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Gravity Fault Subsidence and Beach Ridges Progradation in Quinta-Cassino (RS) Coastal Plain, Brazil

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Abstract

Ground penetrating radar (GPR) surveys have being applied to investigate very near-surface stratification of sedimentary units in coastal plains and to define their depositional conditions. This paper presents, however, low-frequency GPR survey to investigate fault-related depositional systems at greater depths. The Quinta-Cassino area in the Rio Grande do Sul Coastal Plain (RGSCP, Brazil) shows a wide strandplain that is made off by very long, continuous, and linear geomorphic features (beach ridges). This strandplain extends for ~70 km southward. The beach ridges show low-angle truncations against the Quinta escarpment, and also truncations in the strandplain. The traditional approach points that RGSCP was developed by juxtaposition of four lagoons/barrier systems as consequence of sea level changes; previous model assumes that no deformational episode occurred in RGSCP. The geophysical and geological surveys carried out in this area showed the existence of listric fault controlling the beach ridges in the escarpments and hanging-wall blocks. The radargrams could distinguish Pleistocene basement unit anticlockwise rotation, thickening of beach ridges radarfacies close to listric normal faults, and horst structures. These deformational features indicate that the extensional zone of a large-scale gravity-driven structure controlled the mechanical subsidence, the Holocene sedimentation and its stratigraphic and geomorphic features in the Quinta-Cassino area to build up an asymmetric delta. The results point to a new approach in dealing with RGSCP Holocene evolution.

Keywords

Gravity Tectonics, Normal Faults, Ground Penetrating Radar Survey,

1. Introduction

The Rio Grande do Sul Coastal Plain (RGSCP) is the emerged segment of the Pelotas Basin, the southernmost of Brazil's Atlantic basins. It is up to 100 km wide and extends for more than 600 km in NE direction. The RGSCP has been characterized by juxtaposition of deltaic alluvial plains and four lagoons/barrier systems (**Figure 1**) developed as consequence of sea level changes from Middle Pleistocene to Holocene [1].

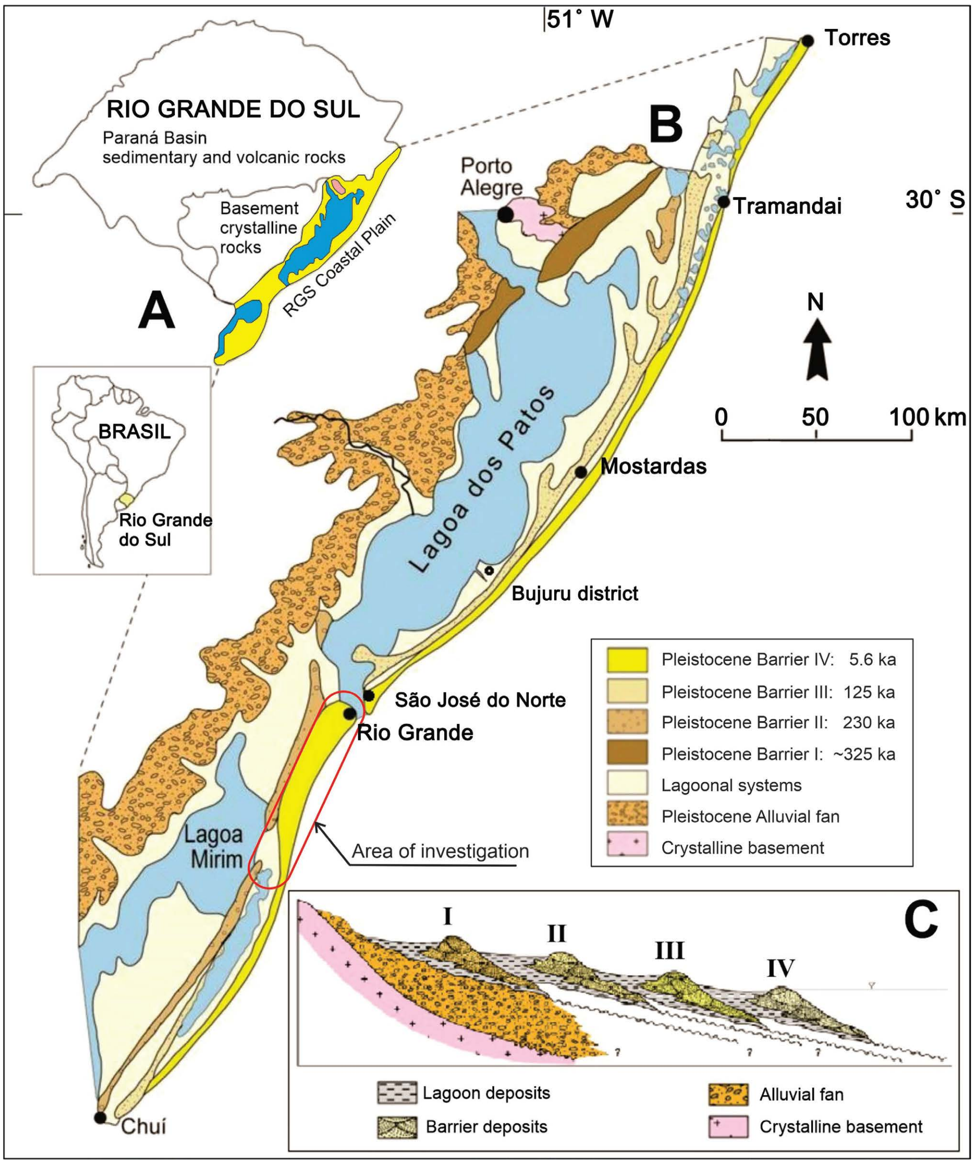

Figure 1. Rio Grande do Sul Coastal Plain location (A), its regional geological map (B), and the model for its depositional systems (C). Modified from [4] and [5]. Lagoon/Barrier system ages according to [6]. The red rounded rectangle circumscribes the area of investigation in **Figure 2**.

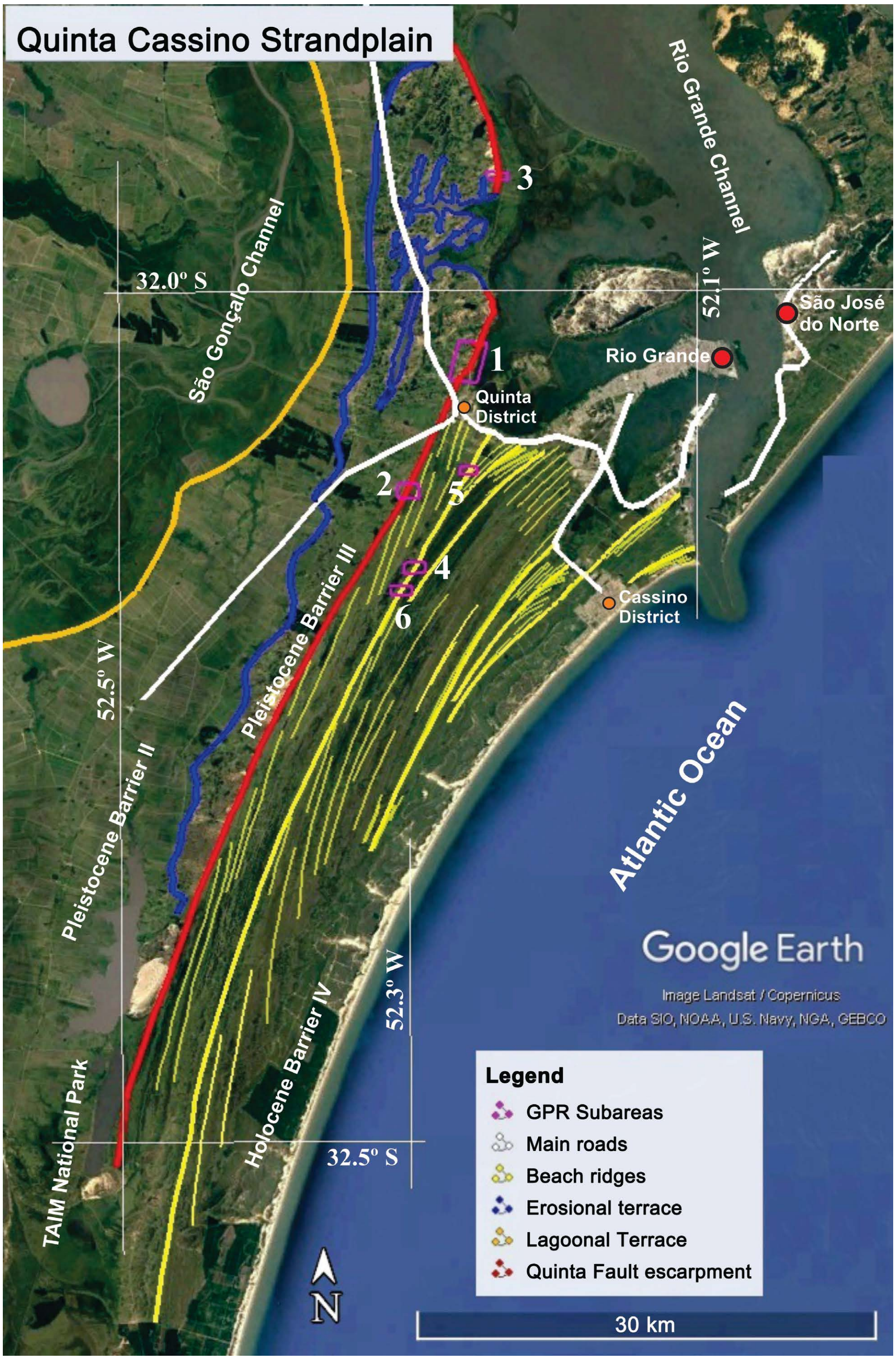

Figure 2. Geology of the Quinta-Cassino area, located to the south of Rio Grande channel. Numbered subareas: 1) **Figure 4** and **Figure 6**; 2) **Figure 3** and **Figure 7**; 3) **Figure 5** and **Figure 8**; 4) **Figure 9**; 5) **Figure 10**; 6) **Figure 11**.

The RGSCP Holocene deposits (Barrier/Lagoon system IV) exhibit a much wider extent in the segment to the south of Rio Grande channel. It is dominated by an expressive half-fan series of linear features (beach ridges, [2] and [3], **Figure 2**).

The wide strandplain developed to the south of the Rio Grande channel was first described by Godolphin [7] and is limited to the west by an erosional cliff due to the Quinta Transgression (Pleistocene-Holocene transition). Godolphin [7] proposed minor sea level oscillations during the Holocene regressive stage, to give rise a series of seven sets of coastal ridges (FR1: 6000 y.BP; to FR7: from 350 y.BP).

Long and Paim [2] also distinguished seven sets of linear to curvilinear ridges (F1 to F7) based on truncation relationships and described the contact between Pleistocene and Holocene sediments as an erosional cliff. On the other hand, Long and Paim [2] argued that F1 ridges series were developed by lower deposition energy conditions due to the width of the Lagoa dos Patos estuary. The following ridges sets, arcuated to the ocean, were developed as a consequence of meandering and channeling changes under the influence of the Rio Grande channel outlet flow [2].

Milana *et al.* [3] produced a detailed map of individual ridges of the Holocene strandplain in the Quinta-Cassino area of the RGSCP, and distinguished at least 18 sets of coastal ridges, grouped into 5 stages. Based on ridges lineaments truncation, ridges topographic altitude and ridges erosion evidence, they [3] suggested different conditions of longshore sediment transport, wind intensity and sediment supply in building the successive prograding coastal ridges sets.

Dillenburg *et al.* [8], on the other hand, identified 6 sets of relict foredune ridges, whose limits between are distinguished by ridge truncations and the formation of transgressive dune sheets (TDS). According to Dillenburg *et al.* [8], the Quinta-Cassino barrier progradation during Holocene was not uniform. The variable rates of progradation would be due to changes in sediment budget produced by environmental changes (changes in the wave climate, wind, and precipitation). They [8] argued that, at time of first foredune ridges set formation (6 ka), the sea level was still rising; and, that the following foredune ridges set were developed regressive sea level.

The previous investigations are based on sedimentary facies, depositional systems, chronostratigraphic techniques, and environmental conditions. No neotectonic deformational episode and no mechanical subsidence are considered for RGSCP sedimentary strata juxtaposition: "*the Pelotas Basin has remained oblivious to major tectonic movements*, *which translates into the symptomatic absence of faulting. If there were any*, *they resulted from aseismic processes in the sedimentary package that today constitutes the slope of the continental margin*" [9].

Fontoura *et al.* [10] and Strieder *et al.* [11], however, showed preliminary evidence of major faults in the RGSCP. Cooper *et al.* [12] [13] have also showed evidence for major deformation in the Santa Catarina Coastal Plain. And Fontoura [14] presented a detailed GPR investigation to reveal a major growth fault at Lagoa do Peixe National Park.

The aim of this paper is to show that gravity-driven large-scale faults control mechanical subsidence and sedimentation of the prograding beach ridges in the Quinta-Cassino strandplain (RGSCP). The aim of this paper is not to investigate inner sedimentary structures or sedimentological features, but the fault geometry and the sedimentary unit's architecture in this large strandplain south to Rio Grande channel. In this way, ground penetrating radar (Rough Terrain Antenna - RTA, 50 MHz, Ramac GPR) surveys and field surveys were carried out to determine the regional structural framework developed by the Quinta Fault and its branches.

2. Geophysical and Geological Survey Methods

The Pleistocene-Holocene contact in the Quinta area (RGSCP) has been characterized as an erosional cliff [2] [7]. It is a low relief, gently arcuated (in plain view) escarpment that extends from Quinta (north) to Lagoa Mirim (south, Uruguay border). The Pleistocene sediments to the west of the escarpment are classified as Barrier II and III [1] [4], and stand up into a low plateau, 10 - 15 m above the actual sea level.

Fonseca [15] regarded this curvilinear geomorphic feature to a neotectonic structure (Mangueira Lineament). Based on this geomorphic feature, three areas were selected for geophysical and geological survey: 1) Quinta (southern), 2) Quitéria (central), and 3) Torotama (see **Figure 2** for location). These selected areas were surveyed to geophysically investigate what kind of geological structure controls the escarpment.

The geophysical surveys were carried out through 50 MHz RTA Ramac ground penetrating radar (GPR) equipment. This frequency was selected to investigate that structure as deep as possible (>20 m depth was attained with good resolution). The mean EM wave velocity was estimated to be 0.08 m/ns, so that vertical resolution is ~0.4 m. The mean velocity was estimated from diffraction hyperbolas along GPR profiling. Then, the EM wavelength is not adequate small-scale sedimentary structures, but to sedimentary units' geometry, interrelationships, and continuity.

Two parallel GPR lines were surveyed in Torotama and Quitéria areas, along gravel roads cutting across Pleistocene-Holocene escarpment. In the Quinta area, five parallel and oblique lines were surveyed, since no water filled depression is present and a better scanning for the fault geometry can be produced. Another three survey areas were defined to investigate the contact between the sets 1 and 2, and 1 and 3 (**Figure 2**), as defined by [2] [7]. The GPR lines were surveyed perpendicular to high angle regarded to the Quinta escarpment, beach ridges and TD direction.

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 do 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: dewow filter; bandpass filter (butterworth, but sometimes trapezoidal); migration (v = 0.297 m/ns) for removing surface reflections in unshielded antenna; topographic correction; 3D topographic migration (e.g. v = 0.08 m/ns) and butterworth filtering. The colorbar was selected to emphasize structural features and radarfacies interrelationships.

3. Geology of the Surveyed Areas

A geologic survey was carried out through aerial-photographs, high resolution Google images, and field work in the area under geophysical investigation, to investigate the main surficial sedimentary units over which GPR data were acquired. Such investigation helps to define the main geological features and contribute to discriminate them in radargrams. The aim was not to fully characterize each sedimentary unit in terms of their sedimentological properties and inner structures, but to identify the sedimentary unit's organization (architecture) and the deformational structures.

The simplified geological maps images analysis and field work are presented in **Figures 3-5**, 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, and it crops out to the west of the Quinta escarpment (an erosional cliff, or a fault scarp?). Westward, the Pleistocene Barrier III is not fault bounded, but there exists an erosional terrace, that separates it from Barrier II. This both Pleistocene systems may be recognized by two erosional tiers (13 - 18 m, and 4 - 11 m) above mean see level (**Figure 2** and **Figure 5**).

The Holocene Barrier (IV) is composed by different sedimentary deposits, as recognized in fieldwork (**Table 1**). These sedimentary deposits are named due to their geometric, descriptive features, and crosscutting relationships, to distinguish them in the geophysical sections.

The beach ridges make up a strandplain that is wider in the Rio Grande channel

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 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.

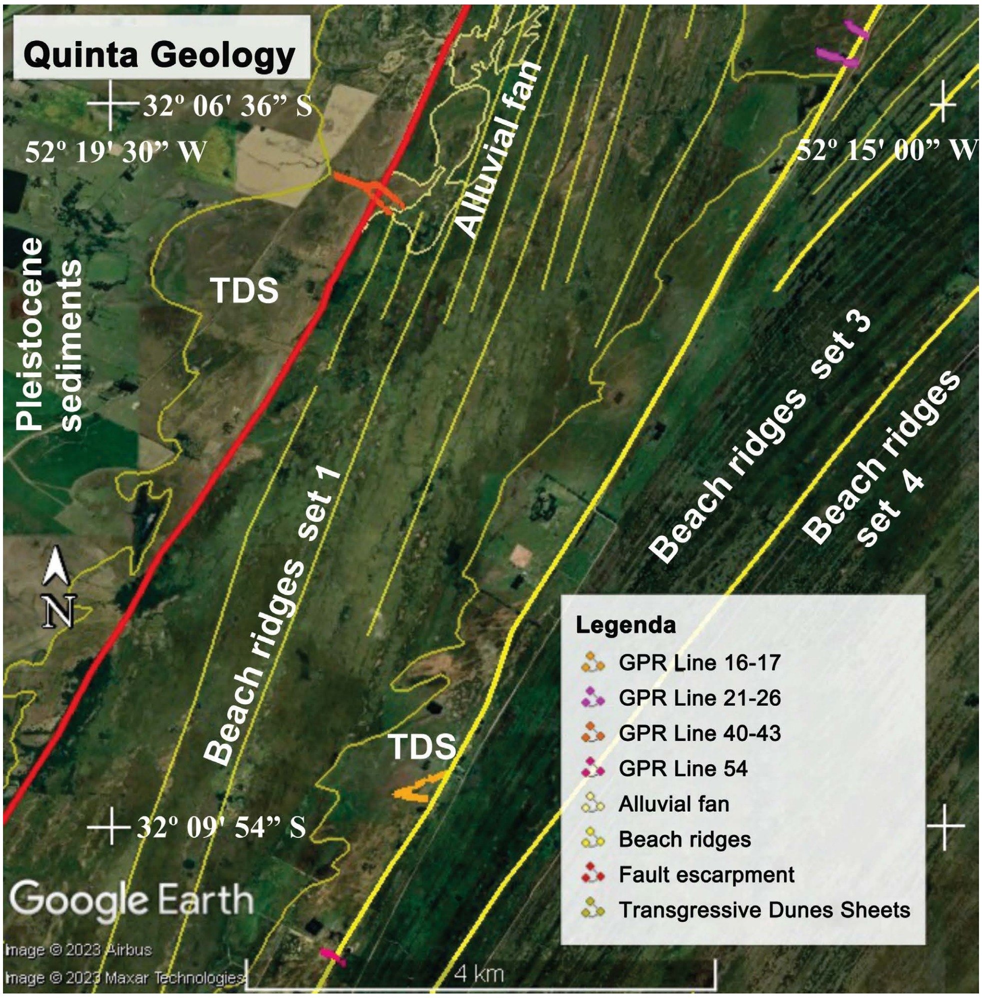

Figure 3. Simplified geologic map of the Quinta area, showing the location of main GPR line surveys. Thick yellow lines separate the beach ridges sets.

(north) and narrows toward the south. These beach ridges are linear to curvilinear features and can be continuously followed by more than 20 km. The ridges and the depressions are 70 to 300 m wide. The ridge-depression couples show truncations that make possible to distinguish at least 8 major sets (**Figure 2** and **Figure 3**); the truncation trace is also a curvilinear feature that can be followed by more than 100 km. Sets 1 to 7 are those initially proposed by [2] [7], while set 8 is interpreted in the northeastern segment, close to marine Rio Grande port dike.

The aim of this paper is to investigate the fault geometry and the sedimentary unit's architecture in this large strandplain south to Rio Grande channel. In this way, the main nomenclature and definitions take the descriptive character based on Otvos [16], who defined beach ridges as: "*Shore-parallel, narrow, elongated sand or gravel ridge formed by wave action near high tide-level on high-tidal beach berm surfaces, often directly underlain by intertidal sediments. Usually capped by a foredune ridge. Shore-parallel backshore dune ridges accumulated by wind over eolian sand sheet that may, in turn overlie prograded intertidal*

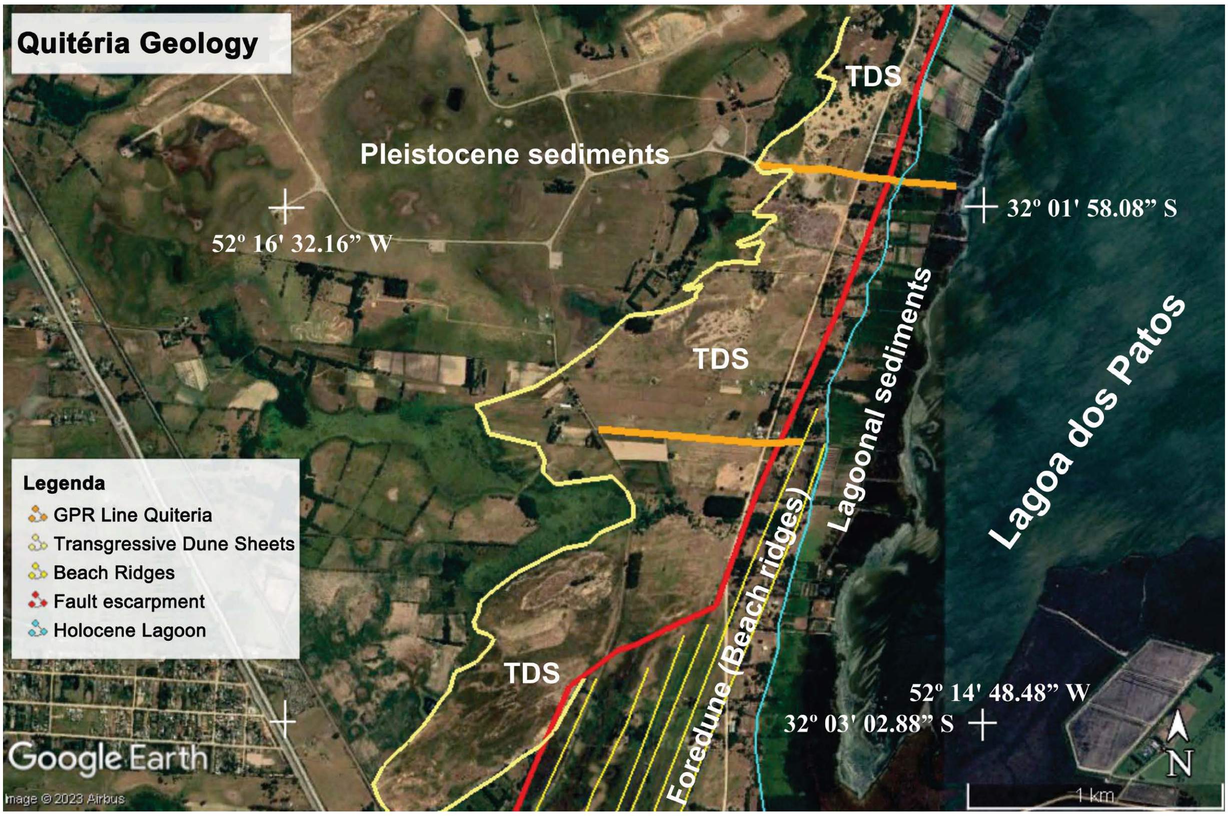

Figure 4. Simplified geologic map of the Quitéria area, showing the location of main GPR line surveys.

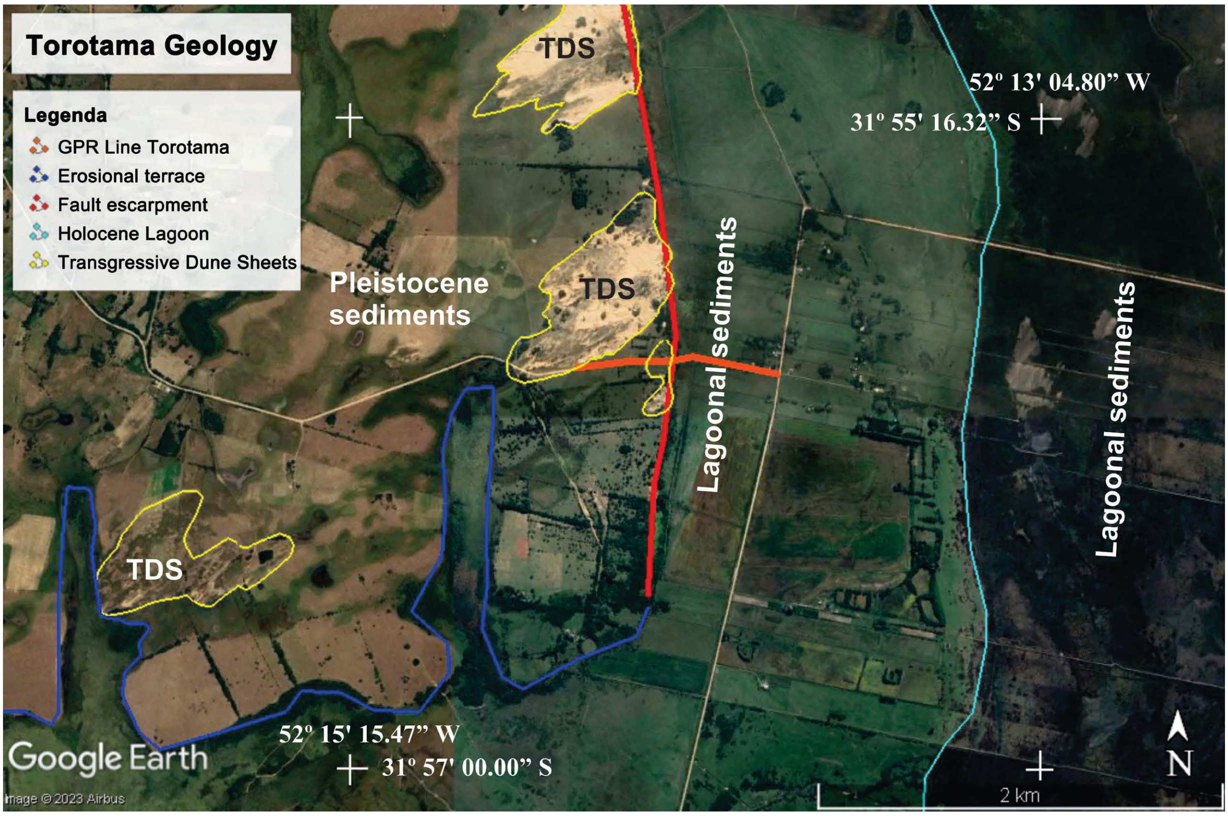

Figure 5. Simplified geologic map of the Torotama area, showing the location of main GPR line surveys.

beach deposits also belong to this category"; and strandplain as: "*Prograded beach ridge plain composed of locally truncated sets of broadly shore-parallel intertidal sand or gravel ridges, usually capped by dunes. Forms the surface in regressive barrier islands, barrier spits, and mainland barriers*".

Alluvial fans are distinguished at the base of the Quinta escarpment, related to incised drainage cutting across that scarp (**Figure 3**). They are composed by sandy material eroded from the structural high and deposited upon the beach ridges, since they interrupt the ridges in plan view. These features were reported by [3] [7].

The dunefield barrier is well developed in the shore zone, where a belt of climbing transgressive dunes (TD) overlay the beach ridges. Landward, the transgressive dune sheets (TDS) predominate, and TD are sometimes isolated and lower than those present in shore zone. It is interesting to note that thicker TDS are developed just west of the trace-line separating beach ridges sets (**Figure 3**). It is also interesting to observe that TDS bypass Quinta escarpment and give rise a narrow belt of TDS and some groups of TD. In both cases, TDS is seeing to migrate upslope.

The actual Lagoonal sediments in the northern segment of the area are deposited by Lagoa dos Patos. **Figure 4** shows the Lagoonal sediments truncating the beach ridges. Southward, in the Taim National Park, TD and TDS sediments cover their lagoonal deposits.

4. Geophysical Surveys: Fault Geometry and Radarfacies

The radarfacies discrimination followed Neal [17] proposal and Fontoura [14] proposal for radarfacies boundary reflectors truncation geometries due to faults. The description of the identified radar surface boundaries (s) and radarfacies (f) follows the chronologic sequence proposed by [17] [18]. **Table 2** summarizes the radar surface boundaries and radarfacies distinguished in the Quinta-Cassino area.

Figures 6-8 present radargrams for GPR lines which location is shown in **Figures 3-5**, respectively. **Figure 6(A)** shows that lateral (**QC-f$_{n+4}$-td**: 4a) and frontal (**QC-f$_{n+4}$-td**: 4b) radar signature for TD overlay a structural high (a horst) made off Pleistocene sediments (**QC-f$_{n+1}$-ps**) radarfacies. **Figure 6** reveals upward concave boundary surfaces (**LP-s$_{n+1}$-lf**) that flatten in dip direction, which characterize a listric normal fault. They truncate lateral upper radarfacies, as also the lateral Pleistocene radarfacies. In the eastern end of the radargrams (**Figure 6(A)**, **Figure 6(B)**), Pleistocene radarfacies are unconformable overlayed by beach ridges radarfacies (**QC-f$_{n+2}$-br**).

The beach ridges radarfacies (**QC-f$_{n+2}$-br**) shows parallel eastward gently dipping reflectors onlapping the listric fault (**LP-s$_{n+1}$-lf**). It can be distinguished as a stack of different beach ridges subunits, which display downlap and toplap relationships with lower and upper geophysical units, respectively (**Figure 6(B)**). The western limit of beach ridges subunits may show arched reflectors (like an anticlinal), which are regarded to relict berm feature.

Table 2. Summary of radar surface boundaries (s) and radarfacies (f) distinguished for GPR survey lines in the Quinta-Cassino area and their interpretation (RS, Brazil).

Stage	Facies ID	DESCRIPTION	INTEPRETATION
-1	**QC-f_{n-1}-pf**	Radarfacies underlying the upper Pleistocene sediments, displays regular reflections which are truncated (*toplap-offlap*) in its upper boundary	Pre-fault radarfacies undergone hanging-wall collapse and erosion
1	**QC-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 of fault escarpment (Barrier III). It also undergone hanging-wall collapse and erosion
	QC-s_{n+2}-et	*Offlap-toplap* for reflectors of the underlying lower Pleistocene sediments	An erosional surface developed on the top of footwall block and on down-throwing hangingwall
	QC-s_{n+1}-lf	Upward concave listric geometry surface that truncate Pleistocene sediments (west) and beach ridges radarfacies (east)	Listric normal fault. See also associated branching normal faults.
2	**QC-f_{n+2}-br**	Eastward gently dipping reflectors, some upper western arched crests, displaying *onlap* against normal faults and its subunits, and downlap on Pleistocene basement	Beach ridges stacks with different crest preservation degree
	QC-s_{n+3}-tl	Surface at the top of the beach ridges radarfacies, showing toplap for underlying reflectors	Irregular surface that is the unconformity overlying beach ridges radarfacies
3	**QC-f_{n+3}-af**	Horizontal and irregular reflectors in the hanging-wall close to listric surface	Alluvial fans: local sedimentary accumulation of sand due to drainage erosion from the structural high (fault footwall)
	QC-s_{n+4}-dl	Discrete *onlap-downlap* features upon previous radarfacies on Quinta escarpment, or horizontal irregular reflectors far from escarpment	Surface defining the unconformity between overlying TD and TDS and the underlying beach ridges radarfacies
4	**QC-f_{n+4}-tds**	Horizontal and steeply dipping sigmoidal reflections, as also as thin horizontal reflection near the topographic surface	Transgressive dunes (TD) and thin dune sheets (TDS) overlying previous sedimentary radarfacies: 6a—steeply dipping reflections: lateral limbs of recent dunes; 6b—horizontal reflections: frontal dune strata, and thin wind covers
	QC-s_{n+5}-tl	Surface at the top of the beach ridges radarfacies, showing toplap for underlying reflectors	Unconformable irregular surface that limits the underlying beach ridges radarfacies
5	**QC-f_{n+5}-lag**	Horizontal well defined reflectors far from fault escarpment, showing discrete toplap for underlying radarfacies	Lagoonal sediments close to Lagoa dos Patos, showing some interfingering with aeolian TDS sediments
	QC-s_{n+n}-df	Minor truncation of inner reflections of radarfacies	Minor listric normal faults merging into master one, or diachronic synthetic and antithetic normal faults

Types of radarfacies (f)

ps = Pleistocene sediments
pf = pre-fault units underlying the Pleistocene
br = beach ridges
af = alluvial fans
lag = lagoonal sediments
tds = transgressive dunes and dune sheets

Types of boundary surfaces (s)

lf = listric normal fault
et = erosional truncation
ol = onlap
dl = downlap
tl = toplap
df = diachronic normal faults

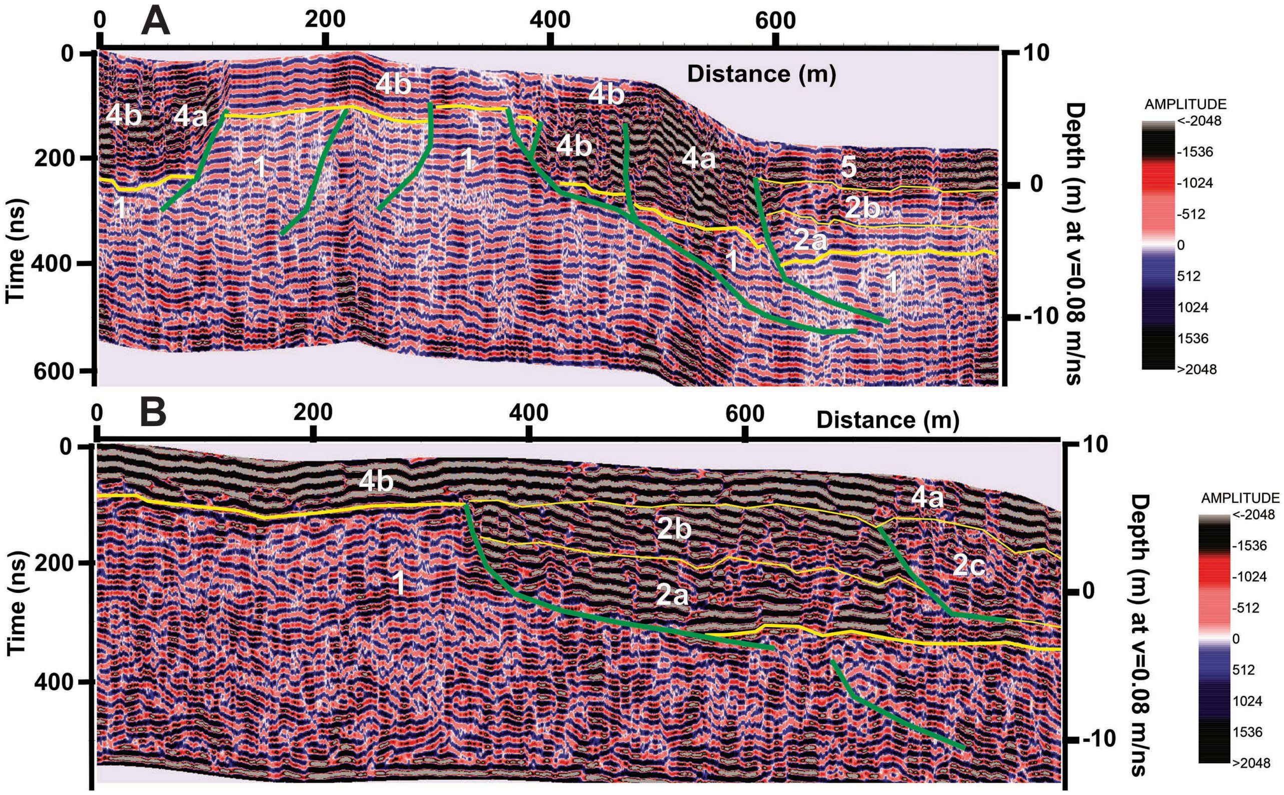

Figure 6. Radargrams for GPR survey lines in the Quitéria subarea (Quinta escarpment, Rio Grande Brazil). (A) Quiteria 1 GPR line in the north (Line 1). (B) Quiteria 2 GPR line in the south (Line 2). Radarfacies ID as in Tabel 2. Green lines: normal listric faults. Thick yellow lines: Pleistocene-Holocene boundary surface. Thin yellow lines: Holocene radarfacies surfaces. The x-axis is on top of each figure and represents the total distance of GPR line (meters). The y-axis is shown in two-way traveltime (ns, on left) and the orthometric height (meters) according the coupled post-processed geopositioning survey.

The beach ridges radarfacies are unconformable overlayed by alluvial fan radarfacies (**QC-f$_{n+3}$-af**: Figure 7) and by lagoonal deposits radarfacies (**QC-f$_{n+5}$-lag**: Figure 6, Figure 8) close to Lagoa dos Patos. The reflectors of this both upper radarfacies seem to be conformable overlaying beach ridges mainly far from the fault scarp, but this appears to result from resolution of the low frequency antenna. In fact, Figure 3 and Figure 4 clearly show that these upper radarfacies are unconformable overlaying beach ridges.

The alluvial fan radarfacies (**QC-f$_{n+3}$-af**) is a thin sand sheet (1 - 2 m) due to Pleistocene footwall block erosion (Figure 7). But, actually, erosion is also on TDS climbing fault scarp and on footwall block summit. Consequently, it is hard to distinguish between alluvial fan reflectors (**QC-f$_{n+3}$-af**), TDS (**QC-f$_{n+4}$-td**), and lagoonal deposits (**QC-f$_{n+5}$-lag**), at their contact zone using 50 MHz GPR antenna (Figures 6-8). Interfingering is observed in thick deposits at fault scarp base.

Figures 6-8 show an upward inclination for Pleistocene reflectors (like a drag fold) or its gentle anticlockwise rotation in the hanging-wall blocks. These features suggest varying fault displacement rates and amount of displacement, block to block.

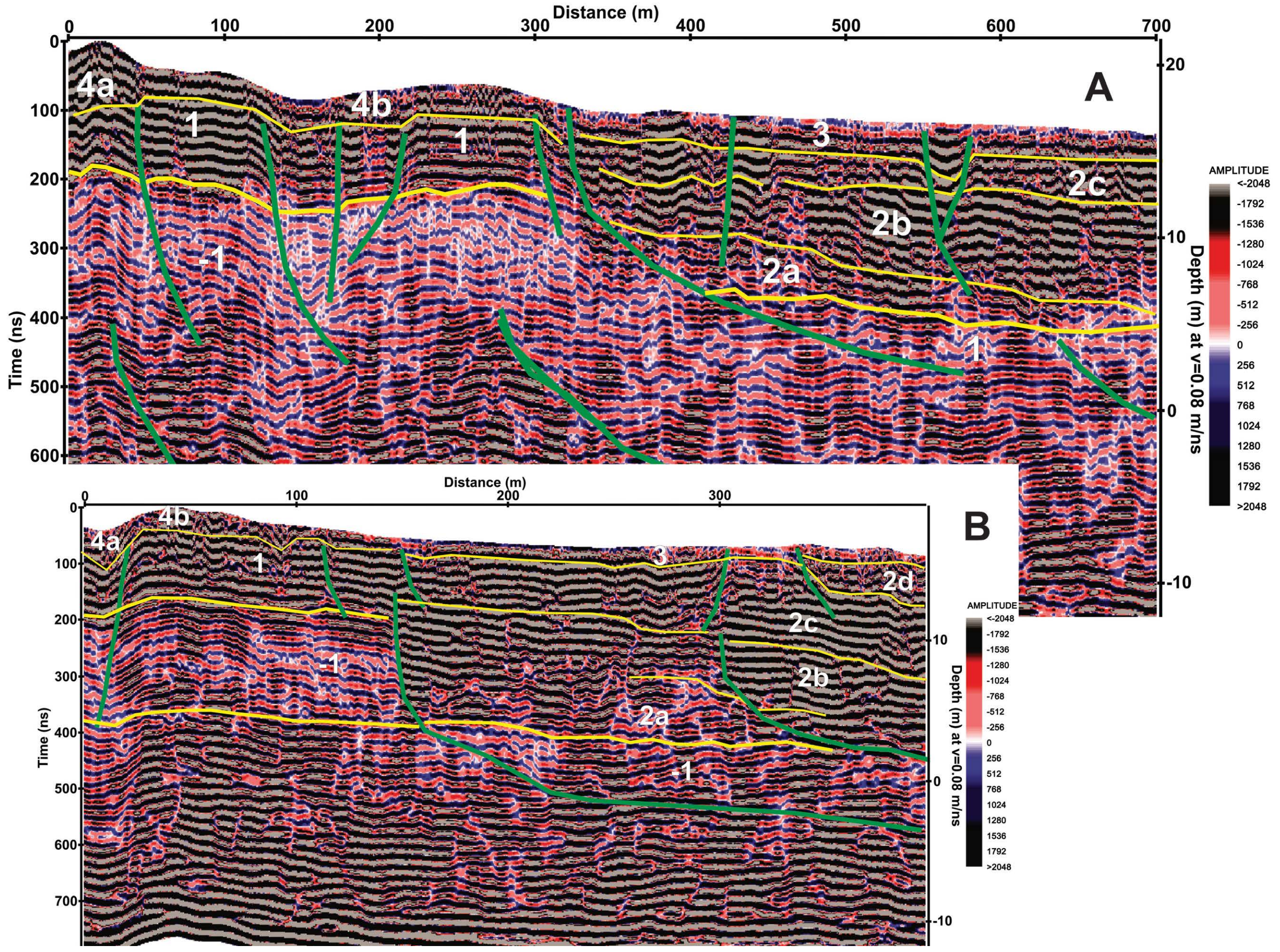

Figure 7. Radargrams for GPR survey lines in the Quinta subarea (Quinta escarpment, Rio Grande Brazil). (A) Quinta 40 GPR line in the north. (B) Quinta 43 GPR line in the south. Legend as in **Figure 6**.

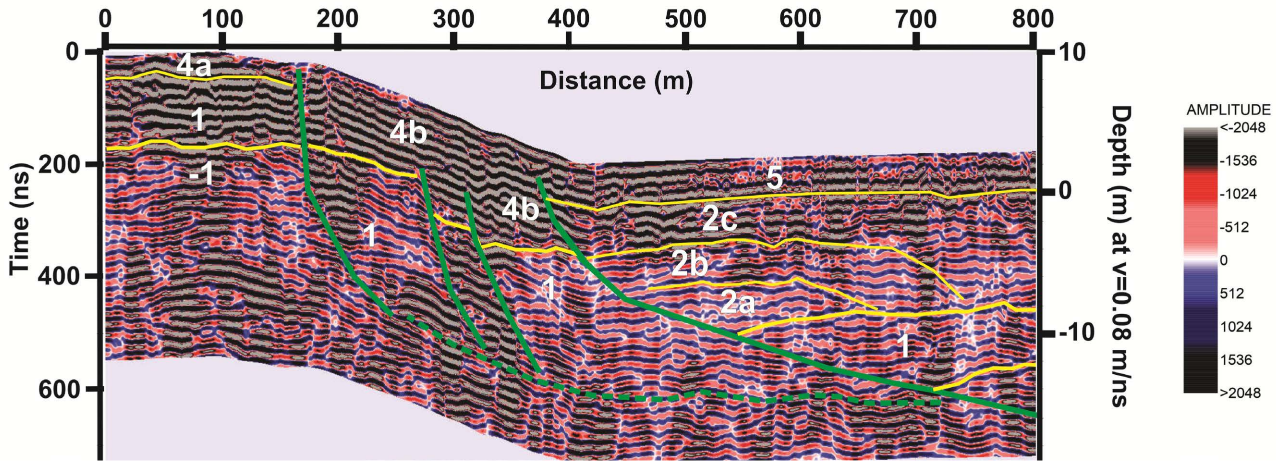

Figure 8. Radargrams for GPR survey lines in the Torotama subarea (Quinta escarpment, Rio Grande Brazil). Legend as in **Figure 6**.

A second group of GPR lines was located to investigate the trace separating beach ridges 1, 2 and 3, since they merge toward the south (see **Figure 3**). **Figure 9** and **Figure 10** show the stacking subunits of gently dipping foreshore reflectors

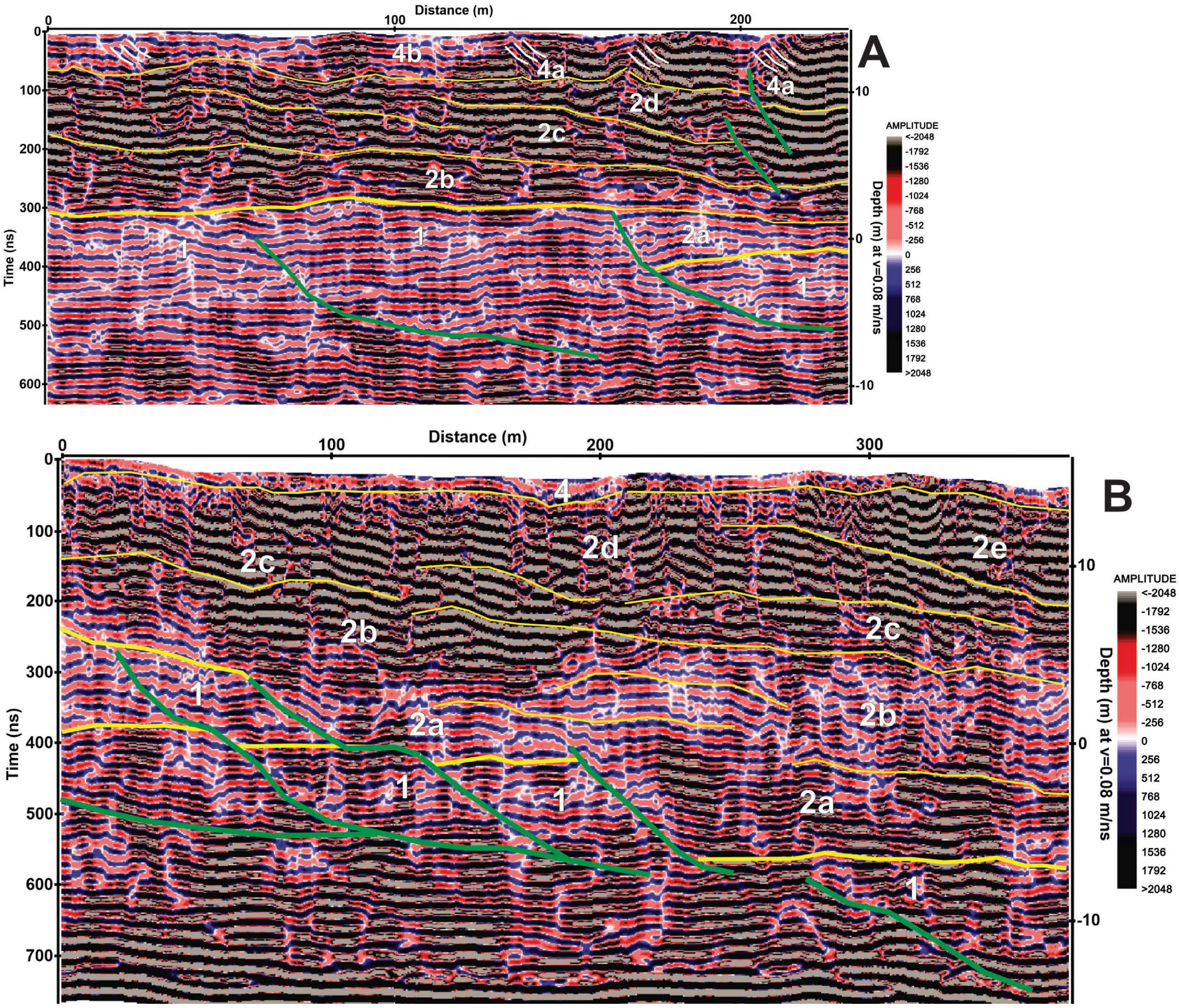

Figure 9. Radargrams for GPR survey lines in the Quinta subarea (limit between BR1 and BR2, Rio Grande Brazil). (A) Quinta 21 GPR line in the north. (B) Quinta 26 GPR line in the south. Legend as in **Figure 6**.

of the beach ridges radarfacies (**QC-f$_{n+2}$-br**). The beach ridges radarfacies subunits can be distinguished by onlap features at their base. In some cases, the upper arched berm reflectors can be observed to climb the lower subunit, which displays a toplap feature suggesting erosion (**Figure 11**). This upper arched berm reflectors is similar to well preserved beach ridges GPR signature presented by Vespremeanu-Stroe *et al.* [19].

The main normal fault influence is observed in the displacement of Pleistocene sedimentary unit, the basement for beach ridges sediments deposition. The hanging-wall of the lowermost beach ridges radarfacies (**QC-f$_{n+2}$-br**) subunit is thicker and correlates with a greater number of beach ridges subunits.

Figure 11 (GPR Line 54) is located well to the south of the merging traces for BR1, BR2 and BR3 sets. It shows a horst structure similar to that shown in **Figure 6(A)** (Quiteria 1 GPR line). The downlap feature at the base of the beach ridges radarfacies (**QC-f$_{n+2}$-br**) indicates its limit with Pleistocene basement.

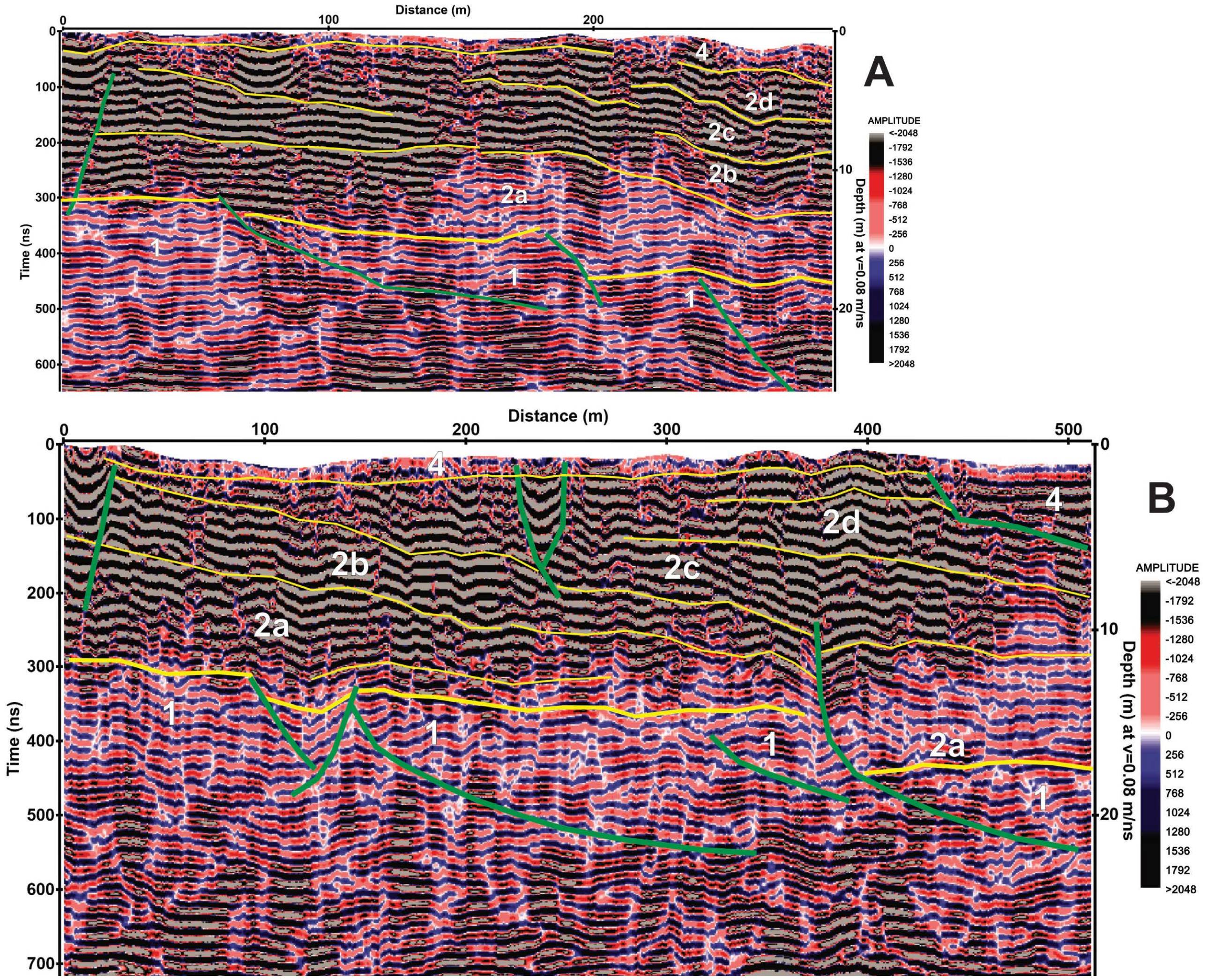

Figure 10. Radargrams for GPR survey lines in the Quinta subarea (limit between BR1, BR2 and BR2, Rio Grande Brazil). (A) Quinta 21 GPR line in the north. (B) Quinta 26 GPR line in the south. Legend as in **Figure 6**.

5. Discussion on Evolution of the Quinta-Cassino Strandplain

The Quinta erosional cliff [2] [7] is here shown to be a normal fault escarpment: the Quinta Listric Fault. It should have begun its displacement ~7.5 ka, considering the deepest and oldest ^{14}C ages in the Holocene interval [8]. The upper beach ridges estimated age (~6.0 ka: [3] [7]) is in accordance with ^{14}C age in the Holocene interval [8] in sediments close to fault escarpment.

The Quinta Listric Fault is part of the gravitational tectonic supported by Pelotas Basin since Upper Miocene [20]. Santos [20] showed that Pelotas Basin gravitational tectonics started in the continental slope, and upper normal fault branches propagate westward into the platform.

The radargrams presented above show that Quinta Listric Fault is a branching normal fault, displaying synthetic and antithetic faults. The horst structures and the Pleistocene basement rotation in the hanging-wall block were also observed. These indicate that space problem for displacing hanging-wall was accommodated

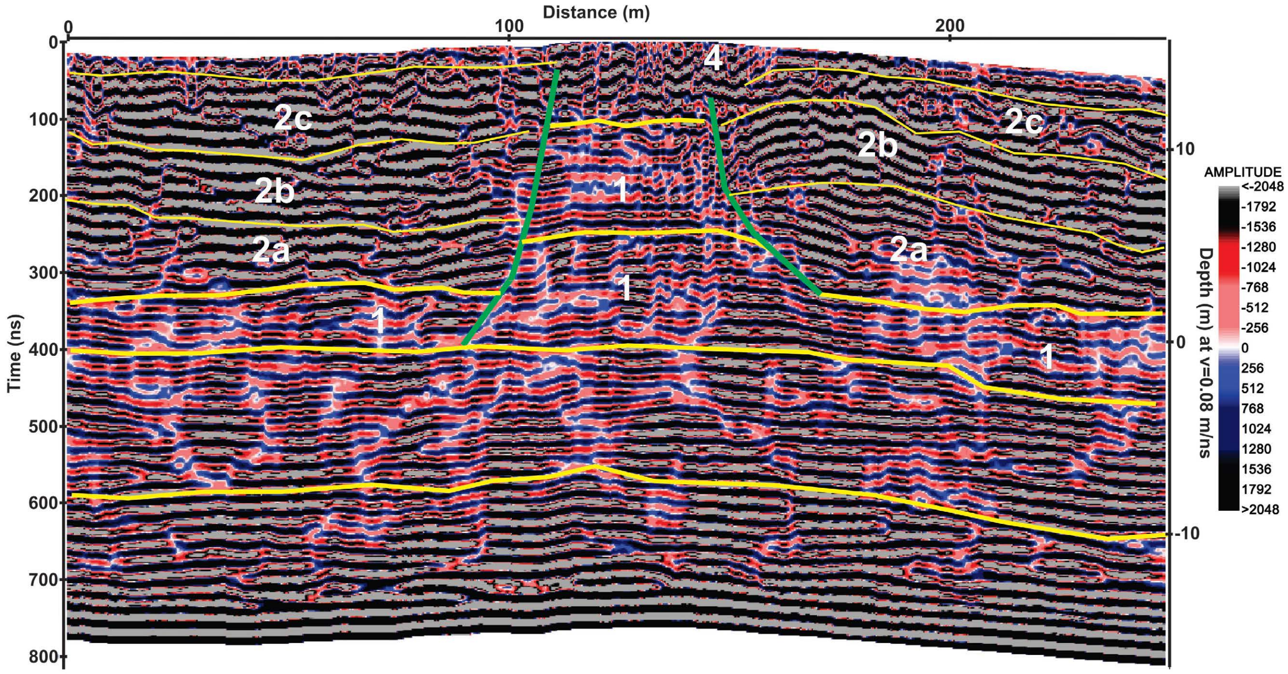

Figure 11. Radargrams for GPR survey lines in the Quinta subarea (GPR Line 54: limit between BR1 and BR3, Rio Grande Brazil). Legend as in **Figure 6**.

through an imbricate fan of faults and lead to the development of horst and grabens in the mechanically subsiding area.

The superficial OSL ages agree with the beach ridges progradation. Milana *et al.* [3] sampled the exposed edge of the beach ridges (except for RG2). Dillenburg *et al.* [8], on the other hand, sampled the edges of the TDS. Despite the difference in sampled sedimentary units, and the fact that TDS covers beach ridges, the OSL ages consistently decrease seaward. Additionally, it is to observe that these seaward younging TDS are mostly aligned upon the trace lines dividing beach ridges sets (see figures 3 and 4; Figure 2 of [3]; Figure 9 of [8]).

These results indicate that each trace line separating beach ridges sets is a branching listric normal fault, and TDS are mainly developed in the footwall block. From Quinta main fault scarp seaward, each successive beach ridges set is the footwall for the next one. Despite the branching normal fault in the strandplain do not show the same topographic amplitude as Quinta fault escarpment, they are enough for sand blowing from beach to be deposited in the low relief scarps and on the footwall summit.

These results also account for beach ridges truncation along trace line separating sets in the north segment and in the southern segment. Gravity-driven listric normal faults are concave in section and plan view (see **Figure 2** to view ridge set limits geometry). Gravity-driven listric normal faults produce blocks with distinctive displacements (and rates) and tilting, despite the overall movement in their extensional sector [21] [22].

The alternating ridge truncation at trace line separating each ridges set, despite some erosion can be claimed to occur, can be a major result of different displacement rates and amounts for the evolving branching faults. In such a gravity tectonic scenario, ridge truncation cannot be attributed completely to coastal erosion as initially suggested by [7] and well detailed by [3]. The detailed mapping and numbering of beach ridges presented by Milana *et al.* [3] and their truncation give support to interpret the fault branching sequence: the older (master) fault is the Quinta Listric Fault, and the younger one is close to the shore.

It is to be observed that these branching listric normal faults represent the extensional zone of a large-scale gravity-driven structure. Its compressional zone structures counterpart should be developed in the upper Atlantic Continental Shelf. Some of these features were reported by Santos [20], but in the Atlantic Continental slope.

The gravity-driven listric fault system controlling Quinta-Cassino strandplain puts questions in the classical barrier model for the area [23]. First, the barrier model assumed that no tectonic deformation and no mechanical subsidence are present in the RGSCP [9]. Second, the Quinta major listric Fault should had produced enough mechanical hangingwall subsidence to enable southward discharge of the Lagoa dos Patos. These both tectonic aspects can lead to an asymmetric delta to be build up as Quinta-Cassino strandplain [3]. In this way, the half-fan geometry of the beach ridges can be divided into two: 1) that inflected landward (set 1, close to Quinta Listric Fault), and 2) those inflected oceanward (sets 2 to 8). The first set (F1), then, "*shows a concavity towards the mainland, testimony to a relatively low depositional energy due to the wide opening of the estuary*" [2]. The following beach ridges sets, "*each one characterized by a degree of concavity of the different ridges…oriented towards the ocean, show that they were formed under the influence of the outflow of lagoon waters in a high-energy environment*" [2].

6. Conclusions

The Quinta-Cassino strandplain was developed under the influence of an imbricated fan of gravitational listric fault, whose Pleistocene basement was cut by synthetic and antithetic faults. The faulted blocks display different rates and amounts of displacement and rotation. The tectonic subsidence of the Quinta-Cassino area led to the development of an asymmetric delta mainly under the influence of high-energy outflow of lagoon waters (Lagoa dos Patos).

Gravity tectonics, rather than sea level or climate changes, or longshore currents, is the major controlling mechanism for sedimentation and stratigraphic evolution of the Quinta-Cassino strandplain. This tectonic process does not suppress the operation of other important mechanism, such as: sea level and climate changes, longshore currents, erosion and deposition rates, sediment influx rates. But it controls them. For example: mechanical subsidence overcomes sea level changes; longshore current changes must be evaluated regarded to the differential fault blocks movements.

The Quinta Fault scarp represents the first tectonic barrier for beach ridges development as a closely attached geomorphic feature. The subsequent branching faults also show that beach ridges are closely attached to less expressive fault scarps. These aspects do not suppress, once more, the existence of minor fault-controlled lagoons. However, they were clogged earlier in the development of the Quinta-Cassino strandplain.

This new investigation approach is under development in other areas to evaluate the extent the gravitational tectonic took in the RGS coastal plain. It is clear that more geophysical survey is needed to have a complete scenario for the gravitational tectonic influencing the Holocene sedimentary and stratigraphic features of the RGSCP.

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Conflicts of Interest

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

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