.D. & Dean, W.E. 1982. Lacustrine and associated clastic depositional environments. *In*: SCHOLLE, P.A. (Ed.). Sandstone depositional environments. Am. Assoc. Petroleum Geologists, 410p.

Hein, C.J.; Fitzgerald, D.M.; Cleary, W.J.; Albernaz, M.B.; Menezes, J.T.; Klein, A.H F. 2013. Evidence for a transgressive barrier within a regressive strandplain system: implications for complex coastal response to environmental change. Sedimentology, 60:469-502.

Hesp, P.A. 1984. Foredune formation in southeast Australia. *In*: Thom, B.G. (Ed.). Coastal geomorphology in Australia, Academic Press, p.69-97.

Hesp, P.A.; Dillenburg, S.R.; Barboza, E.G.; Tomazelli, L.J.; Ayup-Zouain, R.N.; Esteves, L.S.; Gruber, N.L.S.; Toldo Júnior, E.E.; Tabajara, L.L.C. de A.; Clerot, L.C.P. 2005. Beach ridges, foredunes or transgressive dune fields? Definitions and an examination of the *Torres* to *Tramandaí* barrier system, southern Brazil. An. Acad. Bras. Ciênc., 77(3):493-508.

Hogben, N. & Lumb, F.E. 1967. Ocean waves statistics. London: National Physical Laboratory. Ministry of Technology.

Horn Filho, N.O. 2003. Setorização da província costeira de Santa Catarina, em base aos aspectos geológicos, geomorfológicos e geográficos. Geosul, 37:45-78.

Horn Filho, N.O. & Diehl, F.L. 1994. Geologia da planície costeira de Santa Catarina. Alc., 1(1):95-102.

Horn Filho, N.O; Diehl, F.L. & Amin Jr., A.H. 1996. Quaternary geology of the Central-northern coastal plain of the Santa Catarina state, southern Brazil. *In*: INTERNATIONAL GEOLOGICAL CONGRESS, 30, Abstracts... Beijing: IUGS, p.202.

Horn Filho, N.O.; Gré, J.C.R.; Klingebiel, A. 1995. Evolution Holocene de la plaine cotiere de L'État de Santa Catarina (Brésil): caracterisation morphologique et sedimentologique de la progradación des cordons littoraux. *In*: BORDOMER - COASTAL CHANGE 95, Bordeaux, Résumés... p.979-980.

Horn Filho, N.O.; Abreu de Castilhos, J.; Gré, J.C.R.; Diehl, F.L. 1994. The coastal Pleistocene of the Santa Catarina state, Southern Brazil - geological aspects. *In*: INTERNATIONAL GEOLOGICAL CORRELATION PROGRAM 253 - THE TERMINATION OF THE PLEISTOCENE IN SOUTH AMERICA, Abstracts... Ushuaia, p.9-10.

Horn Filho, N. O.; Schmidt, A. D.; Estevam, C. N.; Oliveira, U. R. de. 2020. Atlas geológico-oceanográfico das praias arenosas oceânicas de Santa Catarina, Brasil. Universidade Federal de Santa Catarina, Centro de Filosofia e Ciências Humanas, Departamento de Geociências, Programa de Pós-graduação em Geografia. Florianópolis: Edições do Bosque (NUPPE/CFH/UFSC) (no prelo).

Johnson, D.W. 1919. Shore processes and shoreline development. New York: Hafner Publishing, 584p.

Lacerda, L.D.; Araujo, D.S.D; Cerqueira, R.; Turcq, B. 1984. Restingas: origem, estrutura, processos. Niterói: CEUFF. 477p.

Martin, L. & Suguio, K. 1986. Coastal Quaternary deposits of the states of Paraná and Santa Catarina. *In*: INTERNATIONAL SYMPOSIUM ON SEA LEVEL CHANGES AND QUATERNARY SHORELINES. São Paulo, 124p.

Martin, L. & Suguio, K. 1989. Excursion route along the Brazilian coast between Santos (state of São Paulo) and Campos (north of state of Rio de Janeiro). *In*: INTERNATIONAL SYMPOSIUM ON GLOBAL CHANGES IN SOUTH AMÉRICA DURING THE QUATERNARY. São Paulo: Associação Brasileira de Estudos do Quaternário - ABEQUA, Special Publication n°2; 136p. il.

Martin, L.; Suguio, K.; Flexor, J.M.; Azevedo, A.E.G. de. 1988. Texto explicativo do mapa geológico do Quaternário costeiro dos estados do Paraná e Santa Catarina. Brasília: Departamento Nacional de Produção Mineral - DNPM, 1988. n°28; 31p. il. 1 mapa.

Mason, O.K. 1990. Beach ridge geomorphology of Kotzebue sound: implications or paleoclimatology and archeology. 262p. PhD Thesis. University of Alaska.

Mudat, J.E., Melo, A.T., Ribeiro, D., Souza, D.R., Neves, J., DI Pietro Filho, J.E., Kitahara, M.V., Horn Filho, N.O., Oliveira, U.R. 2006. Geologia e geomorfologia costeira da folha Sombrio, SC. *In*: SIMPÓSIO NACIONAL DE GOMORFOLOGIA/REGIONAL CONFERENCE ON GEOMORPHOLOGY, IV. Anais...Goiânia, p.1-13.

Otvos, E.G. 2000. Beach ridges - definitions and significance. Geomorphology, 32:83-108.

Polette, M. 1993. Planície do Perequê/ilha de São Sebastião - diagnóstico e planejamento ambiental costeiro. São Carlos. 136p. Dissertação de mestrado. Programa de Pós-Graduação em Ecologia e Recursos Naturais, Universidade Federal de São Carlos.

Redman, J.B. 1852. On the alluvial formations and the local changes of the south coast of England. Proceedings Institution of Civil Engineers, v.11, p.162-223.

Redman, J.B. 1864. The east coast between the Thames and the Wash estuaries. Proceedings Institution of Civil Engineers, v.23, p.186-257.

Schwarz, M.L. 1971. The multiple causality of barrier islands. Jour. Geol, 79:91-94.

Short, A.D. 1984. Beach and nearshore facies: southeast Australia. Mar. Geol., 60:261-282.

Smith, R.A. 1991. Beach resorts: a model of development evolution. Landscape and urban planning, 21:189-210.

Stapor, F.W. 1982. Beach ridges and beach ridges coasts. *In*: SCHWARTZ, M.L. (Ed.). The Encyclopedia of beaches and coastal environments. Pennsylvania: Hutchinson Ross Publishing Company, p.160-161.

Stapor, F.W.; Mathews, T.D. & Lindfors-Kearns, F.E. 1988. Episodic barrier island growth in south-west Florida: a response to fluctuating Holocene sea level? Geol. Soc. Mem., 3:149-202.

Suguio, K. 1992. Dicionário de geologia marinha (com termos correspondentes em inglês, francês e espanhol). São Paulo: T.A. Queiroz, 172p.

Tanner, W.C. 1987. Spatial and temporal factors controlling overtopping of coastal ridges. *In*: Singh, P.V. (ED.). Flood Hydrology. D. Reidel Publishing Co., Dordrecht, p.241-248.

Tanner, W.F. 1992. 3000 years of sea level change. Bul. Amer. Meteor. Soc., 73(3):297-303.

Tanner, W.F & Demirpolat, S. 1988. New beach ridge type: severely limited fetch shallow water. Trans., 38:367-373.

Taylor, M.J. & Stone, G.W. 1996. Beach-ridges: a review. Jour. Coas. Res, 12:612-621.

Thom, B.G. 1964. Origin of sand beach-ridges. Austr. Journ. Sci., 26:351-355.

Villwock, J.A. 1972. Contribuição à geologia do Holoceno da província costeira do Rio Grande do Sul, Brasil. Porto Alegre. 133p. Dissertação de Mestrado de Geociências. Instituto de Geociências. Universidade Federal do Rio Grande do Sul.

Villwock, J.A.; Tomazelli, L.J.; Loss, E.L. Dehnhardt, E.A.; Horn Filho, N.O.; Bachi, F.A.; Dehnhardt, B.A. 1986. Geology of the Rio Grande do Sul coastal province. Quat. Sou. Amer. Ant. Pen., 4.

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