

Rio Grande Relay Zone, Rio Grande do Sul Coastal Plain, Brazil: I—Retiro-Estreito Main Fault and Sedimentation on Subsidence

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Abstract

This paper shows the results of geophysical and geological surveys carried out in the southern tip of the Retiro-Estreito Main Fault, and important fault scarp extending more than 60 km NE in the Rio Grande do Sul Coastal Plain (RGSCP). The investigated areas include mainly the Ilha dos Marinheiros (Rio Grande County) and Retiro (São José do Norte County). Ground Penetrating Radar (GPR, 50 MHz RTA antenna), drillholes for heavy minerals (HM) exploration and fieldwork were applied to investigate deformational structures controlling the faulted Pleistocene sedimentary units (basement) and the Holocene sedimentary radarfacies geometry and their inner reflectors architecture. The Retiro-Estreito Main Fault is part of a group of recently recognized gravity sliding tectonic structures. The radargrams enabled to distinguish that the Retiro-Estreito Main Fault shows strain partitioning into a sequence of normal splaying faults, giving rise to a stepped structure in the hangingwall block toward the east. The Retiro-Estreito Main Fault footwall block was later faulted by propagating splay fault from the southern Quinta Main Listric Fault and gave rise to the Retiro Horst. Diachronous fault displacements, each one showing different displacement magnitude and chronology, gave rise to complex fill pattern radarfacies, mainly in the first sedimentary stages (beach ridges) in the hangingwall fault block. After the Retiro Horst was built up, significant beach ridges radarfacies structural pattern is developed, followed by Retiro Horst and foot-

wall block erosional degradation, building up backshore and washover radar-facies in the footwall block, and foreshore radarfacies in the hangingwall block of the Retiro-Estreito Main Fault. These sedimentary units were deposited still under a high mechanical subsidence rate. The vanishing period of the normal fault's displacements (final sedimentary stage) is characterized by widespread thin transgressive dune sheet (TDS) cover and by transgressive dunes (TD) prograding southwestward to isolate the Retiro-Estreito lagoon, and to build up the main Holocene sedimentary barrier close to the Atlantic Ocean. The Retiro-Estreito lagoon shows evidence of advanced clogging processes, such as erosional degradation of fault scarp and TD + TDS southwestward progradation.

Keywords

GPR Survey and Processing, Gravity Tectonics and Local Subsidence, Normal Faults Branching, Structural Barriers, Holocene Sedimentary Barrier

1. Introduction

GPR technique has long been successfully used to near-surface recent to active fault investigations [1]-[6]. In the Brazilian Atlantic coastal plain, however, few GPR surveys were focused on recent faulting investigations (e.g., [7] [8]), even though some evidence for major deformation has been presented (e.g., [9] [10]).

Recently, [11]-[13] have brought new insights into the Holocene sedimentary evolution of the Rio Grande do Sul Coastal Plain (RGSCP), southern Brazil, by showing the influence of gravity sliding normal faults and their control on sedimentation processes (Figure 1).

Three main normal faults were identified: Quinta Main Listric Fault [11], Lagoa do Peixe Listric Growth Fault [12], and Retiro-Estreito Main Fault [13]. The northern tip zone for the Retiro-Estreito Main Fault and its interplay with the Lagoa do Peixe Listric Growth Fault and sedimentation was discussed by [13].

The southern tip zone of the Retiro-Estreito Main Fault, however, was not yet investigated. It is located at the Rio Grande channel, which is also the northern tip zone for the Quinta Main Listric Fault. It is to be noted that the largest segment of Quinta-Cassino strandplain [12] ends abruptly at Rio Grande channel area, as well as the Retiro-Estreito Main Fault at north. The structural framework of the Retiro-Estreito Main Fault and Quinta Main Listric Fault has not yet been investigated.

The aim of this paper is to present new geological and geophysical elements that enable to understand the structural features and sedimentation controlled by the Retiro-Estreito Main Fault at its southern tip zone, in the São José do Norte (Retiro area) and Rio Grande (Ilha dos Marinheiros area) counties (Figure 2). 50 MHz RTA Ramac GPR surveys, drillholes for heavy minerals (HM) exploration and field surveys were carried out to investigate the structural and sedimentary features at these areas.

The aim of this paper is not to fully investigate inner sedimentary structures or

sedimentological features (detailed sedimentary characteristics, depositional systems), since this low-frequency GPR antenna poses some constraints in this subject. Higher frequency antennas (100 - 250 MHz shielded ones) would be appropriate. Therefore, the 50 MHz RTA antenna proved to be valuable to distinguish Pleistocene from Holocene units, to define some key radarfacies and radar surfaces and their architectural features and mainly to identify the fault truncations. The discussion, then, is addressed to show the fault's influence on the architecture and geometry of the identified sedimentary radarfacies.

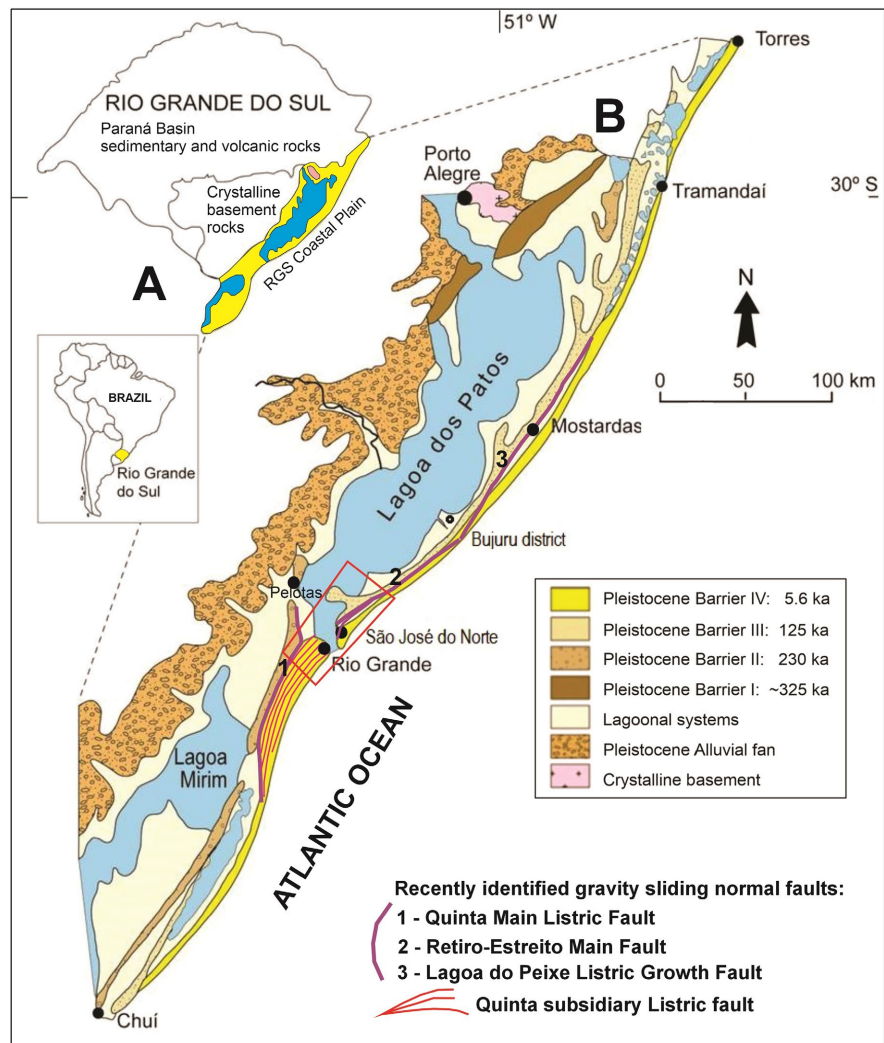


Figure 1. Rio Grande do Sul Coastal Plain location (A), and its regional geological map (B). Modified from [14] and [15]. Lagoon/Barrier system ages according to [16]. The red rounded rectangle circumscribes the area of investigation in Figure 2.

The companion paper (*II—Asymmetric delta development and gravity fault subsidence in Quinta-Cassino strandplain*) will be addressed to regional structural framework, sedimentation vs. subsidence relationships, and regional geological evolution. This companion paper will be mainly based on evaluation and discussion of previously published data.

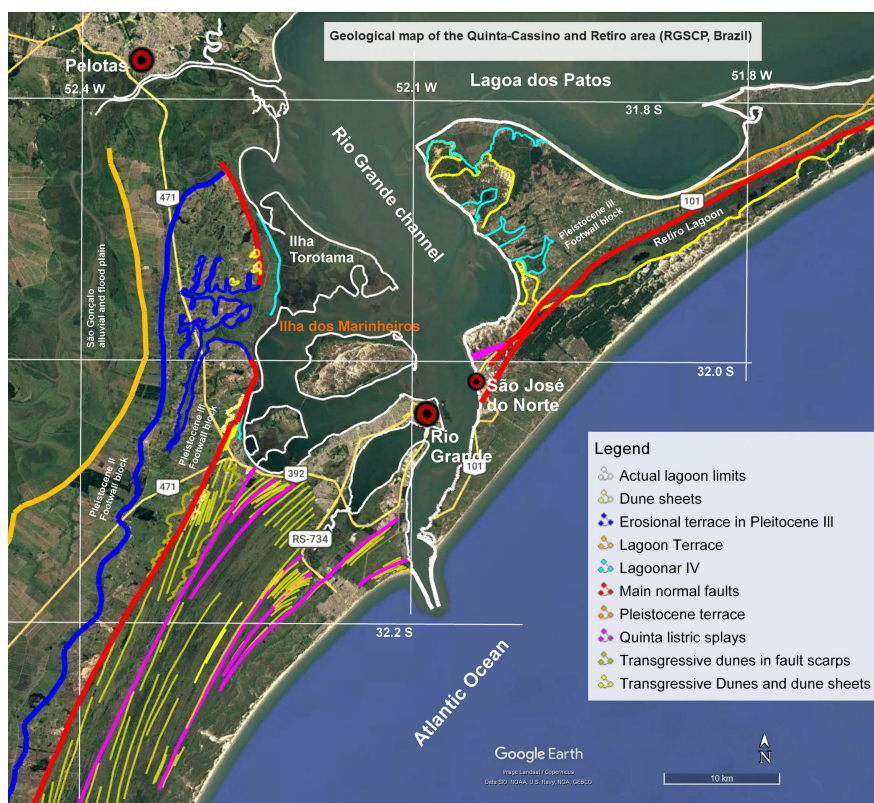


Figure 2. Geology of the Quinta—Cassino and Retiro areas, both sides of the Rio Grande channel. This map extends geological features earlier presented by [11]–[13], presenting additional elements which will be discussed later in this paper.

2. Near-Surface Geophysical and Geological Survey Methods

The procedures for geological and near-surface geophysical surveys applied in the present works follow those presented by [11]–[13].

A geologic survey was carried out through aerial photographs, high-resolution Google images, and field work in the Ilha dos Marinheiros (Rio Grande County) and Retiro area (São José do Norte County). They were carried on investigating the main surficial sedimentary units over which GPR data were acquired, and also to evaluate the drillholes for HM exploration.

The near-surface geophysical surveys were carried out by means of 50 MHz RTA Ramac ground penetrating radar (GPR) equipment. The 50 MHz RTA Ramac antenna has a Tx-Rx offset equal to 4.2 m and was held very coupled to the ground.

The mean EM wave velocity was estimated through diffraction hyperbola to be 0.08 - 0.09 m/ns, so that vertical resolution is 0.40 - 0.45 m. This EM wavelength can be used to investigate sedimentary units' geometry, interrelationships, and continuity.

The 50 MHz RTA Tx-Rx offset was built to balance the shallow blind spotting, the diffraction hyperbola curvatures and the velocity estimations. Lowering the Tx-Rx offsets would decrease the blind spot and increase the near-surface resolu-

tion but would produce steeper hyperbola arms (point source diffractions, mainly for air wave) and poorer velocity estimations. Then, considering the estimated local velocities (0.08 - 0.09 m/ns) and the Tx-Tx antenna offset, one has an estimated upper blind zone ~2.5 m, which correspond to upper soils and sediments. This shallower zone, however, is not under the scope of this work, which is why upper fault tips are mainly located below that. This upper zone would be best investigated through higher frequency shielded antennas (100 - 250 MHz).

The Ramac acquisition system (GroundVision) does permit to set measurements parameters to investigate variable deeper by adjusting time window and sampling frequency (number of samples). Increasing the time windows, deeper features can be recognized, but the sampling frequency is reduced (and the structural features resolution). The time window to be applied is also controlled by EM energy loss, since these GPR surveys were carried out in coastal plain terrane where a shallow water table persists out of dune fields, and the saline wedge drives EM signal degradation toward the coastline. In this way, a group of test surveys was conducted to define the best time window (550 - 620 ns) and sampling frequency (800 - 900 MHz) to balance the investigation depth above the EM energy loss and the structural features resolution (radarfacies limits and faults). The procedure enabled GPR lines with good signal return up to 30 m depth.

Two highly oblique GPR lines were surveyed in the Ilha dos Marinheiros to evaluate possible geological connections between southern and northern segments related to Rio Grande channel for Lagoa dos Patos (the main lagoon in the RGSCP). In the Retiro area, the GPR lines were surveyed close to drilling sections produced for HM exploration, to get better control over GPR sections interpretation.

The GPR survey lines were all accompanied by DGPS (Emlid, Reach RS + model, base and rover receptors) control, with kinematic and post-processed corrections (Leica Geo Office and PPP-IBGE). The GPR line positioning procedure does permit a high horizontal (7 mm + 1 ppm), and vertical precisions (14 mm + 1 ppm).

GPR data was post-processed in Reflex-W software and included the following main steps: DC drift, dewow filter; divergence compensation gain; bandpass filter (butterworth, but sometimes trapezoidal); migration ($v = 0.297$ m/ns) for removing surface diffraction in unshielded antenna; topographic correction; 3D topographic migration (e.g., $v = 0.08 - 0.09$ m/ns) and bandpass filtering. The unshielded antenna 50 MHz RTA does not attenuate air-wave and records diffractions due to surface objects. Then, two migration steps were applied to collapse diffraction hyperboles for surface objects and after for subsurface objects or geological structures.

Figure 3 shows the resulting radargrams in some of the sequential processing steps, in order to put in evidence geophysical artifacts produced during surveying GPR lines with unshielded antennas. **Figure 3(A)** shows the GPR line after DC drift and Dewow removals, and divergence compensation gain to remove EM wave propagation attenuation; it can be assumed as a raw, unprocessed radargram. **Figure**

3(B) shows the bandpass filtered (trapezoidal filter centered on 50 MHz) radargram; one can see many steeper diffraction hyperboles due to EM wave diffraction in surficial obstacles ($v = 0.297$ m/ns). This kind of diffraction feature is even stronger for offset zero (Tx and Rx with no offset), and for antennas not well-grounded. **Figure 3(C)** shows the same radargram after migration for removing surface diffraction in an unshielded antenna, and before topography migration for underground diffractions. Comparing **Figure 3(B)** and **Figure 3(C)** makes it possible to realize the improvement in the continuity of reflections due to sedimentary structures. The completely pos-processed GPR line 6 is presented in Section 4 (Geophysical surveys: Fault Geometry and Radarfacies) besides its interpretation.

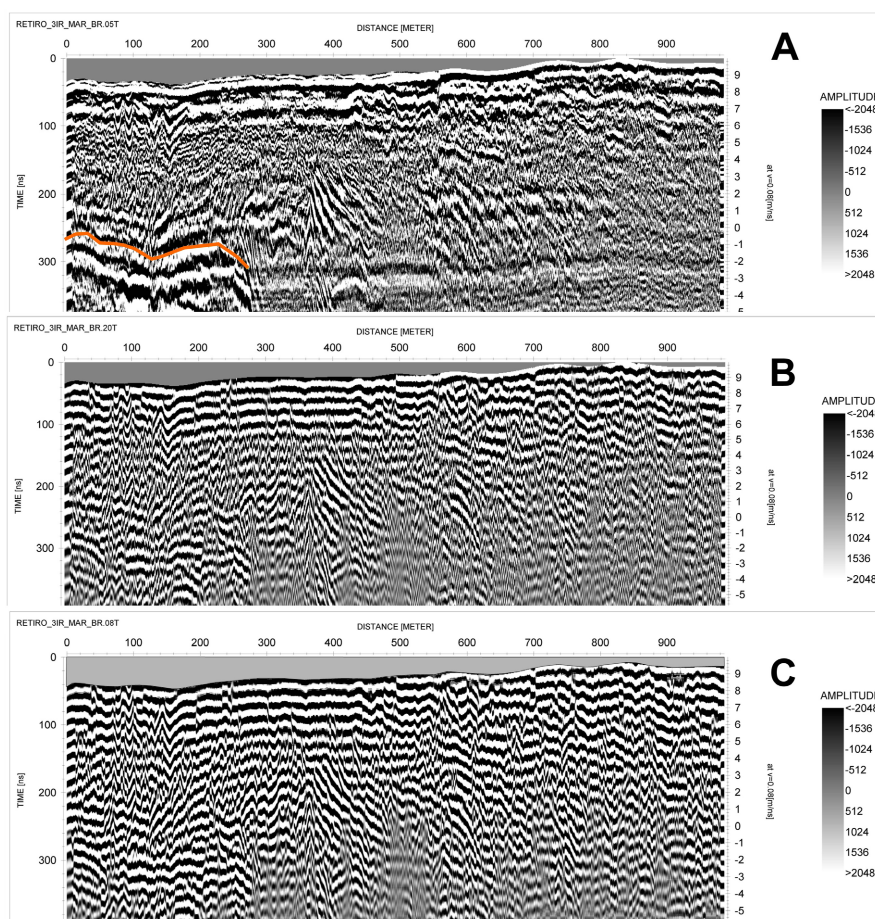


Figure 3. Radargrams demonstrating some processing steps results. (A) Raw radargram for GPR line 6 (DC drift and Dewow filters, divergence compensation gain only). (B) bandpass filter, without any migration processing. (C) After migration for removing surface diffraction in unshielded antennas. All radargrams were corrected for topography. The orange line in (A) defines the top of the Pleistocene Barrier III sedimentary sequence.

The interpretation of radargram is based on radarfacies and radar surfaces after [17]. Radarfacies describe a set of reflections lying between radar surfaces and are characterised by distinguishing the shape of reflections, the dip of reflections, relationship between reflections and reflection continuity, and the reflections trun-

cation [17]. Reflector's truncation and displacement are the main criteria for fault identification.

3. Geology of the Surveyed Areas

The simplified geological map images analysis and field work are presented in **Figure 2** and **Figure 4**, and **Table 1** summarizes the main lithological features of each stratigraphic unit distinguished during the geological survey.

The Pleistocene Barrier III is the key stratigraphic unit for GPR surveys, since it can be easily recognized even in raw radargrams, and because it does permit to recognize major normal faults (see **Figure 3(A)**) and its influence upon Holocene sedimentary structures and stratigraphy. The Pleistocene Barrier III crops out to the west of the Quinta and Retiro-Estreito fault escarpments (Footwall fault blocks) and extends to the São Gonçalo alluvial and flood plain and Lagoa dos Patos as an erosional terrace, as discussed by [11] [12].

The Holocene Barrier (IV) can be distinguished into different geomorphic features and sedimentary deposits, namely 1) beach ridges, 2) alluvial fans, 3) transgressive dunefield barrier and 4) lagoonal deposits (**Table 1**; for details, see [11]-[13]).



Figure 4. Detail geological map on both sides of Rio Grande channel, extending geological and sedimentary features previously discussed in [12]. The location of new GPR survey lines (1 to 6) and drillhole section (A, B, C) in the Retiro area is presented.

Table 1. Summary of the main stratigraphic units cropping out in the selected areas for GPR surveying.

Stratigraphic unit		Geological and lithological features
Barrier IV	Lagoonal deposits	Fine-grained sands and silts interlayered with variable proportions of organic matter and clay are being deposited close to Lagoa dos Patos.
	Dunefield barrier	Transgressive Dune Sheets (TDS) and Transgressive Dunes (TD) developed by NE onshore winds.
	Alluvial fan	Fans of sand due to erosion by drainage cutting across the fault escarpment.
	Beach ridges	Narrow and very elongated sand ridges, intercalated with narrow depressions of mud and marsh, both parallel to shoreline
Pleistocene Barrier III		Fine to medium-grained sands, mostly horizontal, parallel stratification, slightly compacted, and impregnated by Fe ³⁺ hydroxides and clay.

The field investigation shows that actual lagoonal sediments in the northern segment of the Quinta-Cassino (Rio Grande County) area and in the Retiro area (São José do Norte County) are deposited by Lagoa dos Patos (the main lagoon), and they truncate the beach ridge features to the south of Ilha dos Marinheiros (**Figure 2**). It is also observed that TD and TDS sediments cover beach ridges, lagoon deposits, and most segments of the main normal faults.

Figure 5 presents the drillhole sections elaborated from HM exploration data. The northeastern most one (DH Section 1) was drilled east of the Retiro-Estreito Main Fault (in the hanging wall) and over thick TD deposits (**Figure 5(A)**). Unfortunately, as an exploration procedure, the drilling stopped when mud, peat or even Pleistocene sediments were found.

The central drillhole section (DH Section 2, **Figure 5(B)**) is also located in the hanging wall of the Retiro-Estreito Main Fault, but closer to the fault than DH Section 1 (**Figure 5(A)**). The drillholes of this section did not recover fine-grained sands and HM, as in the previous and the following sections. The upper part of the DH Section 2 drillholes is made up of brown and light brown fine-grained sand (some dispersed dark brown clay). These kinds of materials can be interpreted as resulting from erosion from Pleistocene Barrier III and deposited as alluvial fans close to fault escarpment (see **Figure 6** in [11]).

The southwestern most drillhole section (DH Section 3, **Figure 5(C)**), on the other hand, is in the footwall of the Retiro-Estreito Main Fault. The GPR survey lines 3 and 4 were located southwestward (~900 m) of DH Section 3 due to field operational issues, but it was possible to correlate and interpret the radarfacies. **Figure 4**, however, shows that both GPR lines and DH section are located mainly over TDS and TD.

The TD cover in the GPR survey lines 3 and 4 is thinner than in northeastward DH Section 3. The thinning of the TD in the GPR line survey at this point is well constrained in the vicinity of the main federal road (BR-101). This observation may be due to a more intense footwall erosional process northward, or even due

to the differential downthrows of normal fault blocks, since both GPR lines and DH section have similar topography.

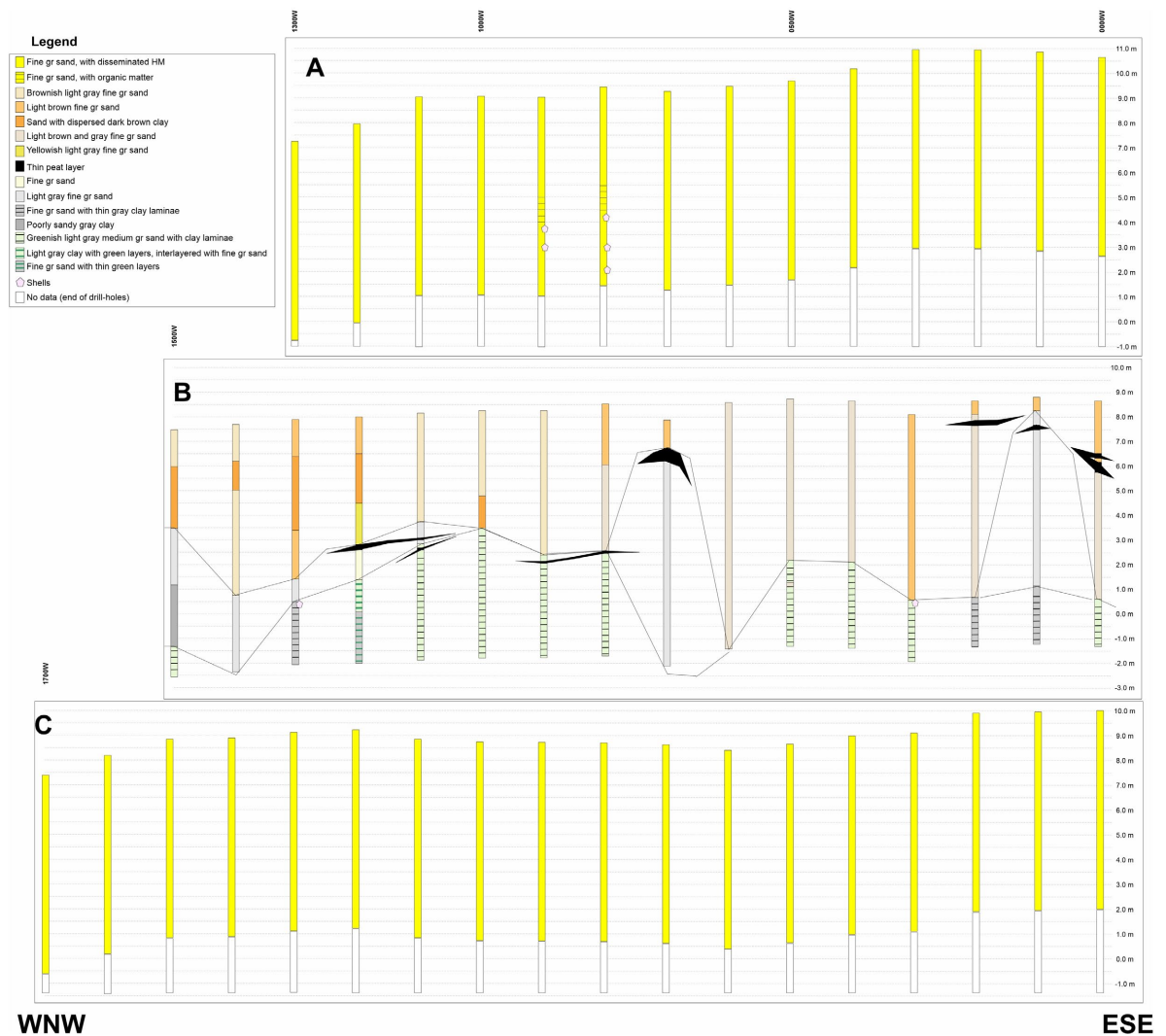


Figure 5. Simplified drillhole sections for HM exploration, illustrating the sediments characteristics from NE ((A) DH Section 1), to the SW ((B) DH section 2, and (C) DH Section 3). See **Figure 4** for DH sections location.

4. Geophysical Surveys: Fault Geometry and Radarfacies

The radarfacies discrimination followed [11] [17] and the identified radar surface boundaries (**s**) and radarfacies (**f**) follow the relative chronological sequence proposed by [17] [18]. South of Rio Grande channel, in the Quinta-Cassino area, the radarfacies were completely described by [11], and no additional evaluation is required in this regard. In the Ilha dos Marinheiros (Rio Grande County), two additional GPR lines were surveyed, and the radar surface boundaries and radarfacies are summarized in **Table 2**. To the north, in the Retiro area (São José do Norte County), however, four new GPR lines were surveyed and HM exploration drill-holes sedimentary features are incorporated to support interpretation; their radar surface boundaries and radarfacies are also summarized in **Table 2**.

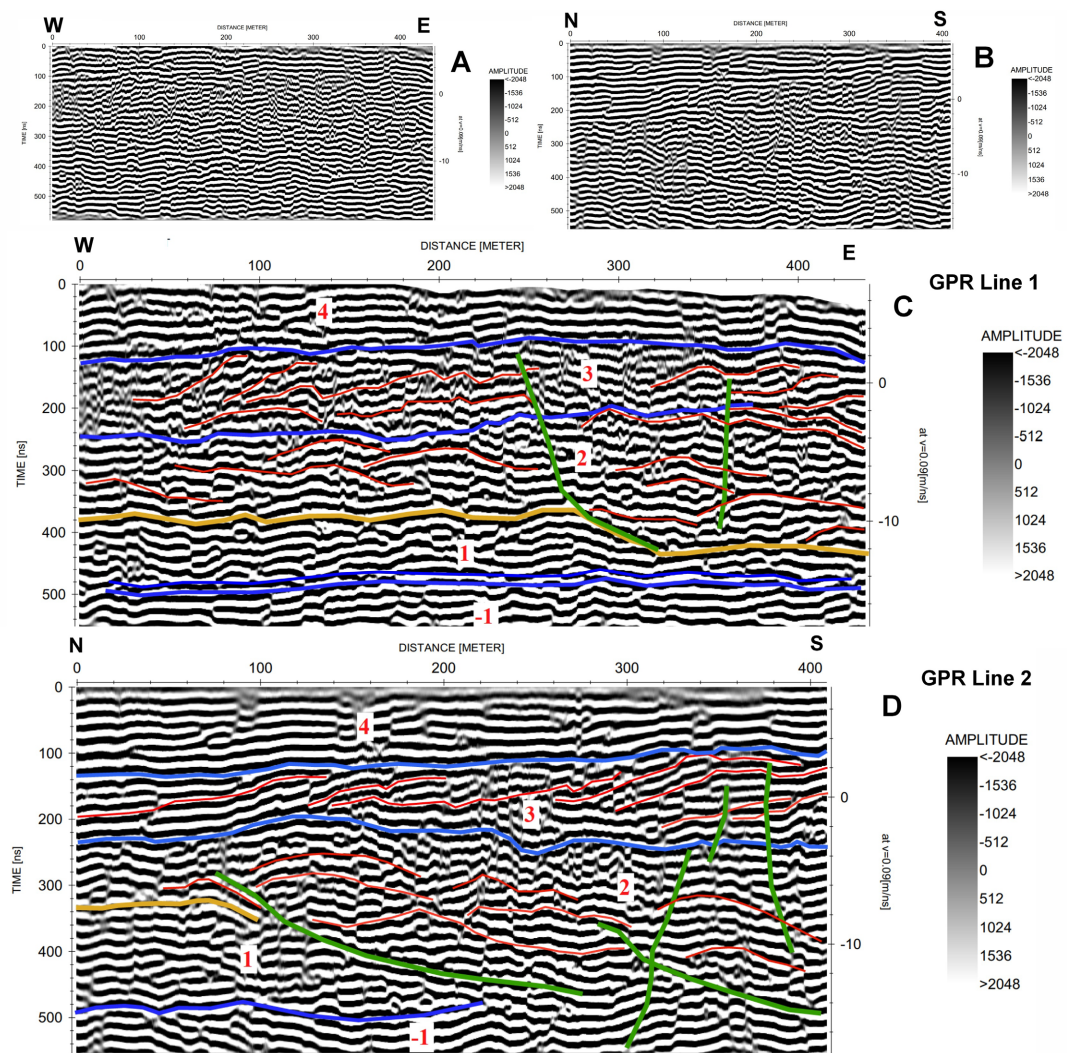


Figure 6. GPR lines surveyed in Ilha dos Marinheiros (Rio Grande County). (A) Uninterpreted WE GPR line 1. (B) Uninterpreted NS GPR line 2. (C) Interpreted WE GPR line 1. (D) Interpreted NS GPR line 2. Legend: Holocene radarfacies surface boundaries (blue lines); upper Pleistocene radarfacies surface boundary (orange line); inner radarfacies reflectors (red lines); normal faults (green lines). Numbers = radarfacies sedimentary events described in **Table 2**.

Table 2. Summary of radar surface boundaries (**s**) and radarfacies (**f**) distinguished for GPR survey lines in the Ilha dos Marinheiros and Retiro areas and their interpretation (Rio Grande, RS, Brazil).

Stage	Facies ID	Description	Intepretation
-1 1	MR-f _{n-1} -pf	Radarfacies underlying the upper Pleistocene sediments, displays regular reflections which are mostly conformable to truncated (<i>offlap</i>) in their upper boundary	Pre-fault radarfacies undergone hangingwall collapse and erosion
	MR-f _{n+1} -ps	Pleistocene sediments (poorly compacted) cropping out west of Quinta escarpment (Barrier III)	Pleistocene sediments cropping out at the footwall top west in Quinta Main Listric Fault (Barrier III). It also undergone hangingwall collapse and erosion
	MR-s _{n+1} -lf	Upward concave listric geometry surface that truncate Pleistocene sediments (west) and complex filled radarfacies (east)	Listric normal fault

Continued

	MR-s_{n+1}-et	Horizontal or arcuated upper surface for Pleistocene sediments. Overlaid by different radarfacies and reflectors configuration	Erosional truncation before fault controlled Holocene accumulation
2	MR-f_{n+2}-br	Eastward gently dipping reflectors, some westward large arched crests at the base, displaying complex fill pattern, and showing conformable reflectors to the base, but <i>onlap</i> upon gently deeping upward arcuated fault surfaces	Beach ridges stacks with different crest preservation degree and differential displacements due to diachronous normal faulting.
	MR-s_{n+2}-tl	Irregular surface at the base of the beach ridges radarfacies, showing <i>toplap</i> to concordant reflectors in the underlying unit	Irregular surface that is an unconformity overlying complex beach ridges radarfacies
3	MR-f_{n+3}-bf	(3a) North-westward gently dipping reflectors, some eastward arched crests, that climbs over its subunits and showing <i>downlap</i> for underlying reflectors. Far west, it is almost horizontal and parallel to lower surface boundary. (3b) Eastward gently deeping reflectors, small sigmoidal features, displaying parallel architecture in topset	(3a) Backshore and washover deposits overlaying beach-ridges (3b) Foreshore deposits overlaying beach-ridges
	MR-s_{n+3}-tl	Surface at the base of the upper lagoonal radarfacies, showing <i>toplap/offlap</i> , or parallel reflectors in the overlying unit	Conformable regular surface that limits the underlying beach ridges radarfacies
4	MR-f_{n+4}-lag	Horizontal well-defined reflectors far from fault escarpment	Lagoonal sediments close to Lagoa dos Patos, showing some interfingering with overlying aeolian TDS sediments
	MR-s_{n+4}-dl	Irregular surface underlying recent dune sediments	Surface upon which recent dune sediments prograde
5	MR-f_{n+5}-dm	Horizontal and steeply dipping reflectors, as well as thin horizontal reflectors near the topographic surface	Recent Holocene dune field (TD) and thin wind cover (TDS) overlying previous sedimentary radarfacies: 5a—horizontal reflectors: windward dune strata, and thin wind covers; 5b—steeply dipping reflectors: lateral limbs of dunes; 5c—steeply dipping reflectors: frontal limbs of dunes (leeward side).

Neal [17] suggested labelling for radarfacies and radarsurfaces for relative radar stratigraphic sequence of sedimentological events and their interpretation. Three codes-based labelling: **MR-f_n-1-pf**, ... >> Location – Radarfacies or Radar surface – Type of Radarfacies or Radar surface.

Radarfacies (**f**) and surfaces (**s**) nomenclature follow Neal [17] proposition for chronological stages sequences:

MR = site location (Marinheiros and Retiro areas). **f_{n-1}**, ..., **s_{n+1}**, ... **s_{n+4}**, **f_{n+5}** = relative radar stratigraphic sequence for facies and boundary surfaces.

Types of radarfacies (f)	Types of boundary surfaces (s)
ps = Pleistocene sediments	lf = listric normal fault
pf = pre-fault units underlying the Pleistocene	et = erosional truncation
br = beach ridges, with complex fill	ol = onlap
bf = backshore + washover and foreshore deposits	dl = downlap
lag = lagoonal sediments	tl = tolap of = offlap
dm = recent dunes and thin wind cover (Upper Holocene)	df = diachronic normal faults

The interpretation procedures follow the main criteria discussed in [11]-[13]. Despite regional RGSCP lagoon-barrier systems are chronologically well constrained, the present investigated area has no radiocarbon or OSL absolute age data. In this

way, **Table 2** presents only relative stratigraphic stages, different from Lagoa do Peixe [12] and Quinta-Cassino areas [11] [19].

Figure 6 presents radargrams surveyed in the Ilha dos Marinheiros, while **Figure 7** and **Figure 8** present radargrams for GPR lines surveyed close to DH sections 1 and 3 (see **Figure 4** for location). All radargrams show the influence of normal faulting on radarfacies geometry and continuity.

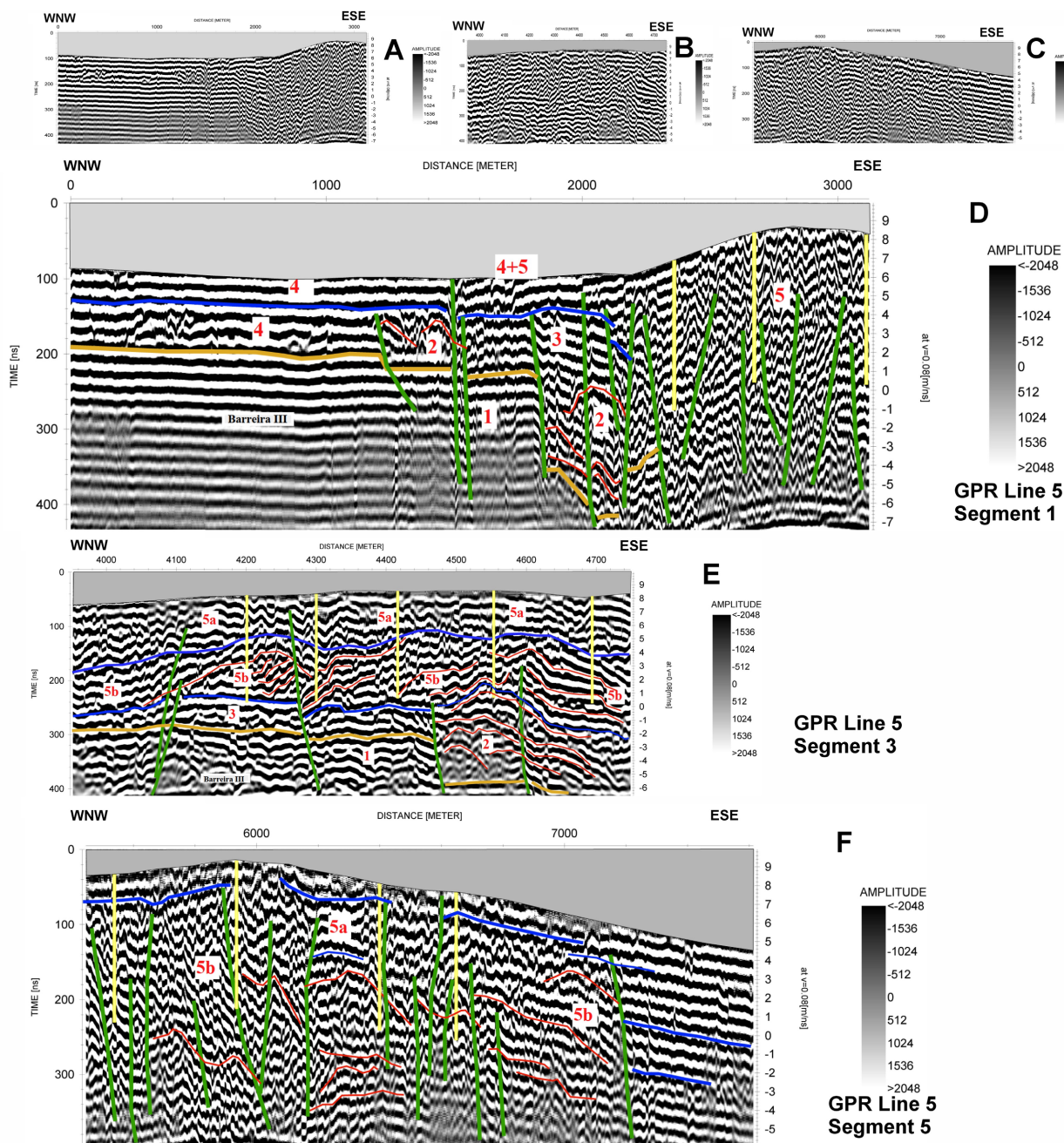


Figure 7. GPR lines surveyed in the northern Retiro area (São José do Norte County). (A) Uninterpreted GPR line 5, segment 1. (B) Uninterpreted GPR line 5, segment 3. (C) Uninterpreted GPR line 5, segment 5. (D) Interpreted GPR line 5, segment 1. (E) Interpreted GPR line 5, segment 3. (F) Interpreted GPR line 5, segment 5. Legend as in **Figure 6**. Numbers = radarfacies sedimentary events described in **Table 2**.

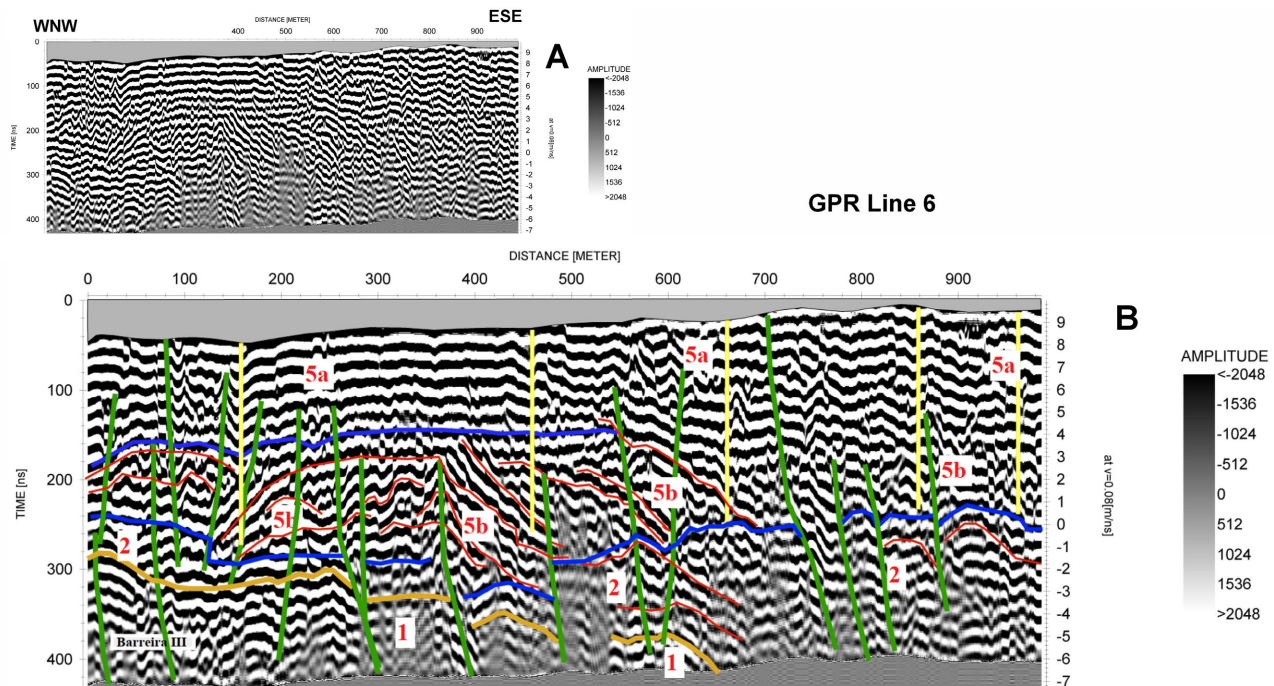


Figure 8. GPR lines surveyed in northern Retiro area (São José do Norte County). (A) Uninterpreted GPR line 6. (B) Interpreted GPR line 6. Legend as in **Figure 6**. Numbers = radarfacies sedimentary events described in **Table 2**.

The GPR lines in the Ilha dos Marinheiros were surveyed over surficial lagoon deposits (**Figure 6**), the uppermost radarfacies (**MR- f_{n+4} -lag**), which display regular horizontal reflectors. It overlays radarfacies (**MR- f_{n+3} -bf**), which shows north-westward gently deeping clinoforms and tends to level off towards the west. The (**MR- f_{n+3} -bf, 3a**) radarfacies seems to represent backshore or washover sedimentary deposits. The boundary between both these radarfacies is a regular surface (**MR- s_{n+3} -tl**) with a toplap/offlap relationship for topsets.

The lower boundary for radarfacies with clinoforms (**MR- s_{n+2} -tl**) is quite more irregular and shows downlap for the bottomsets of clinoforms. The next down radarfacies (**MR- f_{n+2} -br**) show eastward gently dipping reflectors, some large westward arched crests at the middle and base, suggesting truncated beach-ridges and complex fill. The bottomsets show onlap upon gently deeping upward arcuated fault surfaces (**MR- s_{n+1} -lf**), but when the fault surface horizontalizes, the reflectors become conformable to the base. The lowermost radarfacies (**MR- f_{n+1} -ps** and **MR- f_{n-1} -pf**) represent the Pleistocene sediments (Barrier III) truncated by normal listric faults. The vertical fault displacement for the Pleistocene boundary surface in **Figure 6** is greater than 3 m.

In the Retiro area (São José do Norte County), the northernmost GPR lines (GPR line 5) were surveyed from BR-101 federal road to close to the Atlantic Ocean beach; then, it was divided into three WNW-ESE segments (**Figure 7**), and into two NNE-SWS oriented segments (**Figure 8**). One additional GPR line (GPR line 6) was surveyed parallel to the GPR line 5—segment 3, extending toward E, and under higher resolution acquiring parameters (**Figure 9**).

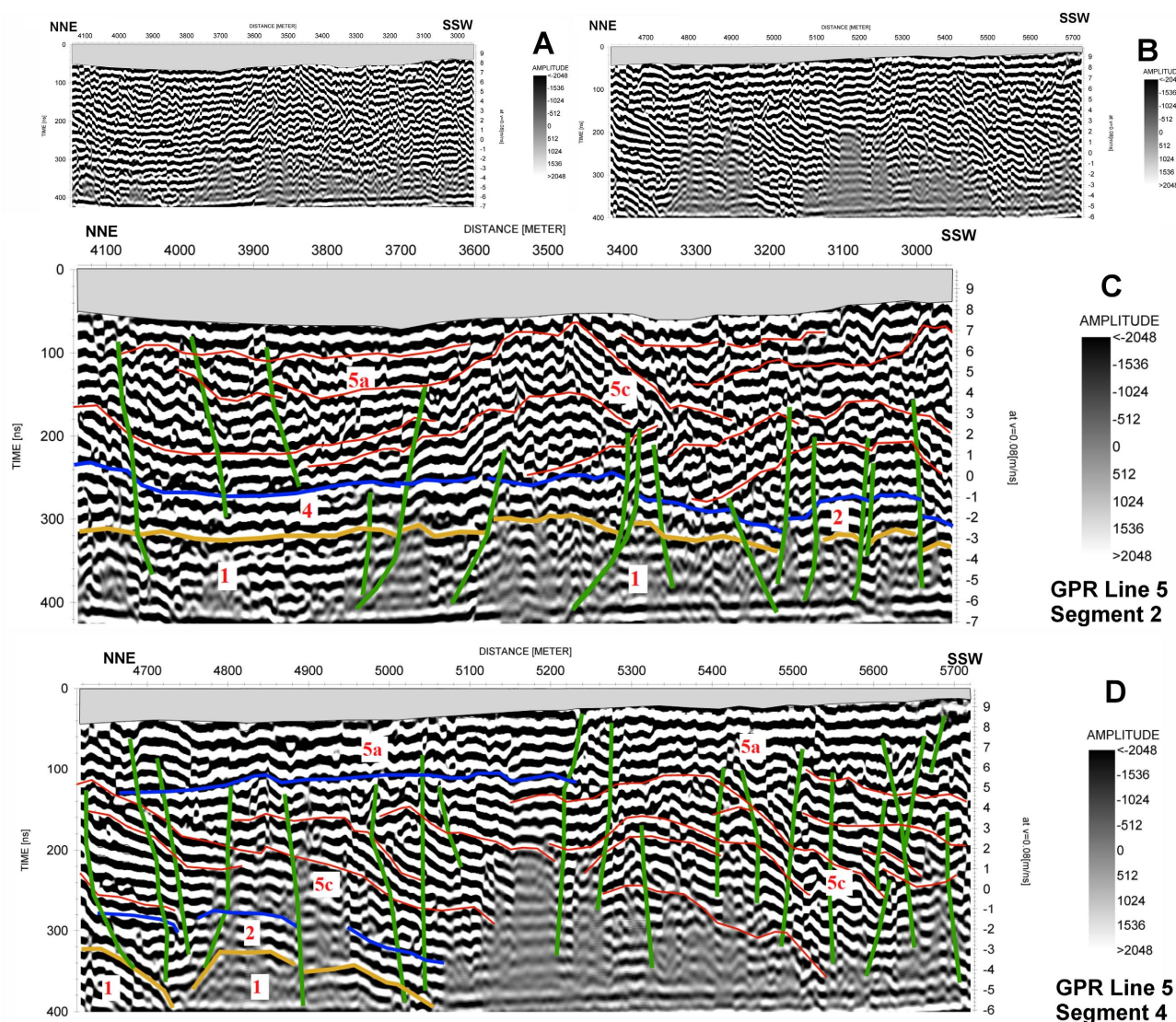


Figure 9. NNE-SSW GPR lines surveyed in the northern Retiro area (São José do Norte County). (A) Uninterpreted GPR line 5, segment 1. (B) Uninterpreted GPR line 5, segment 3. (C) Uninterpreted GPR line 5, segment 5. (D) Interpreted GPR line 5, segment 1. (E) Interpreted GPR line 5, segment 3. (F) Interpreted GPR line 5, segment 5. Legend as in **Figure 6**. Numbers = radarfacies sedimentary events described in **Table 2**.

It is important to note that, for interpretation purposes, the WNW-ESE segments of GPR line 5 are perpendicular to the coast and to transport direction of actual transgressive dune field (TD and TDS), while NNE-SSW segments are parallel to those directions. The WNW-ESE segments of GPR line 5 are also perpendicular to Retiro-Estreito Main Fault.

To the south, close to São José do Norte town, two GPR lines were also surveyed (**Figure 10**): GPR line 3 (westward of the BR-101 road, extending to Lagoa dos Patos), and GPR line 4 (eastward of the BR-101 road). Some HM drillholes (**Figure 5(A)**), projected from drillhole section to GPR line positions, were included in **Figure 7** to constrain the interpretation.

The predominant uppermost radarfacies in the northern Retiro area ($MR-f_{n+5}$ -

dm) are the Transgressive Dune Field (TD) and thin Transgressive Dune Sheet (TDS), that make up a sedimentary Holocene barrier close to Atlantic Ocean (Barrier IV). The SW wind transport made it possible to build up important TD far in the continent (close to Lagoa dos Patos), and even in the Ilha dos Marinheiros (see **Figure 2** and **Figure 4**). The lower boundary underlying TD and TDS (**MR- s_{n+4} -dl**) is an irregular surface for dune progradation, displaying downlap relationships for lateral and frontal dune set reflectors (e.g., **Figure 7** and **Figure 8**). Field observations record some interfingering between lagoonal and eolian sediments (e.g., **Figure 7(D)** and **Figure 10(C)**).

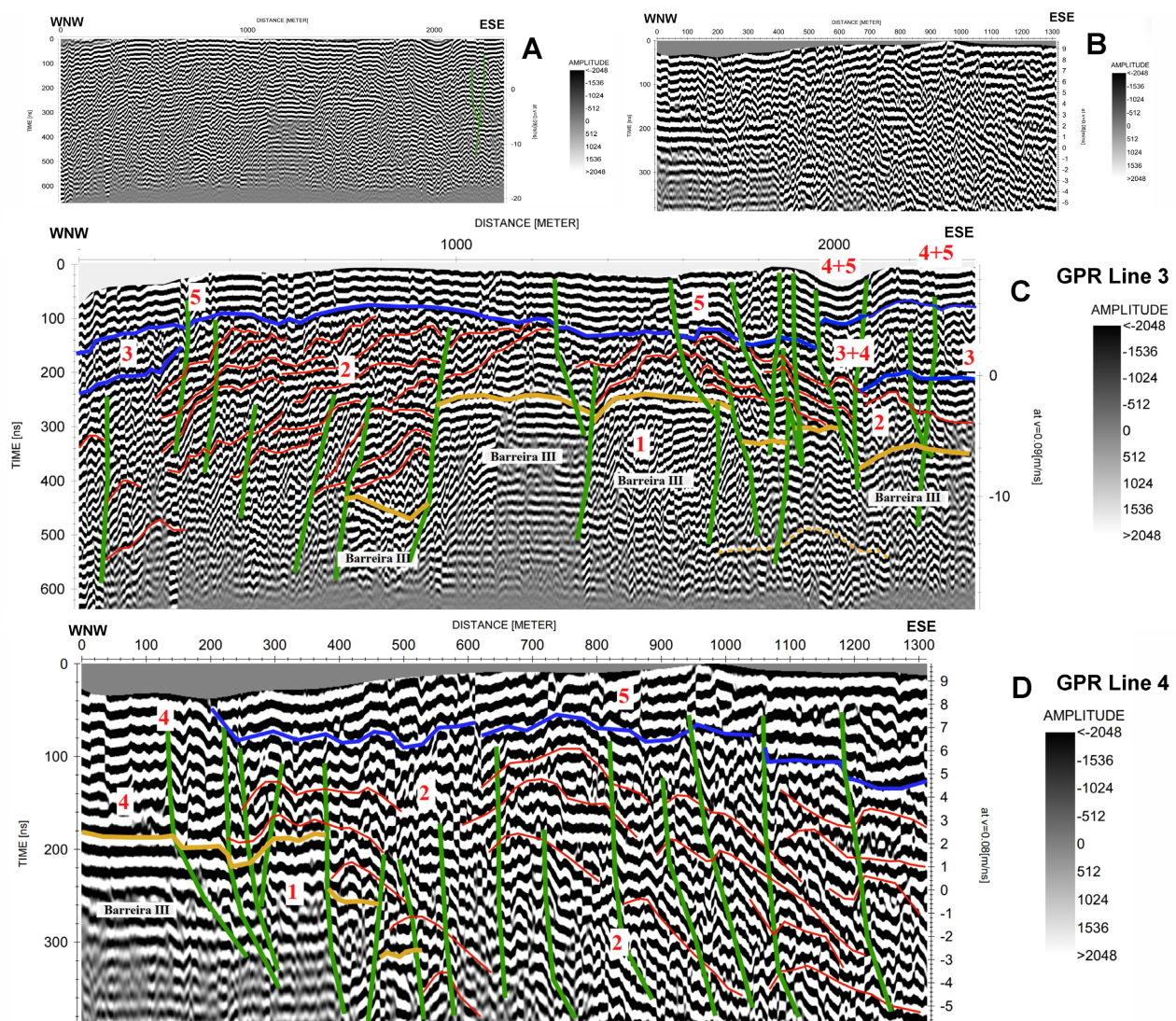


Figure 10. GPR lines surveyed in the southern Retiro area (São José do Norte County). (A) Uninterpreted GPR line 3. (B) Uninterpreted GPR line 4. (C) Interpreted GPR line 3. (D) Interpreted GPR line 4. Legend as in **Figure 6**. Numbers = radarfacies sedimentary events described in **Table 2**.

In the northeastern Retiro area (GPR lines 5 and 6), TD and TDS radarfacies (**MR- f_{n+5} -dm**) overlay radarfacies (**MR- f_{n+3} -bf, 3b**) or radarfacies (**MR- f_{n+2} -br**).

Inner reflector signatures for both these radarfacies are similar to those described in the Ilha dos Marinheiros. The most important aspect of the (**MR-f_{n+3}-bf, 3b**) and (**MR-f_{n+2}-br**) radarfacies is their control by normal faults, that are clearly discernible by different downthrows on the upper surface of Pleistocene sediments (**MR-s_{n+1}-et**). The (**MR-f_{n+3}-bf, 3b**) radarfacies, in the Retiro area, however, are made up of eastward gently deeping reflectors, which suggest foreshore deposits, overlying truncated beach-ridges (**MR-f_{n+2}-br**).

Figure 7(D), **Figure 7(E)**, **Figure 8** and **Figure 10**, located to the east (hanging wall of the Retiro-Estreito Main Fault), show a stepped structure for the upper Pleistocene boundary (**MR-s_{n+1}-et**) and established onlap upon the normal fault boundaries (**MR-s_{n+1}-lf**). To the east, the upper Pleistocene boundary (**MR-s_{n+1}-lf**) is not identified, certainly due to a large normal fault. downthrow (**Figure 7(F)**, **Figure 8**, **Figure 9(D)**). The steeped vertical fault displacement for the Pleistocene boundary surface in **Figure 7** and **Figure 8** ranges from 1 to 7 m.

The GPR lines 3 and 4, on the other hand, are located to the west of the Retiro-Estreito Main Fault (in the footwall). **Figure 10** shows that the upper Pleistocene boundary (**MR-s_{n+1}-et**) displays both synthetic and antithetic normal fault displacements regarding the Retiro-Estreito Main Fault. In fact, these opposed normal fault displacements give rise to a horst structure for Pleistocene sediments (Barrier III). The steeped vertical fault displacement for the Pleistocene boundary surface in this area ranges from 1 to 8 m in the imaged time window. Additionally, since both GPR lines (**Figure 10(C)** and **Figure 10(D)**) are WNW-ESE aligned west and east to BR-101 road, one can easily observe diverging reflectors architecture for **MR-f_{n+2}-br** radarfacies (the beach ridges) on both sides of the Pleistocene horst. The horst structure was, then, a structural barrier for Holocene sedimentation. The horst structure and the first Holocene sedimentary radarfacies (**MR-s_{n+2}-tl** and **MR-s_{n+3}-tl**) were then partially or totally covered by TD and TDS (**MR-f_{n+5}-dm**) radarfacies in the footwall of Retiro-Estreito Main Fault.

5. Discussions on Retiro-Estreito Normal Faulting and Sedimentation

The radargrams presented in **Figures 6-10** show higher normal faulting intensity (density) than that observed in the Lagoa do Peixe Listric Growth Fault [12]. Another main difference arose from these radargrams: instead of one main fault that concentrates the displacement in a listric surface (Lagoa do Peixe Listric Growth Fault), in the southern tip of the Retiro-Estreito Main Fault, there was a strain partitioning into several fault surfaces, giving rise to a stepped fault structure.

The strain partitioning and splaying at fault terminations (tips) are a common feature in fault propagation and growth [20] [21]. This structural feature poses important influences in mechanical subsidence, since faulting is a diachronous process. Mechanical subsidence refers to the downthrow sinking of geological markers due to structural stress field, usually leading to normal faulting. Diachronous process refers, on the other hand, to the formation of a geological structure

whose movement (slip or displacement) does not happen simultaneously across its entire length, such as along a fault or a connected system of faults. In this way, sedimentation on diachronous fault displacements can introduce some complexities in sedimentary structures, which will impact radarfacies reflections architecture.

It is also to be noted that Pleistocene units (**Figure 7(D)**, **Figure 7(E)**, **Figure 8(B)**, **Figure 9(D)**, **Figure 10(D)**) were not observed in eastern radargram segments. This is due to normal fault downthrow increases to the east and the upper Pleistocene contact (**MR-s_{n+1}-et**) is deeper than GPR signal propagation.

The horst in the southern Retiro area, near the town of the São José do Norte (**Figure 10**), is an important structure to evaluate the local mechanical subsidence, the sedimentation process and the radarfacies architecture and geometry. It shows a stepped geometry that is best developed on its eastern side (hangingwall of the Retiro-Estreito Main Fault). It also shows a narrow terrain depression close to the BR-101 road, which is recognized as a graben in the radargram (**Figure 10(C)**). The map view for this terrain depression (graben), however, trends obliquely to Retiro-Estreito Main Fault and is aligned to beach-ridges lines separating sets in the Quinta-Cassino strandplain to the south of the Rio Grande channel.

The horst acts as a structural barrier to beach ridges radarfacies (**MR-f_{n+2}-br**) deposition on both sides. **Figure 10** shows the beach ridges as the lowermost Holocene deposits, displaying foresets deeping toward the east (ocean) but also toward the west (Lagoa dos Patos). **Figure 10(D)** shows beach ridges crest berm climbing up stepped normal faults, which suggests mechanical subsidence rate higher than a sea level lowering rate. It yet shows truncated beach ridges foresets and superposed crest berms also suggesting diachronous displacements in normal faults. These structural and sedimentary features are still recognized in GPR line 5 to the north (**Figure 7(E)**, **Figure 7(F)**, **Figure 8(B)**).

The boundary surface between **MR-f_{n+2}-br** (beach ridges) and **MR-f_{n+3}-bf** (back-shore-washover and foreshore deposits) radarfacies (**MR-s_{n+2}-tl**) is an irregular surface that also shows stepped features (**Figure 7(D)**, **Figure 7(E)**, **Figure 8(B)**, **Figure 10**), and hangingwall side thickening. These features point to the maintenance of diachronous normal fault displacements and to a mechanical subsidence rate higher than sea level change during the third sedimentary event processes (**Table 2**). The **MR-f_{n+3}-bf** (**3a**, **3b**) radarfacies suggests a high-energy depositional event, after a period of major mechanical subsidence. This sedimentary event is responsible for the partial erosion and destruction of the structurally elevated Pleistocene footwall block and horst (the structural barrier). The backshore and washover reflector architecture were recognized in the footwall for the Retiro-Estreito Main Fault in Ilha dos Marinheiro (**Figure 6**) and the southwest Retiro area (**Figure 10(C)**). On the other hand, the foreshore reflectors architecture was recognized in the hangingwall side of the Retiro-Estreito Main Fault (**Figure 7(D)**, **Figure 7(E)**, **Figure 8(B)**).

The erosional destruction of the structural Pleistocene barrier can be recognized

in DH section 2 (**Figure 5(B)**). The thick brownish sediments overlying the gray fine-grained sand and clay laminated sediments do represent alluvial fans derived from Retiro-Estreito Fault scarp. This sedimentary unit was recognized in the Quinta Fault scarp [11] and is still recognized along the central segment of the Retiro-Estreito Main Fault. **Figure 11** shows a segment of the Retiro-Estreito lagoon, where the clogging processes can still be observed and include: erosional degradation of the fault escarpment (alluvial fans) and deposition as an interbedded layer of sands and lagoon sediments (lagoon depocenter) toward thrsoutheast, and transgressive dune and dune sheets progradation toward the southwest. It is to be noted that these clogging processes were also described in the Lagoa do Peixe (the lagoon developed by the Lagoa do Peixe Listric Growth Fault [12]).

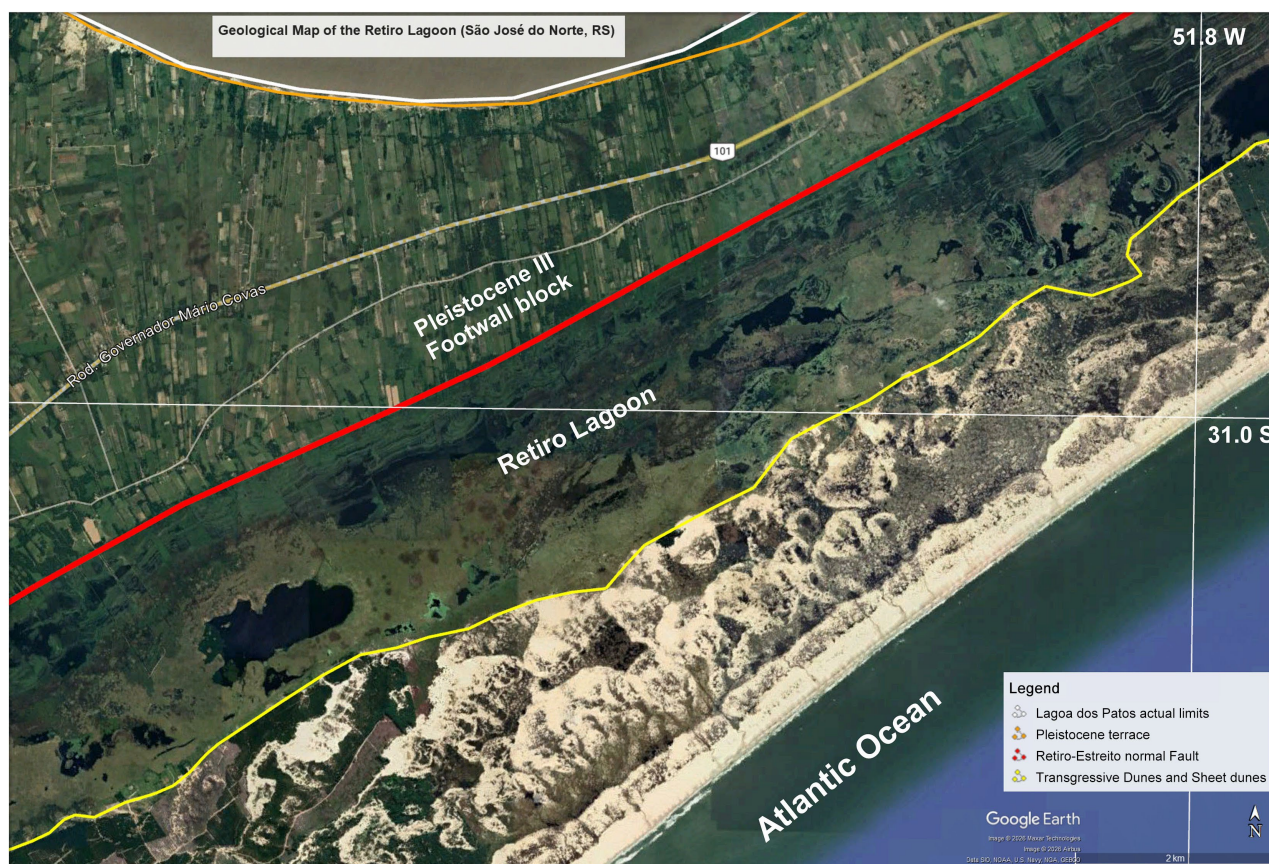


Figure 11. Retiro Holocene lagoon, showing the Retiro-Estreito normal fault and its fault scarp, the fault scarp erosional degradation depositing alluvial fans, and the progradation of TD and TDS.

This investigation is focused on areas in southern tip of the main Retiro-Estreito Fault to evaluate the structural pattern developed close to main fault scarp. However, GPR Line 5 extends from BR-101 road to the Atlantic Ocean beach (**Figure 7**) and reveals that Pleistocene sedimentary units (Barrier III), after the first stepped normal faults in the western segment, are not recorded toward the ocean beach (it is far down the GPR time window limit). This feature indicates that downthrown displacements increase toward the ocean and no significant Pleistocene basement

rotation was necessarily produced in the hangingwall block. This structural framework differs from that recorded for Lagoa do Peixe Listric Growth Fault [12] [13], but is similar (no large Pleistocene basement rotation) to Quinta Main Listric Fault in the Quinta-Cassino strandplain [11].

The absence of significant Pleistocene basement rotation in the Retiro-Estreiro Main Fault implies that the actual sedimentary barrier near the Atlantic Ocean ($MR-f_{n+5}-dm$, TD) is not built upon an underlying structural barrier (an anticline on the Pleistocene units) as recorded in the Lagoa do Peixe area [12] [13].

Figure 4 shows that TD Holocene barrier prograding into the Retiro Lagoon is wider in the north and becomes narrow to the south. East from São José do Norte city (**Figure 12**), the TD Holocene barrier is <1.0 km wide, and thin wind cover (TDS) overlies previously deposited sedimentary units.

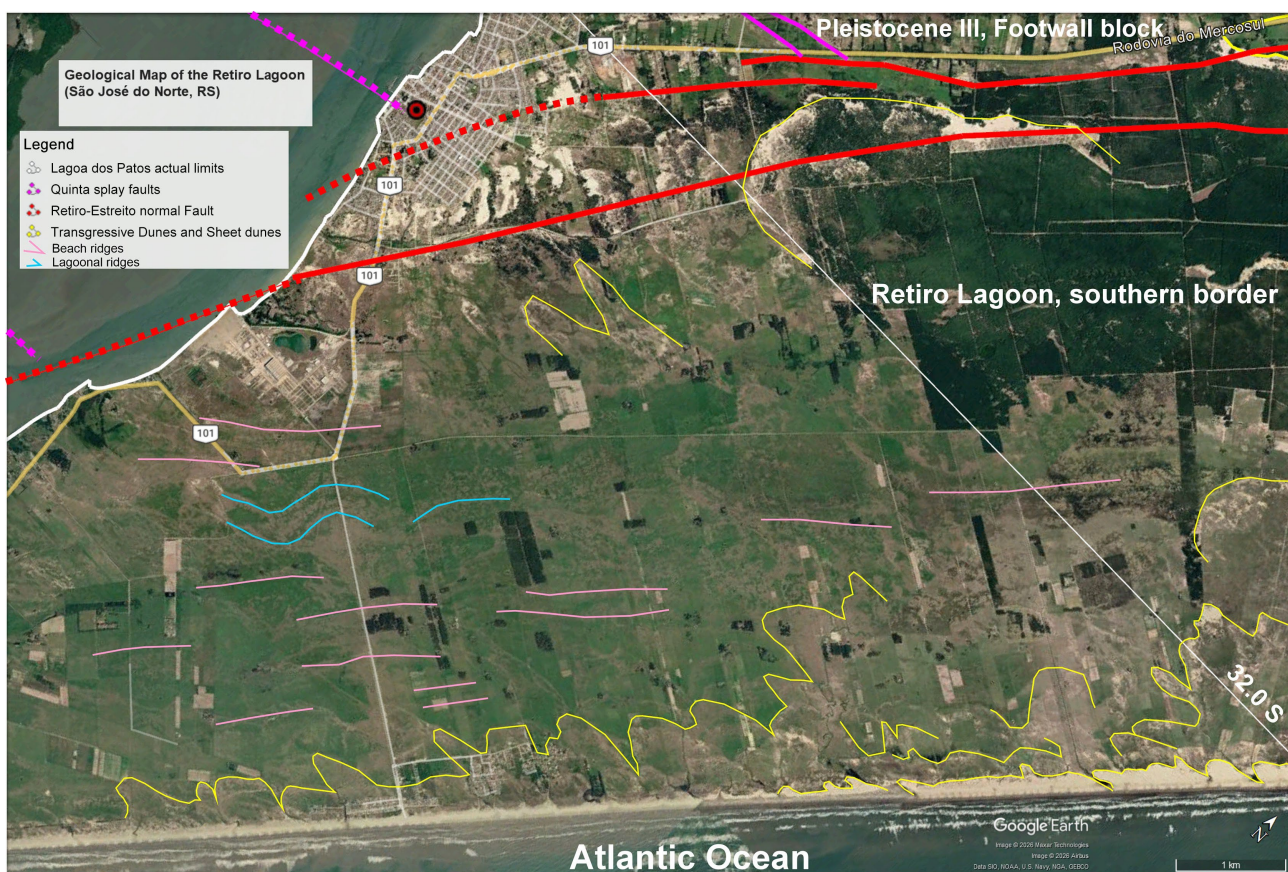


Figure 12. Southern border of the Retiro Lagoon, showing the clogging process and the building up of the narrow Holocene barrier (TD). It shows some remnants of beach ridges underlying thin TDS, and also a group of washover deposits superposed into TD deposits.

Figure 12 is a detailed image from the southern Retiro-Estreiro Main Fault, close to the Rio Grande channel, where beach ridges remnants can still be observed underlying very thin TDS midway between the fault and the ocean, as previously recognized by [22] [23]. Some washover deposits can also be recognized perpendicular to the narrow TD deposits. These Holocene sedimentary deposits (TD, TDS,

washover and beach ridges deposits) make up the Barrier IV, and they show different distribution in the fault hangingwall due to strain intensity along fault (mechanical subsidence amount) and sediment source and supply.

Figure 13 illustrates the faulted Pleistocene units (Barrier III and older) during the Holocene gravity sliding tectonics in the Retiro area (São José do Norte, RGSCP). **Figure 13** shows the radargrams results, which do not record rotation components to establish an anticline toward the Atlantic Ocean. In this area, the Retiro-Estreito Main Fault splays off into a series of diachronous faults, each one showing different displacement magnitude and chronology.

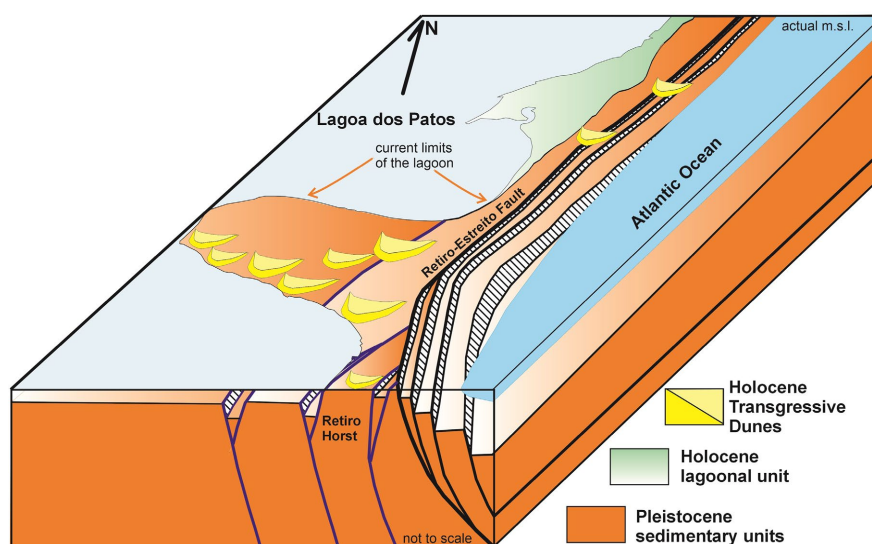


Figure 13. Block diagram illustrating basement (Pleistocene Barrier III) normal faults in the Retiro area (São José do Norte, RS). Holocene sedimentary units were omitted to highlight basement structural features. The actual Holocene lagoonal unit is represented to be a regional reference (gradient colouring means 1 - 2 m to 4 - 5 m above actual m.s.l.). Gradient colouring in plain view for Pleistocene units represents deeper (light) to higher (dark colour) structural levels in relay ramps. Retiro Horst normal faults (dark blue) are related to the Quinta Main Listric Fault.

Figure 14 illustrates a sequence of cross-sections for the Holocene structural and sedimentary evolution of the Retiro-Estreito Main Fault and the clogging process of the Retiro Lagoon. The idealized cross-section is to represent a transect parallel to the GPR lines 3 and 4, but incorporates features from GPR lines 1, 2 and 5. The presented evolutionary sequence takes into account radarfacies geometry and fault truncation as observed in previous radargrams.

Figure 14(A) shows the final lateral and vertical propagation of the Retiro-Estreito Main Fault toward the São José do Norte city and Rio Grande channel. The mechanical subsidence in the fault hangingwall enabled the deposition of the first beach ridges units, and also lagoonal and TDS units (**Figure 14(B)**). The continuity of the faulting subsidence and the onset of new faults splays truncate and displace downward the initial Holocene deposits (**Figure 14(C)**). The diachronous fault displacement and splays renewed mechanical subsidence in the fault hang-

ingwall prompted new stages of beach ridges and lagoonal deposition, developing complex radarfacies geometry and complex fill patterns (**Figure 14(D)**, **Figure 14(E)**). In a later stage, the Quinta Lstric Fault splay propagate toward the Retiro area (**Figure 14(E)**) and finally modify the structural framework in the footwall of the Retiro-Estreito Main Fault (**Figure 14(F)**).

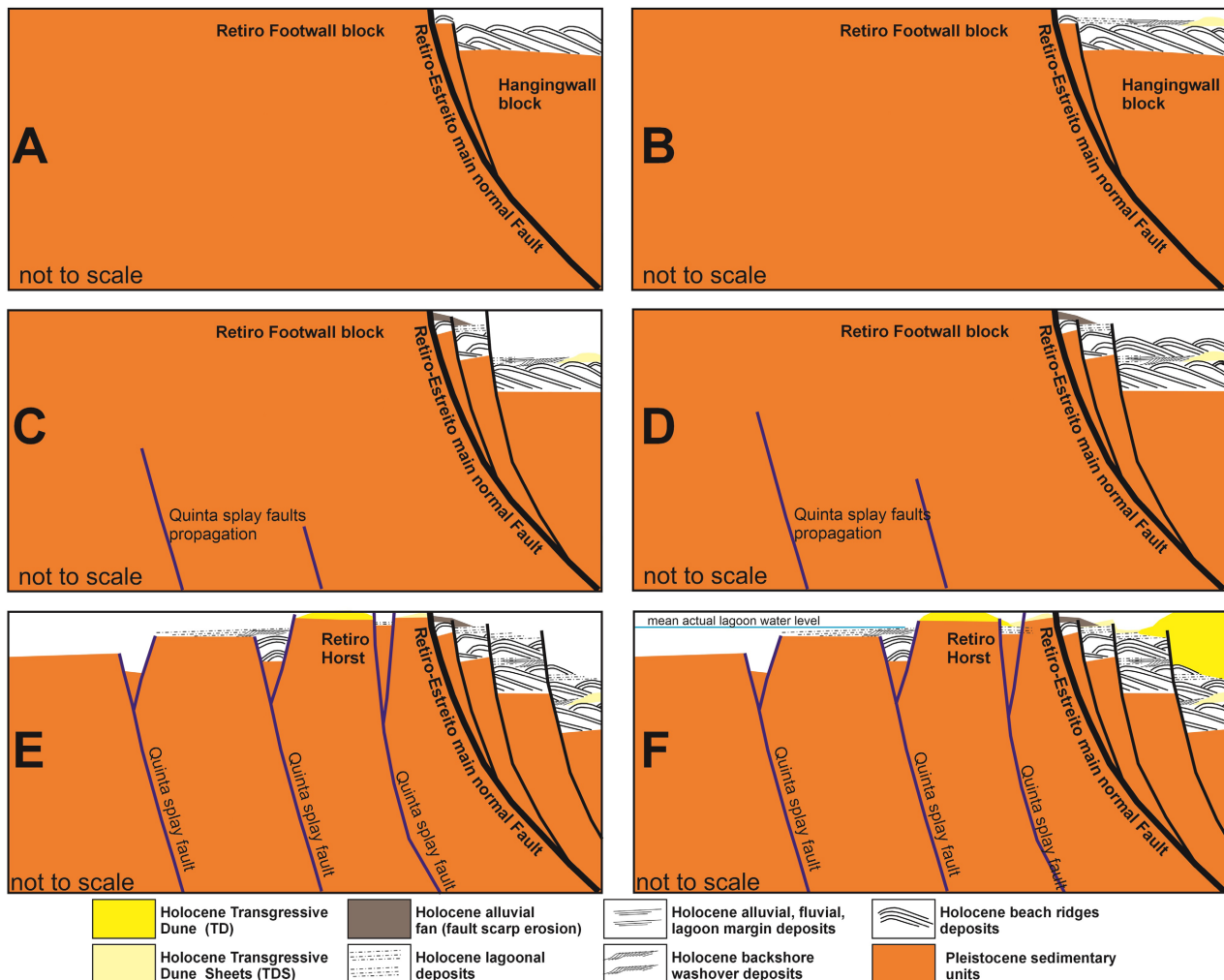


Figure 14. Cross-sections illustrating the Holocene structural and sedimentary evolution of the Retiro-Estreito Main Fault and the clogging process of the Retiro Lagoon. (A) and (B) illustrate the onset of the Retiro-Estreito Main Fault and the sedimentation of beach ridges on the hangingwall fault block. (C) and (D) illustrate the continuation of fault-splaying process, the truncation of previous Holocene sedimentary units, the progress of the hangingwall subsidence, and the propagation of the Quinta splay faults in the footwall block. (E) illustrates the final interaction of the Quinta fault splays, segmentation of the Retiro-Estreito footwall block, and the Retiro Horst development.

The Retiro Horst is developed in this late stage (**Figure 14(E)**, **Figure 14(F)**) and gave rise to local mechanically subsided structures in the previously unfaulted footwall block of the Retiro-Estreito Main Fault. The Retiro Horst, as a local structural high, separates diverging beach ridges patterns (toward west and toward the east; see **Figure 10**), which indicate oceanic currents accessing the Retiro area from the Quinta-Cassino strandplain and from an eastern position. However, this

subject requires a detailed discussion, and it is addressed in the companion paper [19].

6. Conclusions

The southern Retiro-Estreito Main Fault tip zone shows high normal faulting density, giving rise to a stepped structural framework, over which Holocene sedimentary radarfacies were developed. Close to Rio Grande channel, the Retiro-Estreito Main Fault splays up into a series of diachronous faults, each one showing different displacement magnitude and chronology. The basement for Holocene sedimentary units is the faulted Pleistocene units (Barrier III and older ones), which do not record rotation components to establish a growth fault and an anticline toward the Atlantic Ocean.

The stepped structural framework recorded in the Pleistocene sedimentary units is the result of the Holocene gravity sliding tectonics already recognized in the RGSCP. The downthrow displacement in the Pleistocene basement is also recognized to truncate Holocene sedimentary units, giving rise to complex fill patterns mainly in older radarfacies.

The Retiro-Estreito Main Fault footwall block was later faulted due to the north-eastward propagation of the Quinta Listric Fault splays, which gave rise to Retiro Horst. This later Pleistocene basement structural framework anchors sedimentation with diverging polarity (beach ridges) and fault truncation and superposition, indicating diachronous faulting at a mechanical subsidence rate higher than sea level changes.

The sedimentary stage after the Retiro Horst was built is still deposited under a high mechanical subsidence rate. It is characterized by erosional degradation of the Retiro Horst and Retiro-Estreito Main Fault scarp, and deposition of backshore and washover radarfacies in the Retiro Horst, and also foreshore radarfacies in the Retiro-Estreito normal Fault hangingwall block.

The last sedimentation stage, under mechanical subsidence rate lower than sea level changes, includes TDS covering the southern limit of the Retiro-Estreito Fault hangingwall and TD main barrier prograding southwestward to isolate the Retiro-Estreito lagoon. In this actual stage, the Retiro-Estreito lagoon still shows evidence of clogging processes in advanced stages: erosional degradation of its northwest fault escarpment (alluvial fan deltas) and TD and TDS progradation over southwest lagoon border.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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