https://rbgeomorfologia.org.br/rbg
*ISSN 2236-5664*

**Revista Brasileira de Geomorfologia**

v. 23, n. 4 (2022)

http://dx.doi.org/10.20502/rbg.v23i4.2206

*Research Article*

# Alluvial plain morphostratigraphy affected by recent mud and debris flows: a study in the Jacareí River basin (southern coast of Brazil)

## *Morfoestratigrafia de planície aluvial soterrada por corridas de lama e detritos recentes: estudo a partir da bacia do rio Jacareí - Paraná*

**Otacílio Lopes de Souza da Paz [1], Eduardo Vedor de Paula [2]**

[1] Federal University of Paraná, Department of Geography, Curitiba, Brazil. otacilio.paz@gmail.com
ORCID: https://orcid.org/0000-0002-1273-2562
[2] Federal University of Paraná, Department of Geography, Curitiba, Brazil. edugeo@ufpr.br
ORCID: https://orcid.org/0000-0002-1847-0161

Received: 10/03/2022; accepted: 20/08/2022; published: 01/10/2022

**Abstract:** Sedimentary records are important to understand the evolution of river systems. Morphostratigraphic studies associate sedimentary records with landforms. Mud and debris flows, common in the Serra do Mar mountain range, have a marked impact on the morphostratigraphy of adjacent alluvial plains. The objective of this study was to analyze morphostratigraphic units in an alluvial plain affected by recent mud and debris flows. The study area was the Jacareí River alluvial plain (coast of Paraná State, Brazil) which was hit by extreme gravitational events in March 2011. Geospatial and field survey data were analyzed in a GIS environment to produce a morphostratigraphic map. Units were identified in three contexts: formed earlier than 2011, formed by the 2011 mud and debris flows, and formed after 2011. The deposits instantly formed in 2011 present rocks and pebbles (debris flows) and massive sandy facies (mud flows), with a thickness of between 0.5 and 1 meter. They are easily identified due to abrupt changes in particle size, color, presence of roots, and quantity of organic matter. The results shed light on the evolutionary processes at work in the Jacareí River coastal plain landscape, with the 2011 event representing a phase of the sedimentary cycle of alluvial plains along the Serra do Mar mountain range.

**Keywords:** Mass movements; Flash Deposit; Morphosedimentary; Serra do Mar mountain range; Landscape evolution.

**Resumo:** Registros sedimentares são importantes para a compreensão da evolução de sistemas fluviais. Estudos morfoestratigráficos associam registros sedimentares às formas superficiais. Corridas de lama e detritos, comuns na Serra do Mar, certamente afetam a morfoestratigrafia de planícies aluviais adjacentes. Objetivou-se analisar as unidades morfoestratigráficas em planície aluvial afetada por corridas de lama e detritos recentes. A área de estudo foi a planície aluvial do rio Jacareí (litoral do Paraná), atingida em março de 2011 por eventos gravitacionais extremos. Dados geoespaciais e campanhas de campo foram analisados em ambiente SIG, resultando no mapeamento morfoestratigráfico. Foram identificadas unidades em três contextos: formadas anteriormente a 2011, formadas pelas corridas de lama e de detritos de 2011 e formadas após 2011. Os depósitos instantaneamente formados em 2011 apresentam blocos e seixos (corridas de detritos) e fácies arenosas maciças (corridas de lama), com espessura entre 0,5 e 1 metro, sendo facilmente identificados pela mudança abrupta de granulometria, cor, raízes e teor de matéria orgânica. Os resultados levaram a reflexões sobre o processo evolutivo da paisagem da planície aluvial do rio Jacareí, podendo o evento de 2011 se tratar de uma fase do ciclo sedimentar de planícies fluviais às margens da Serra do Mar.

**Palavras-chave:** Movimentos de massa; Depósitos instantâneos; Morfossedimentar; Serra do Mar; Evolução de paisagem.

## 1. Introduction

Sedimentary records contain information that inform studies on the evolution of fluvial systems (BRIDGE, 2009). Sequences of sedimentary facies with specific characteristics, in terms of granulometry, color, structures, etc., can indicate which processes have occurred in the past (MIALL, 2014, 2016b). In the study of sediments, the term facies is understood as a homogeneous unit in a sedimentary deposit, identified from criteria such as color, granulometry, structure, and geometry, among others (MIALL, 2016a; MAGALHÃES JÚNIOR; BARROS, 2020c). Facies or an association of facies can be related to specific forms of fluvial relief (FRYIRS; BRIERLEY, 2013b; MIALL, 2016a), and the correlation between fluvial landforms and stratigraphic characteristics results in the term morphostratigraphic units (BRIERLEY, 1991; BRIDGLAND; WESTAWAY, 2012).

Facies and their likely interpretation have been widely documented for meandering depositional systems, particularly for temperate regions (MIALL, 2016b; THAYER; ASHMORE, 2016; BURNS et al., 2017). In tropical environments, the occurrence of processes that effectively remove sedimentary deposits make it difficult to conduct morphostratigraphic studies (MAGALHÃES JÚNIOR; BARROS, 2020c). Nevertheless, in Brazil, morphostratigraphic features are commonly found in recent deposits in alluvial plains, particularly in areas of flat relief (SANTOS et al., 2008; BAYER; ZANCOPÉ, 2014; MORAIS et al., 2020).

In coastal alluvial plains that border the Serra do Mar mountain range, morphostratigraphic features are scarce, with examples only identified in the mountainous region of Rio de Janeiro (MARÇAL et al., 2015). Extreme mass movement events, such as mud and debris flows, are common on the slopes of the Serra do Mar and certainly influence the landforms and sedimentary facies in the downstream alluvial plains. The identification and characterization of morphostratigraphic units in environments where these processes (gravitational and fluvial) interact has been poorly explored in the national literature.

An example of an alluvial plain with these characteristics can be found in the Jacareí River basin (JRB), located between the municipalities of Morretes and Paranaguá, Paraná State, Southern Brazil. On March 11, 2011, after a accumulated rainfall of 236.8 mm in 24 hours, several landslides occurred on the slopes of the JRB, generating mud and debris flows that covered extensive areas in the alluvial plain (PINTO; PASSOS; CANEPARO, 2012; ZAPATA; SIMIANO; PINHEIRO, 2016).

Part of the Jacareí River alluvial plain was buried during the event, and the previously meandering river was changed to anastomosing, similar to reports in the literature for other locations along the southern Brazilian coast that experienced comparable events (BIGARELLA, 2003). Thus, considering the gaps in the literature and using the JRB as a study area, the aim was to analyze the morphostratigraphic units in an alluvial plain affected by recent mud and debris flows.

## 2. Study area

The JRB is located on the central coast of Paraná State, Brazil (Figure 1). The source of the Jacareí River is in the western slopes of the Serra da Prata mountain range, and its mouth is at the Bay of Antonina, part of the Complete Paranaguá Estuary. The Serra da Prata has a maximum elevation of 1421 m and is part of the Serra do Mar mountain range in Paraná, which originated from differential erosion processes (ANGULO, 2004). The community (or district) Floresta is located on the alluvial plain and is part of the municipality of Morretes. Access to the area is via highway BR 277. The area chosen for the study begins at 30 meters above sea level and ends at the landfill associated with highway BR 277, as it was the section most affected by the event in March 2011 (Figure 2). The study area (alluvial plain) was divided into three sections to assist in the presentation and discussion of the results (Figure 1).

The Serra da Prata represents the south to east margins of the Jacareí River basin (JRB) and is formed by granite-gneissic-migmatitic rock associated with the Cachoeira complex, with elevations ranging from 800 to 1,502 m (MINEROPAR, 2011). The eastern margin is a nucleus of low mountains composed of undifferentiated metamorphic rock from the Rio das Cobras formation, with elevations ranging from 200 to 433 meters (MINEROPAR, 2011). Quaternary sedimentary deposits of colluvium and alluvial fans are found in the middle to lower third of the slopes (ANGULO, 2004; MINEROPAR, 2011). In the section from the plain to highway BR 277, terrigenous sediments predominate; beyond the highway a mosaic of fluvial, marine, paludal and paleo-estuarine deposits can be found (ANGULO, 2004).

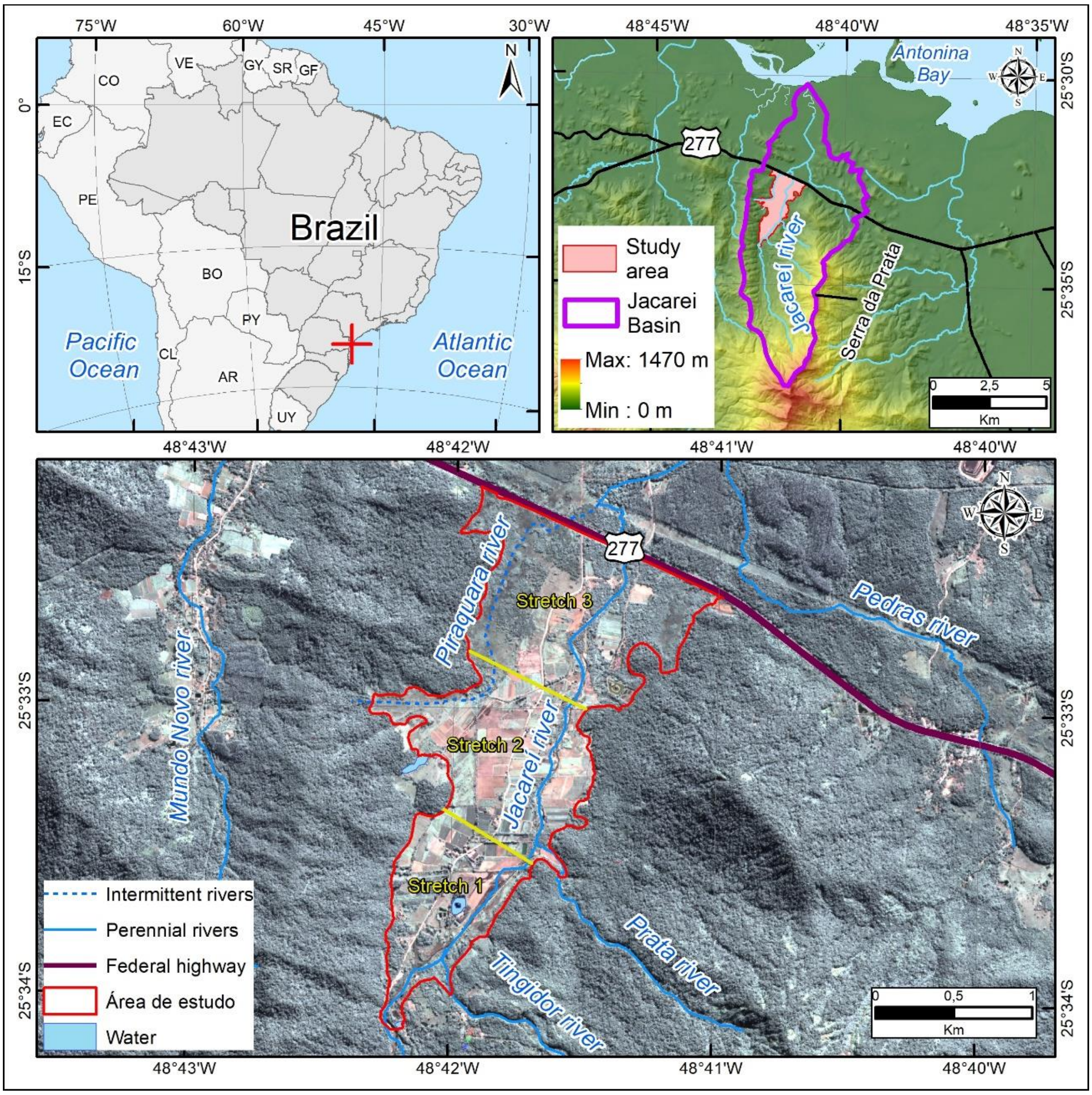



**Figure 1.** Location of the studied section of the Jacareí River alluvial plain.

**Figure 2.** Section of the Jacareí River alluvial plain buried in March 2011. Source: Machado (2011).

## 3. Materials and methods

Geospatial vector data for contour levels (5 m equidistance) and the hydrographic network were collected from the planimetric base map published by the Water and Earth Institute of Paraná (*Instituto de Água e Terra do Paraná*; IAT), code 227307175 at a scale of 1:10,000. A digital terrain model (DTM) with 2.5-m resolution was also acquired from IAT, generated from a 2015 survey using interferometric synthetic-aperture radar (SAR). From this DTM, the slope was extracted using the slope tool in ArcGIS, calculated based on Horn's directional variables (HORN, 1981), and relief was shaded using the Hillshade tool also in ArcGIS, calculated with an azimuth of 315º and altitude of 45º.

A panchromatic orbital image registered by the Worldview-1 satellite on 05/02/2011 with a spatial resolution of 0.5 m was made available by the Paranaguá Environment Secretariat, via institutional requisition. An image was also taken on 06/06/2019 with a Phantom 4 standard model remotely piloted aircraft (RPA), generating an orthomosaic with a 20 cm spatial resolution. All cited geospatial data were organized in a geospatial database (GDB) (PAZ; DAL PAI; PAULA, 2020).

In general, the mapping of morphostratigraphic units consists of the correlation between fluvial landforms and stratigraphic characterization. Initially, river forms were mapped based on photointerpretation from the orbital and suborbital images, with the aid of the planimetric base map, remote sensing techniques, and field survey between 2019 and 2020. The proposed taxonomy of fluvial landforms by Wheaton et al. (2015) was adopted, with modifications.

The first step was the definition of the section to be studied (alluvial plain), considering the following morphometric criteria: a maximum elevation of 30 m and a mean slope of up to five degrees. The first taxonomic level described by Wheaton et al. (2015) refers to the evolutionary stage of the fluvial landform, divided into riverbed, floodplain, terrace, and fan. The riverbed was identified from the vectorization of the river channel and active river bars, based on the 2019 orthomosaic. Fans were identified by photointerpretation of the 2011 image, considering shape (conic) and position (outlet of channels in the plain), and field survey. Terraces were identified with the help of DTM and longitudinal profiles distributed lengthwise (every 10 m) in the study section, considering a 10-m interval, visually verifying acute drops in level greater than two meters (value chosen based on field observations) in relation to the channel height. The points identified digitally were validated in the field and incorporated into the mapping. The remaining area was interpreted as a floodplain.

After the first step, specific fluvial forms were identified in all level 1 units by photointerpretation, with the exception of terraces. The following criteria were used: shape, position, presence of surface water, surface material, extent of the flooding event, and transformations to the landscape. Surface material was used as a criterion to identify terraces during field analysis. The identified units and criteria used are shown in Table 1.

**Table 1.** Mapping classes of fluvial landforms in the Jacareí River plain.

| Geomorphological unit[1] | | Specific river forms[1] | | Criteria employed |
|---|---|---|---|---|
| COD. | Name | COD. | Name | |
| 1 | Riverbed | 1.1 | River channel | Shape, position, and presence of water, considering the 2019 orthomosaic |
| | | 1.2 | Active river bars | Position and material on the surface, considering the 2019 orthomosaic |
| 2 | Floodplain | 2.1 | Wetland (Backswamp) | Position and wet appearance of vegetation, considering the orthomosaic of 2019 |
| | | 2.2 | Inactive river bar | Position and material on the surface, considering the 2011 image |
| | | 2.3 | Crevasse splay | Shape and position, considering the 2011 image |

| | | | | |
|---|---|---|---|---|
| | | 2.4 | Inactive anastomosing riverbed | Shape, considering the 2011 image |
| | | 2.5 | Distal floodplain | Absence of surface sedimentary material: areas not affected by the 2011 event |
| | | 2.6 | Proximal buried floodplain | Areas with undefined surface material, starting from the 2011 image |
| | | 2.7 | Proximal floodplain | Extreme rainfall events, topography, vegetation, recent sedimentation, and information from residents |
| 3 | Fan | 3.1 | Rock fan | From the 2011 image |
| | | 3.2 | Sand fan | From the 2011 image |
| 4 | Terrace | 4.1 | Fluvial terrace I - sandy cover | Field identification |
| | | 4.2 | Fluvial terrace II - rocks and pebbles | Field identification |

[1] Source: Adapted from Wheaton et al. (2015).

Based on the mapping of river forms, field surveys were carried out to identify and characterize sedimentary facies. The collection points were selected based on access through existing roads and trails. Trenches were opened with the help of field tools and machinery, and core samples were collected with a 6 cm Dutch auger for sandy soil and a 20 cm bucket.

Facies identification was performed using the following criteria: visible changes in color, geometry, texture, structure, and presence of mottling, roots, and trunk fragments (MIALL, 2016a; MAGALHÃES JÚNIOR; BARROS, 2020c). The identification of structures was only possible in the excavated trenches due to the limitations of the coring method used. At the coring sample points, a general identification was made with all facies considered as massive structures. Sedimentary material was collected in the central area of each identified facies for analysis of organic matter levels and granulometric characterization.

The georeferencing of the sample collection points was performed using a Garmin Etrex 10 GNSS, receiving both GPS and GLONASS signals. The depth for sample collection was standardized at 1.2 m (length of the auger), except for in open trenches. The sampling points were distributed through the plain, aiming at a minimum of one sample for each identified fluvial landform. The facies were classified using the Miall coding system (MIALL, 1996; 2016b). In addition to trenches and cores, samples were collected on the surface of active river bars and the bottom load of the Jacareí River, specifically for granulometric characterization.

The samples were dried in an oven at 50º for 72 hours and then divided into two 50-gram parts with the help of a Johnes-type quartering machine. The organic matter content was quantified using the muffle furnace method (SUGUIO, 1973; GOLDIN, 1987) as follows: dried samples were put into ceramic vessels, weighed, and placed in a muffle furnace; samples were then incinerated at a temperature of 600°C for four hours; subsequently, the vessels + residues were weighed. The organic matter content (OM) was determined from the loss of mass by incineration (SUGUIO, 1973; GOLDIN, 1987) according to equation 1 :

$$OM\ (\%) = \frac{W - (T - C)\ \times 100}{W} \tag{1}$$

where $W$ is the weight of the dry sample (g); T the weight of the sample (residue) after incineration (g); and C the tare weight of the ceramic vessel.

Granulometric analysis was performed by mechanical sieving, aiming at identifying the percentage of gravel (> 2 mm), sand (between 2 mm and 0.063 mm), and fine material (< 0.063 mm - silt and clay), based on the Wentworth scale (SUGUIO, 1973). A shaker sieve was used for 10 minutes, followed by weighing with an analytic precision scale (0.001g). The predominant granulometric class was used to define the texture of the facies identified in the field, considering the textural triangle adapted from the Soil Survey Manual.

## 4. Results

The synthesis of morphostratigraphic units identified in the Jacareí River alluvial plain in 2019, as well as the list of associated facies, are presented in Table 2. Twelve morphostratigraphic units were identified, including those formed before, during, and after the extreme mud and debris flows of 2011 (Figure 3). Field survey followed by laboratory analyses allowed for the identification of 10 typologies of stratigraphic facies at 12 sampling points, six of which were core samples and seven trenches.

**Table 2.** Morphostratigraphic units and associated facies in the Jacarei River alluvial plain in 2019.

| Morphostratigraphic unit | Specific river forms | Area (ha) | Area (%) | Identified facies (in sequence) | Sampling point (s) |
|---|---|---|---|---|---|
| Units prior to the 2011 event | Fluvial terrace I | 0.1 | 0.0 | Gcm | TR1 |
| | Fluvial terrace II | 1.3 | 0.4 | Gmm, Sm (r), Sm, St and Gm | TR2 |
| | Distal floodplain | 23.4 | 8.1 | Sm (r), Sm, Fsm (p) and Fsm | TD1 |
| Units formed by the 2011 event | Wetland[1] | 20.1 | 7.0 | - | - |
| | Sand fan[1] | 2.8 | 1.0 | - | - |
| | Rock fan | 3.9 | 1.3 | Gm, Sm (p), Sm and Fsm | TR3 |
| | Inactive river bar | 3.6 | 1.2 | Sm, Sm (r), Fsm (r) and Fsm | TD2 |
| | Inactive anastomosing riverbed | 8.1 | 2.8 | Gm, Sm, Fr and Fsm (p) | TD3 |
| | Crevasse splay | 4.2 | 1.5 | Sm (i), St, Sm (r), Sm and Fsm | TR4 |
| | Buried floodplain | 186.9 | 64.7 | Sm, Sm (r), Fsm, Fsm (p), Fr | TD4, TD5 and TR5 |
| Units formed after the 2011 event | Proximal floodplain | 30.4 | 10.5 | Sm, Fr, and Fsm | TR6 and TD6 |
| | Active riverbed (channel + active river bars)[2] | 4.2 | 1.5 | - | C1, C2, C3 and C4 |

[1] Stratigraphy not described due to difficulties in collecting field data. [2] Description only of the material present on the surface of the landforms.

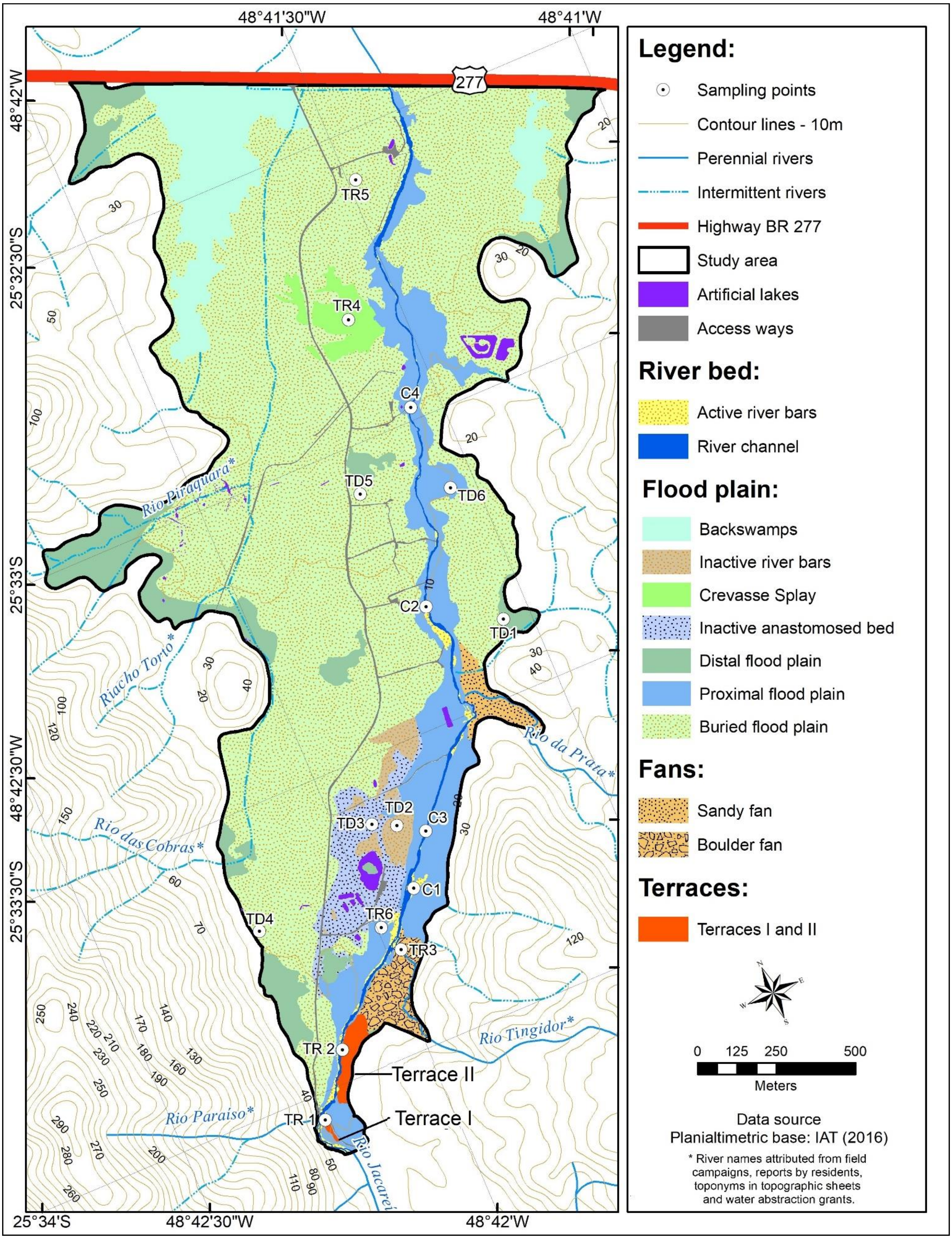



**Figure 3.** Morphostratigraphic units identified in the Jacareí River alluvial plain in 2019.

*4.1. Units prior to the 2011 event*

The units Terrace I and II and the distal floodplain were not affected by the mud and debris flows of 2011. Terraces I and II show drops in elevation in relation to the riverbed of the Jacareí River, marked at 2.2 and 2.7 m, respectively. The distal floodplain unit is located at the beginning of the alluvial plain, close to the foothills of the slopes.

On Terrace I, a Gcm facies was identified, with pebbles between 5 and 7 cm suspended within that were mostly rounded, flattened and imbricated, with a general northeast orientation (Figure 4-A). Terrace II had seven facies (Figure 4-C), five of which have material mostly in the sand fraction, individualized according to the structures found, either massive (Sm) or cross-channeled stratification (St). At the top and bottom of the profile, facies were identified with gravel fractions in massive structure (Gmm).

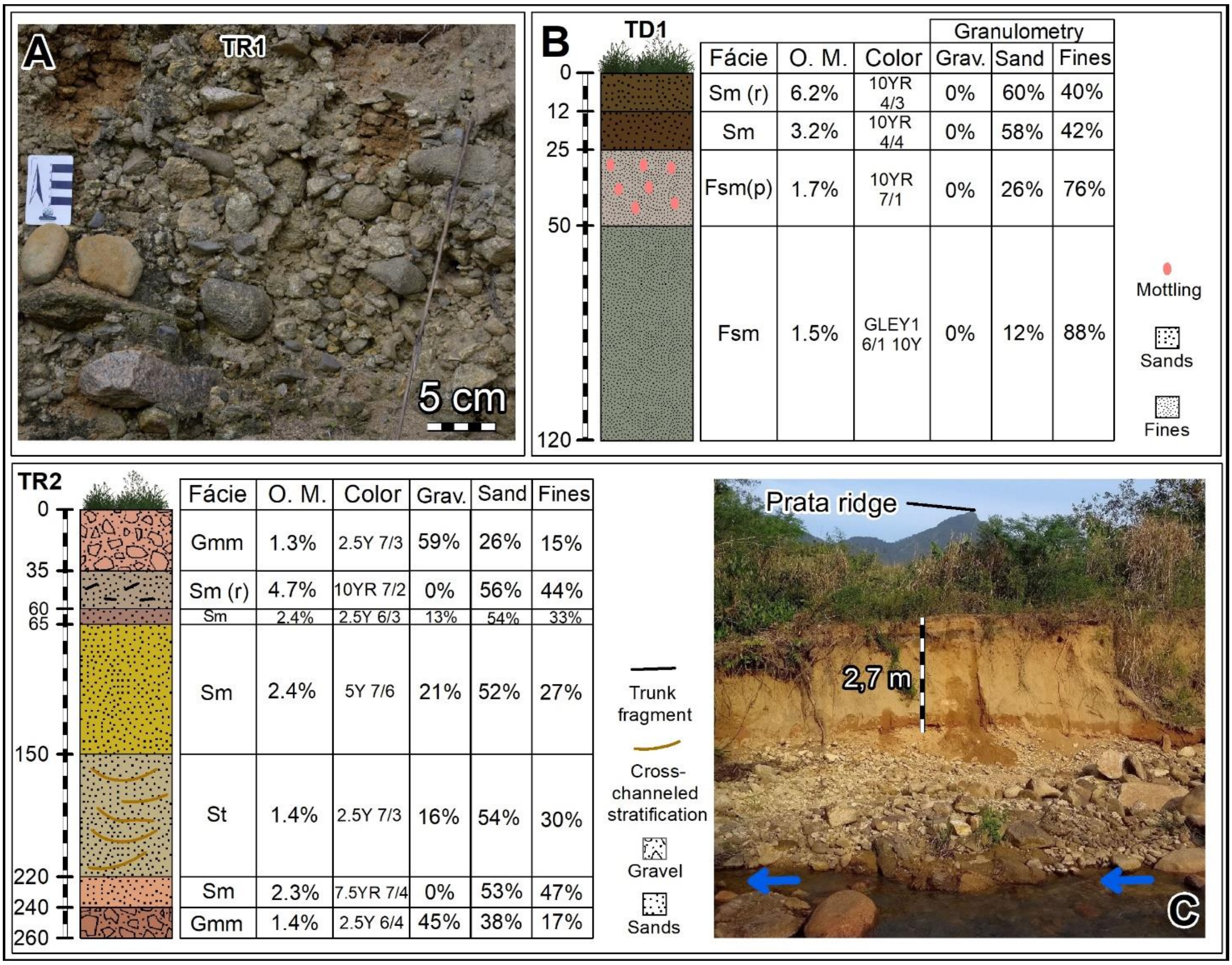



**Figure 4.** Facies found in Terrace I (A – TR1), sedimentary profile of the distal floodplain unit (B – TD1), and sedimentary profile of the Terrace II unit (C – TR2).

At the sampling point of the distal floodplain, four facies were identified (Figure 4-B). The first two facies present a predominance of sandy material in massive structure (Sm), with the first including roots, Sm (r), and the highest level of organic matter content of the profile (6.2%). The third facies has a light gray color (10YR 7/1) and presents a fine granulometry with mottling – Fsm (p). The last facies was greenish gray (GLEY1 6/1 10Y), presenting fine grain size in massive structure (Fsm).

*4.2. Units formed by the 2011 event*

Seven morphostratigraphic units formed by the mud and debris flows of 2011 were identified.
It was not possible to collect samples in the wetland and sand fan units due to inaccessibility. The wetland (or backswamp) unit is composed of two landforms on the banks of the Piraquara and Santana-Jacareí Rivers, both intermittent, and draining into the alluvial plain. As it is a reducing environment, in this unit we expect to find sediments typical of places with the constant presence of water, presenting a grayish color. Also, a sandy layer can be found on the surface resulting from the event in March 2011.

The sand fan unit is composed of a single landform located at the mouth of the Prata River, a permanent tributary on the right bank of the Jacareí River (source in Serra da Prata). From the panchromatic image of 2011 and oblique images captured by RPA in 2020, we can infer the presence of sand to fine materials (silt and clay) in the fractions, which may have some gravel (Figure 5-C). With the RPA in the field, we observed points of fluvial erosion in this landform caused by the Jacareí River, along with removal of material by machines and some collapsing of sandy masses (Figure 5-D).

The rock and boulder fan unit is also a single landform, located at the mouth of the Tingidor River, a right-bank permanent tributary of the Jacareí River. The Tingidor River channel was buried with the formation of this unit in 2011. In the panchromatic image from 2011 we can see that the Tingidor River has carved a new channel, bypassing the fan. We were unable to sample in the center of the landform, given the difficulty of access and its composition predominantly of large rocks and boulders. A trench was identified at the edges of the landform, which was likely excavated during work to reestablish the Tingidor River channel. According to the facies identified and the drop in the profile in relation to the Jacareí River (2.4 m), we can infer that the rock and boulder fan was formed on a pre-existing fluvial terrace.

Five facies were identified in the trench located on the edge of the rock and boulder fan unit (Figure 5-A and B). At the top of the profile, a light red (2.5 YR 7/8) Sm facies (sandy in massive structure) was identified. Next is a facies with gravel supported by the matrix (Gmm), massive structure, and very light grayish brown color (10 YR 7/4). The last three facies of the profile show an abrupt change in color (gray) and texture. Of these, two are sandy facies in massive structure (Sm), with the third presenting mottling, facies Sm (p). The last facies presents fine granulometry in a light gray-blue massive structure (GLEY 2 7/5 BP).

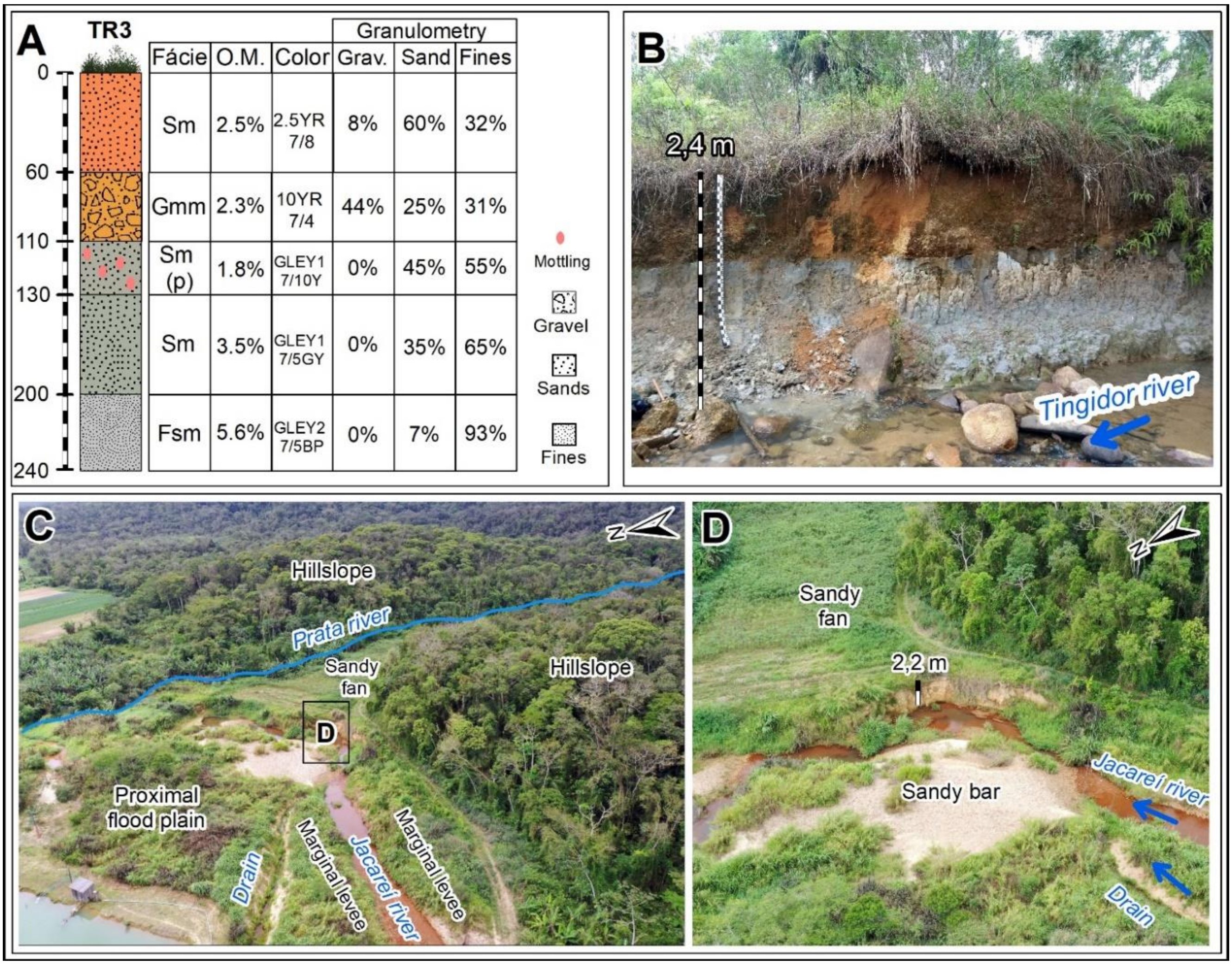



**Figure 5.** (A) Sedimentary profile in the rock fan unit – TR3. (B) View of TR3. (C) Aerial view of the sand fan unit at the mouth of the Plata River. (D) Close up of a point of erosion in the sand fan.

With the washout of the BR 277 bridge over the Jacareí River, water, sediment, and organic matter flowed into Antonina Bay. The flow dynamics created the inactive river bar and inactive anastomosing riverbed units (Figure 6-C). These units are inactive; part of these units was consumed in the reopening of the river channel of the Jacareí River in 2011 and part was incorporated into the floodplain. The coring performed on the inactive river bar unit landform showed about 1 m of sandy material deposited by the 2011 mud flows (Figure 6-A and D).

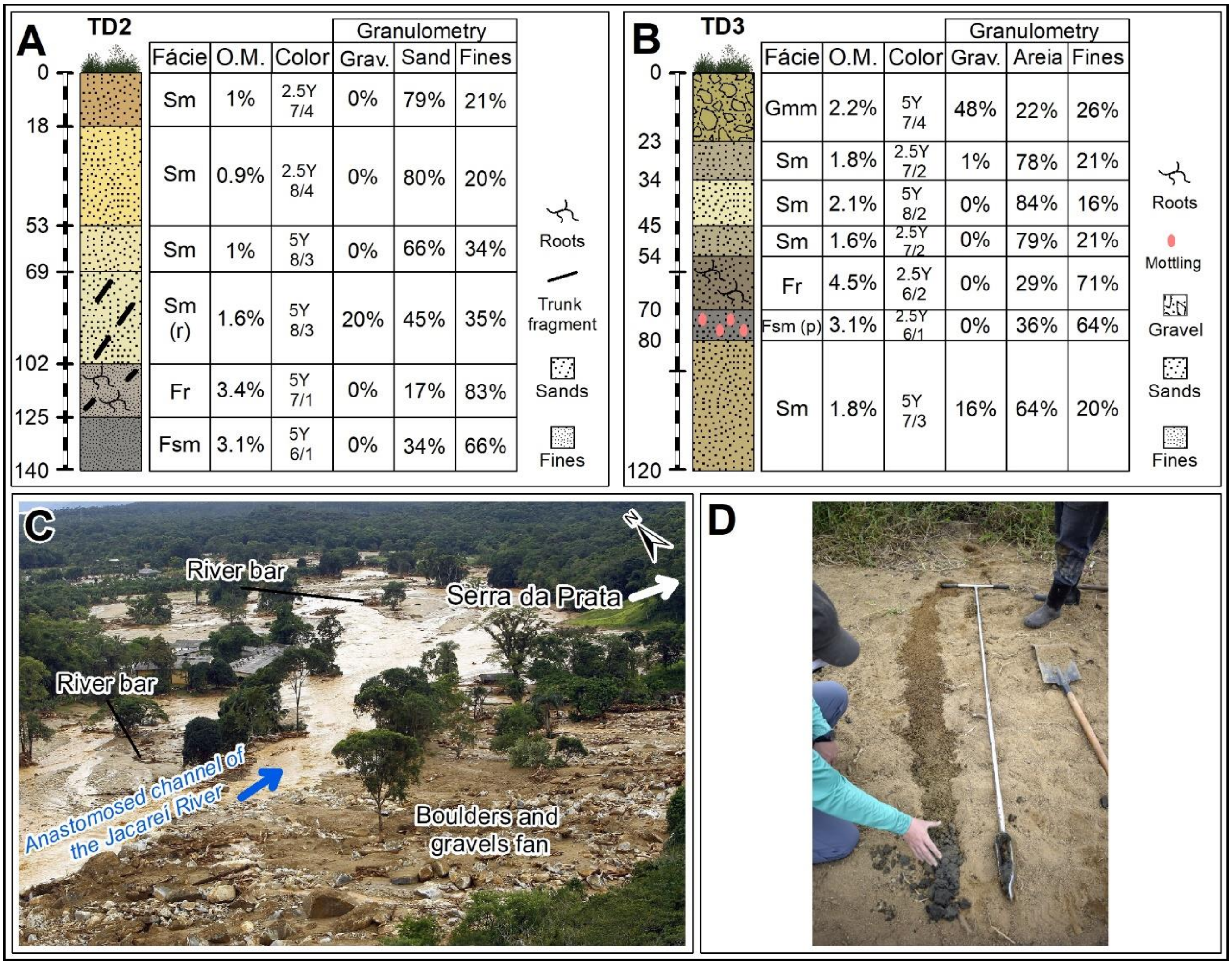



**Figure 6.** (A) Sedimentary profile in the inactive river bar unit – TD2. (B) Sedimentary profile in the inactive anastomosing riverbed unit – TD3. (C) Photograph taken in section 1 of the alluvial plain shortly after the 2011 event. (D) Material sampled from the inactive river bar unit – TD2.

During the coring carried out in the inactive fluvial bar unit, six facies were identified. The first four have sandy material, possibly in massive structure (Sm) with a yellowish color. The final sandy facies presents fragments of tree trunks. The last two facies present fine material, high levels of organic matter (3.4 and 3.1%, respectively), and possibly have a massive structure (Fsm). In the penultimate facies, roots and trunk fragments were identified.

In the inactive anastomosing riverbed unit, a trench was excavated and seven facies were identified (Figure 6-D). The first facies (2011 anastomosing channel bottom) presents gravelly material supported by the matrix (Gmm) in massive structure, followed by three sandy facies in massive structure distinguished by color (Sm). Next, there is an abrupt change with a facies of fine granulometry, high organic matter content (4.5%), and the presence of roots. This is followed by a facies of fine granulometry, grey (2.5Y 6/1) with mottling – Fsm (p). The last facies of the profile is sandy in massive structure (Sm).

With the damming of the Jacareí River channel by tree trunks (close to the BR 277 bridge), there was a rupture of the banks, forming the crevasse splay unit. The literature describes this landform as a rupture deposit, a type of fan that occurs on riverbanks. In addition to being related to the obstruction of the channel, its origin may be associated with a temporary base level formed in the area during the event. As it is a unique landform, a trench was opened with the aid of machinery, and six facies were identified (Figure 7).

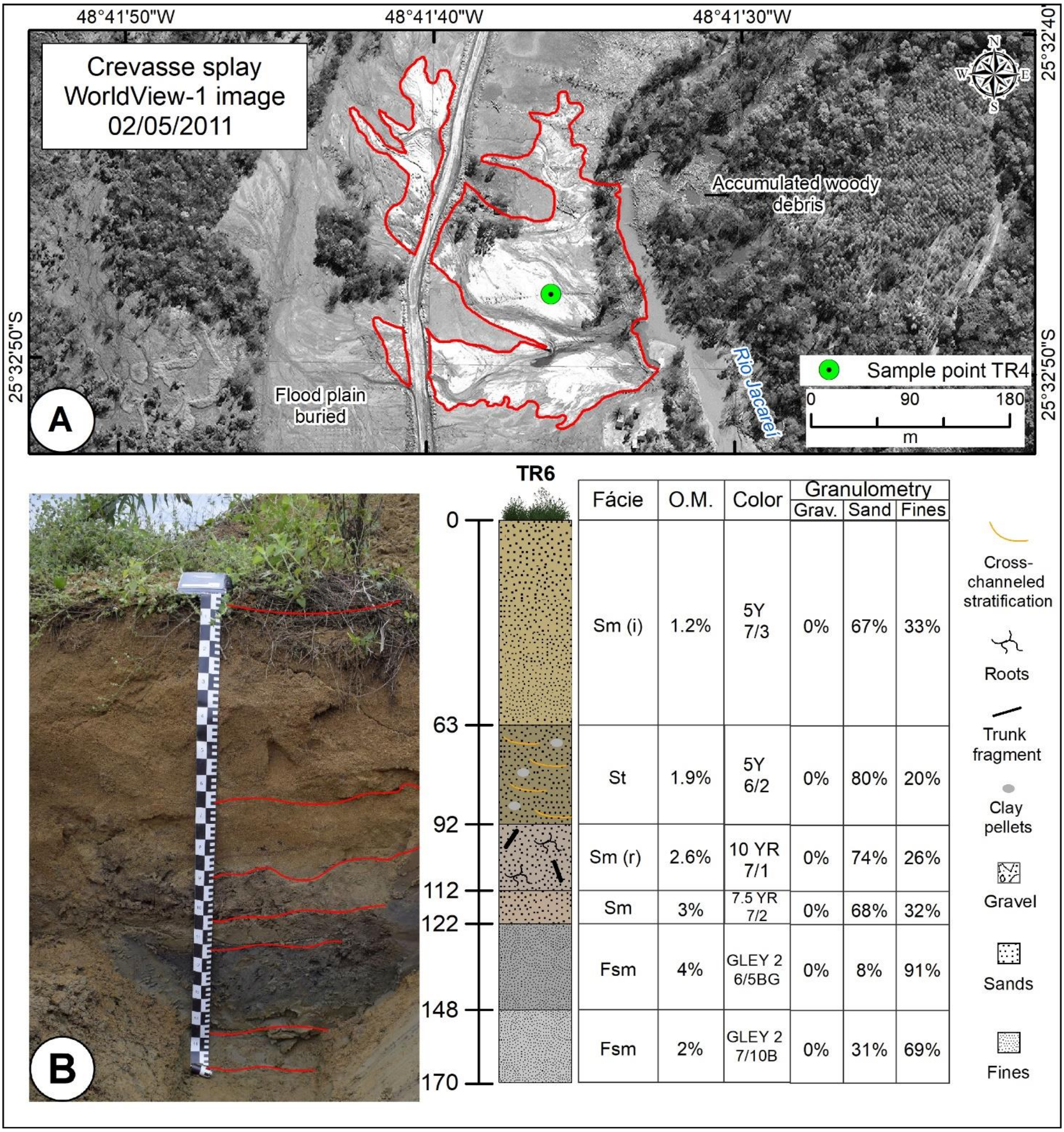
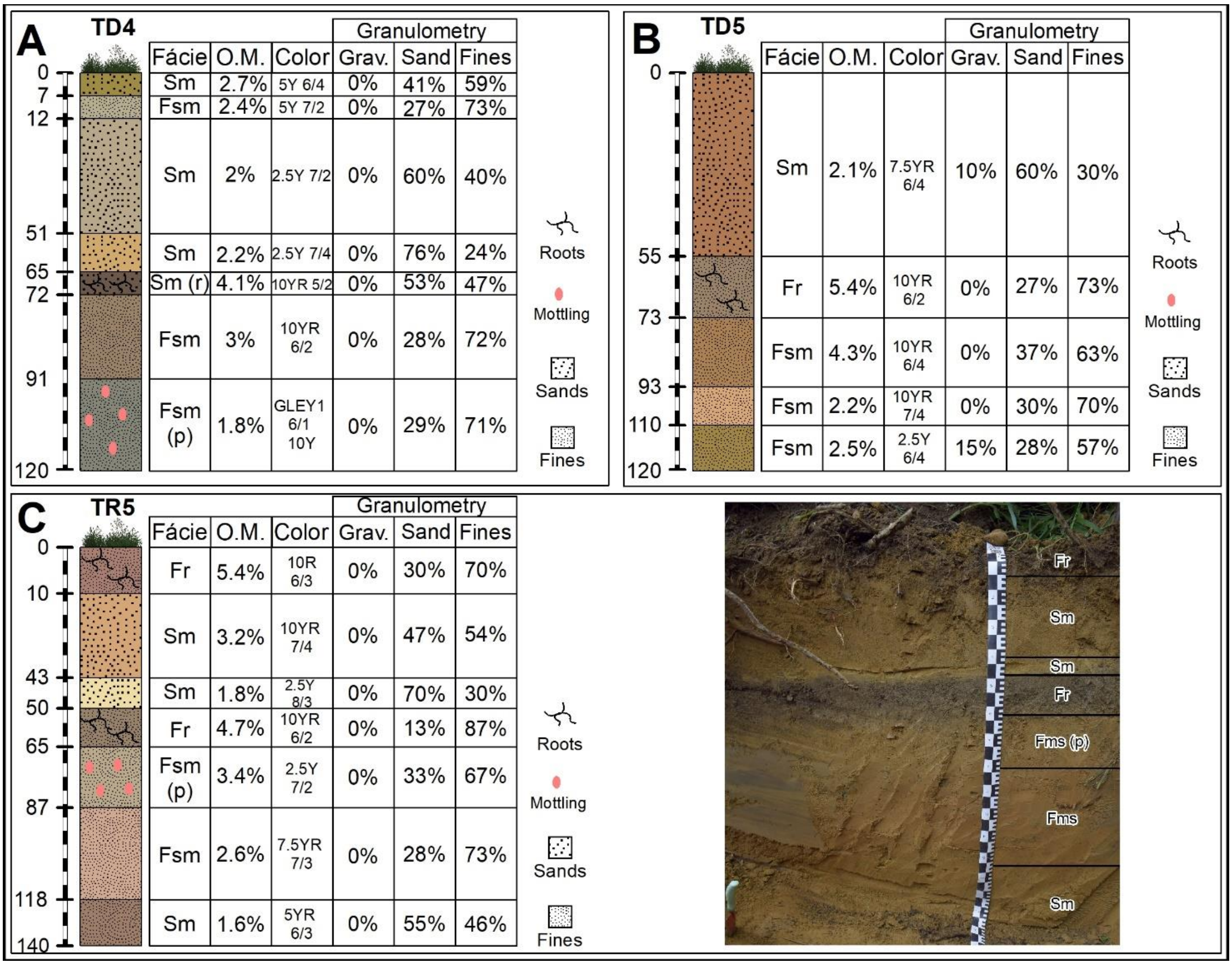



**Figure 7.** (A) Vertical view of the crevasse splay unit. (B) Sedimentary profile and view of trench 6.

The first facies, with sandy granulometry, presented inverse gradation, with coarse material at the top and medium to fine sand at the bottom. The next facies, with a sandy texture, showed a cross-channeled structure (St) and clay pellets (Figure 8). In sequence were two sandy facies in massive structure (Sm), with the third showing inclusions of roots and trunk fragments – Sm (r). The last two facies present an abrupt transition, with grayish color and massive structure (Fsm), and the second last facies presenting the highest organic matter content of the profile (4%).

**Figure 8.** A cross-channeled structure (St) and clay pellets identified in the crevasse splay unit.

Finally, the buried floodplain was the largest unit identified in this study, covering 186.9 hectares or about 65% of the study area. This unit extends throughout the study area, with three sampling points carried out in stretches 1, 2, and 3 of the alluvial plain. It is worth noting that artificial drainage channels and marginal dykes are present in the unit along the only access road to the area, which were created due to the reopening of the road by machinery after the 2011 landslide. At the three sampling points, the pattern identified was sandy facies in massive structure (Sm) of yellowish and brown colors, on top of facies with fine, dark colored material (Fr and Fsm) with the presence of roots and high levels of organic matter (Figure 9).




| Fácie | O.M. | Color | Granulometry Grav. | Sand | Fines |
|---|---|---|---|---|---|
| Sm | 2.7% | 5Y 6/4 | 0% | 41% | 59% |
| Fsm | 2.4% | 5Y 7/2 | 0% | 27% | 73% |
| Sm | 2% | 2.5Y 7/2 | 0% | 60% | 40% |
| Sm | 2.2% | 2.5Y 7/4 | 0% | 76% | 24% |
| Sm (r) | 4.1% | 10YR 5/2 | 0% | 53% | 47% |
| Fsm | 3% | 10YR 6/2 | 0% | 28% | 72% |
| Fsm (p) | 1.8% | GLEY1 6/1 10Y | 0% | 29% | 71% |

| Fácie | O.M. | Color | Granulometry Grav. | Sand | Fines |
|---|---|---|---|---|---|
| Sm | 2.1% | 7.5YR 6/4 | 10% | 60% | 30% |
| Fr | 5.4% | 10YR 6/2 | 0% | 27% | 73% |
| Fsm | 4.3% | 10YR 6/4 | 0% | 37% | 63% |
| Fsm | 2.2% | 10YR 7/4 | 0% | 30% | 70% |
| Fsm | 2.5% | 2.5Y 6/4 | 15% | 28% | 57% |

| Fácie | O.M. | Color | Granulometry Grav. | Sand | Fines |
|---|---|---|---|---|---|
| Fr | 5.4% | 10R 6/3 | 0% | 30% | 70% |
| Sm | 3.2% | 10YR 7/4 | 0% | 47% | 54% |
| Sm | 1.8% | 2.5Y 8/3 | 0% | 70% | 30% |
| Fr | 4.7% | 10YR 6/2 | 0% | 13% | 87% |
| Fsm (p) | 3.4% | 2.5Y 7/2 | 0% | 33% | 67% |
| Fsm | 2.6% | 7.5YR 7/3 | 0% | 28% | 73% |
| Sm | 1.6% | 5YR 6/3 | 0% | 55% | 46% |

**Figure 9.** Sedimentary profiles in the buried floodplain unit. (A) Sedimentary profile of core 4. (B) Sedimentary profile of trench 5. (C) Sedimentary profile and view of trench 5.

The sampling points in the buried floodplain unit demonstrate the process of vertical growth of the Jacareí River alluvial plain induced by the mud and debris flows of 2011. According to the sampling points, the alluvial plain grew in height by an average of 0.5 meters. The landscape around coring point 5 enables us to see this process (Figure 10).

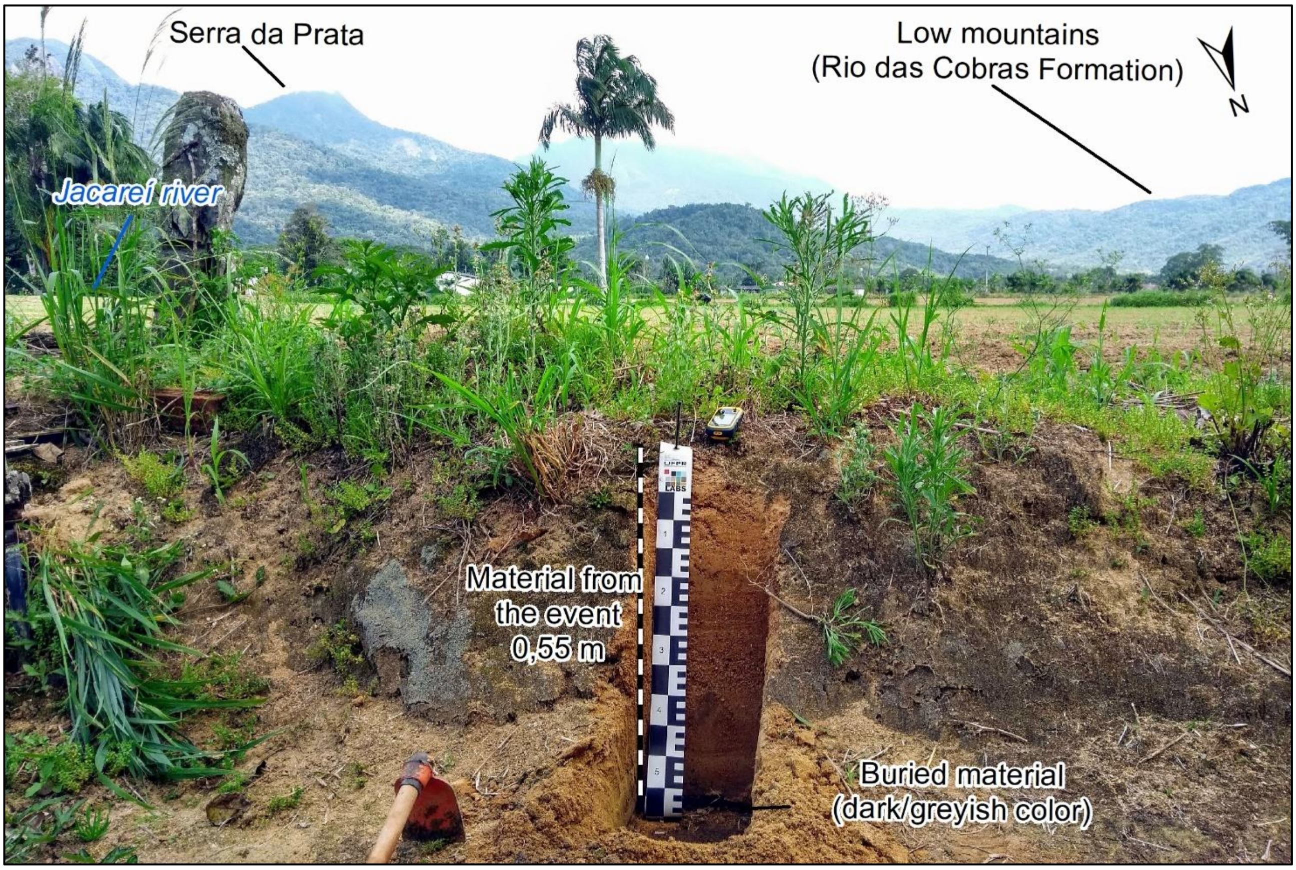



**Figure 10.** View of core sampling site 5 in the buried floodplain unit.

*4.3. Units after the 2011 event*

The proximal floodplain, river bars and river channel are features developed after the 2011 event and are closely related. The proximal floodplain is located around the Jacareí River channel, an area susceptible to periodic fluvial flooding events. This unit was formed by lateral and vertical accretion processes over deposits of mud and debris flows, the anastomosing riverbed, and debris bars. Flood channels and flood basins are also found in this unit.

The proximal floodplain has shrubby vegetation, including the species popularly known as caboa (*Typha domingensis*). Its occurrence was identified by analyzing aerial images around the Jacareí River, using the vegetation stratum and its humid appearance as criteria (Figure 11-D). As for sediments, we identified in the field layers (up to 1 cm) and strata (> 1 cm) of newly deposited material, especially after extreme precipitation events (Figure 11-C).

In sections 2 and 3 no material was found with this granulometry. In trench 6, two sedimentary facies were identified, both sandy in massive structure, superimposed on an accumulation of pebbles (Figure 11-A). In core 6, four facies were identified, the first two being sandy in massive structure superimposed on facies of fine material (Figure 11-B).

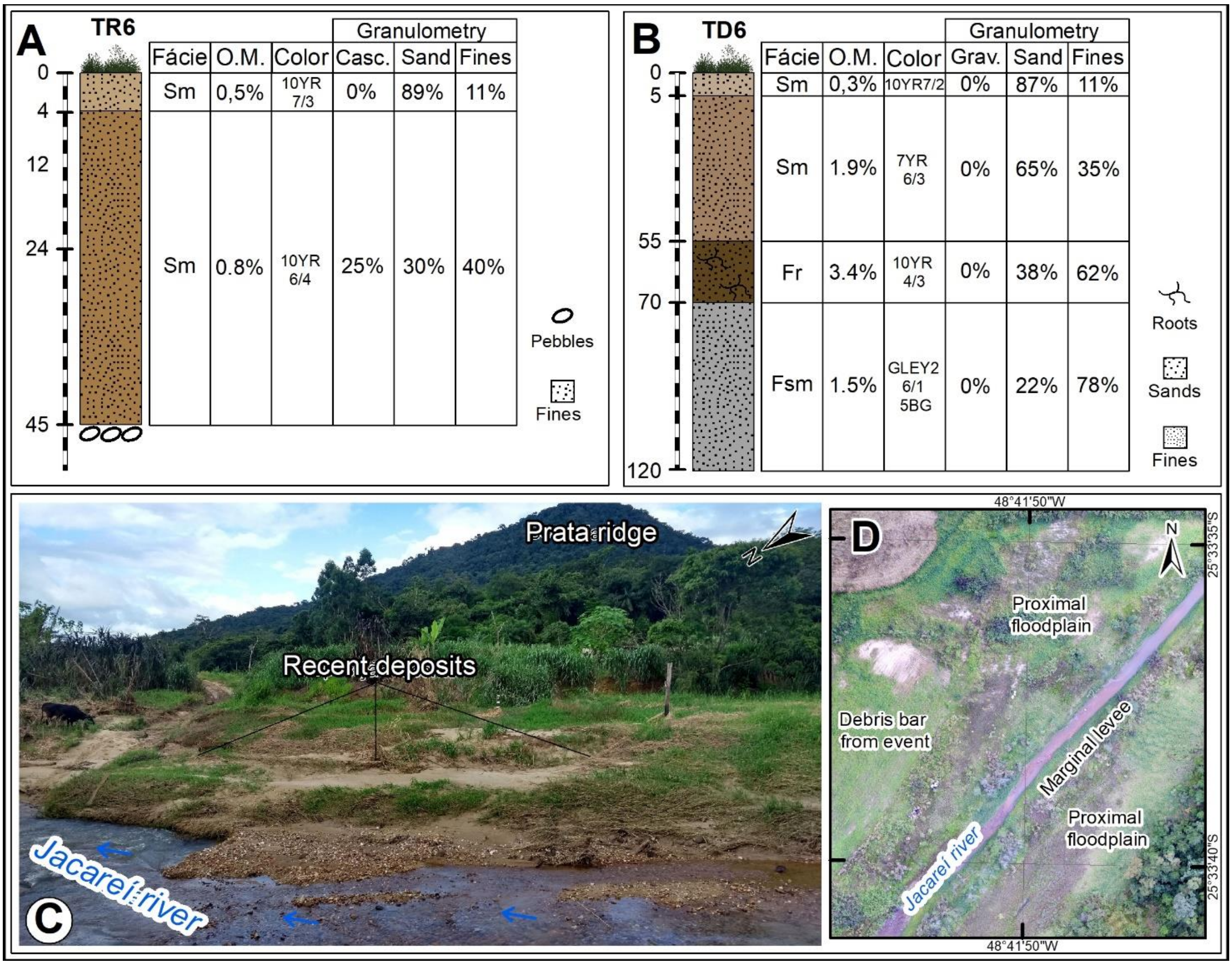



**Figure 11.** (A) Sedimentary profile of trench 6. (B) Sedimentary profile of core 6. (C) Proximal floodplain after a fluvial flood event with the presence of newly deposited material. (D) Vertical view of the proximal floodplain unit.

A different stratigraphic behavior can be observed in section 1 of the proximal flood plain unit, given the clear presence of coarse material (large rocks and boulders that prevented coring or the opening of trenches). The study by Paz and Paula (2021) describes an open trench in this unit (Figure 12), composed of sandy layers over gravel material (pebbles – facies originating from the 2011 event) which, in turn, is superimposed on fine/sandy material, possibly Fsm and Sm facies (prior to the event).

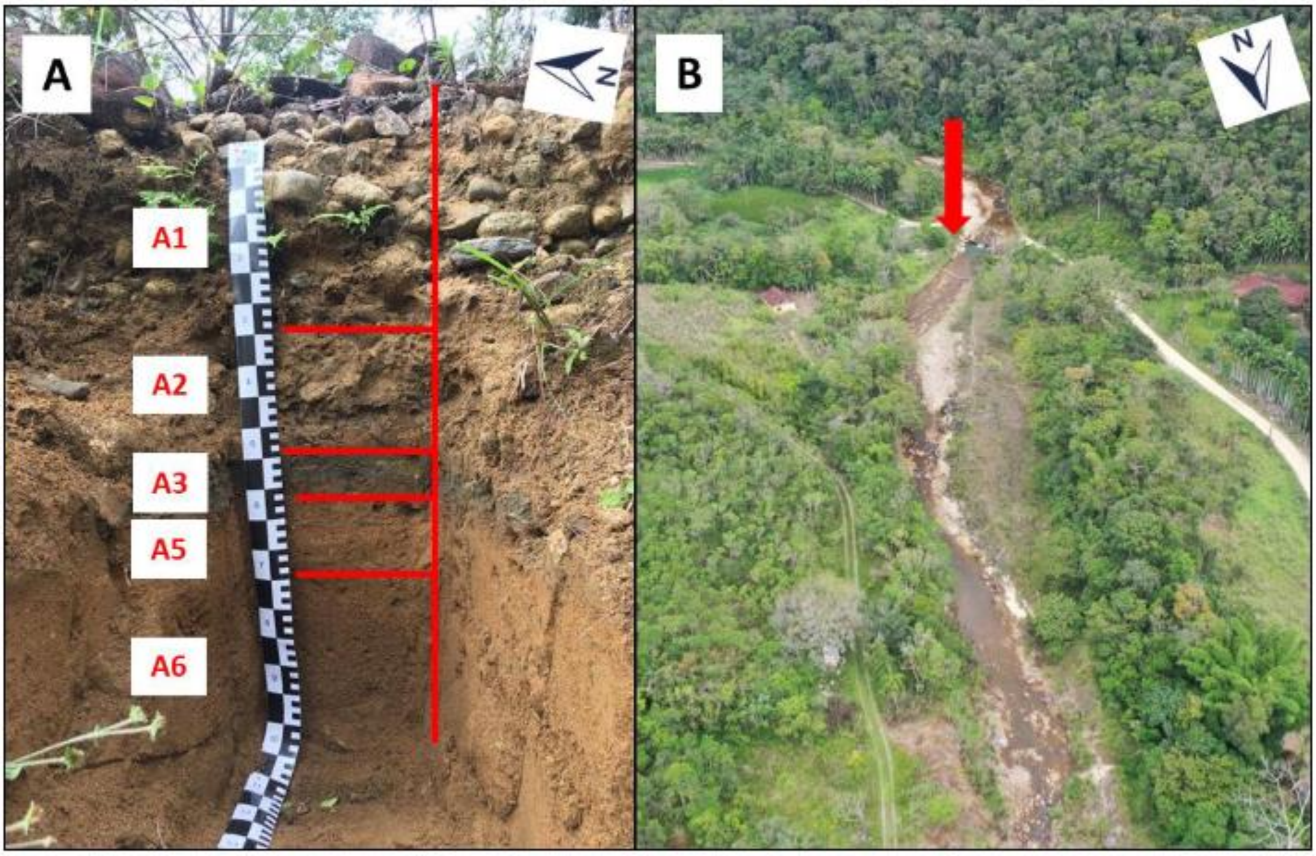



**Figure 12.** (A) Trench excavated in the proximal floodplain unit by Paz and Paula (2021). (B) Location of the trench in relation to the riverbed. Source: Paz and Paula (2021).

The material from the riverbed landforms presented very coarse and coarse granulometry in all samples, with a predominance of gravel and sand (Table 3). At point C1, in an active river bar located in stretch 1 of the alluvial plain, just after the Jacareí River enters the alluvial plain, the sample collected showed 53% gravel.

**Table 3.** Mapped morphostratigraphic units and associated facies in the Jacareí River alluvial plain.

| COD. Sample | Riverbed | Gravel | Sand | Fine |
|---|---|---|---|---|
| C1 | Active river bar - section 1 | 53% | 42% | 5% |
| C2 | Active river bar - section 2 | 10% | 74% | 16% |
| C3 | River channel - section 1 | 7% | 88% | 5% |
| C4 | River channel - section 2 | 0% | 87% | 13% |

Source: Paz and Paula (2021).

*4.4. Discussion*

The terraces located in section 1 of the plain help to understand the history of this landscape, considering changing sea levels. The Gcm facies found on terrace I are typical of turbulent flows, as has been noted in the literature (MIALL, 1996; 2016a). The overlapping and weathering of the pebbles and the location near the foot of the Serra da Prata support the idea that terrace I is a channel deposit, possibly a paleochannel of the Jacareí River.

On terrace II, a Gmm facies was found, which is interpreted in the literature as originating from a viscous flow of debris (MIALL, 1996; 2016a). Based on the surface position of the profile, this material can be inferred as originating from the March 2011 event. Subsequently, a series of sandy facies is observed, interpreted here as different points in the fluvial dynamics of the Jacareí River. The massive structure sandy facies can be related to riverbed deposits, such as channels and sand bars. On the other hand, the St facies, which present a cross-channeled structure, is associated with lateral and frontal accretion or rupture deposits (MIALL, 1996; 2016a).

In the Tingidor River rock and boulder fan, the buried terrace identified from trench 2, the first two facies (Gmm) were deposited by the 2011 event, which are commonly associated with viscous debris flows (MIALL, 1996, 2016b). Subsequent greyish facies are associated with water-saturated marginal environments such as proximal floodplains, marginal lagoons, marshes, or abandoned canals (MIALL, 1996; 2016a).

The three terraces seem to represent different points in the paleoplain landscape of the Jacareí River during the quaternary. The difference in relation to the current height of the Jacareí River may indicate processes of sea level fluctuation and consequent abandonment of the deposit. These materials are not affected by removal processes, which can help to understand the evolution of the floodplain landscape in the foothills of the Serra do Mar mountain range. Thus, additional studies are recommended, particularly dating analyses, that correlate the three terraces to each other and to the fluvial evolution of the Jacareí River plain.

As for the current deposits, abrupt changes in granulometry, color, and presence of roots are clear markers that characterize deposits formed by the March 2011 event. Along the plain, fluvial landforms were identified with sandy deposits in massive structure (Sm), superimposed on fine-grained materials (silt and clay) with brown or grayish colors (Figure 13). Such markers are well preserved and can still be identified in the field.

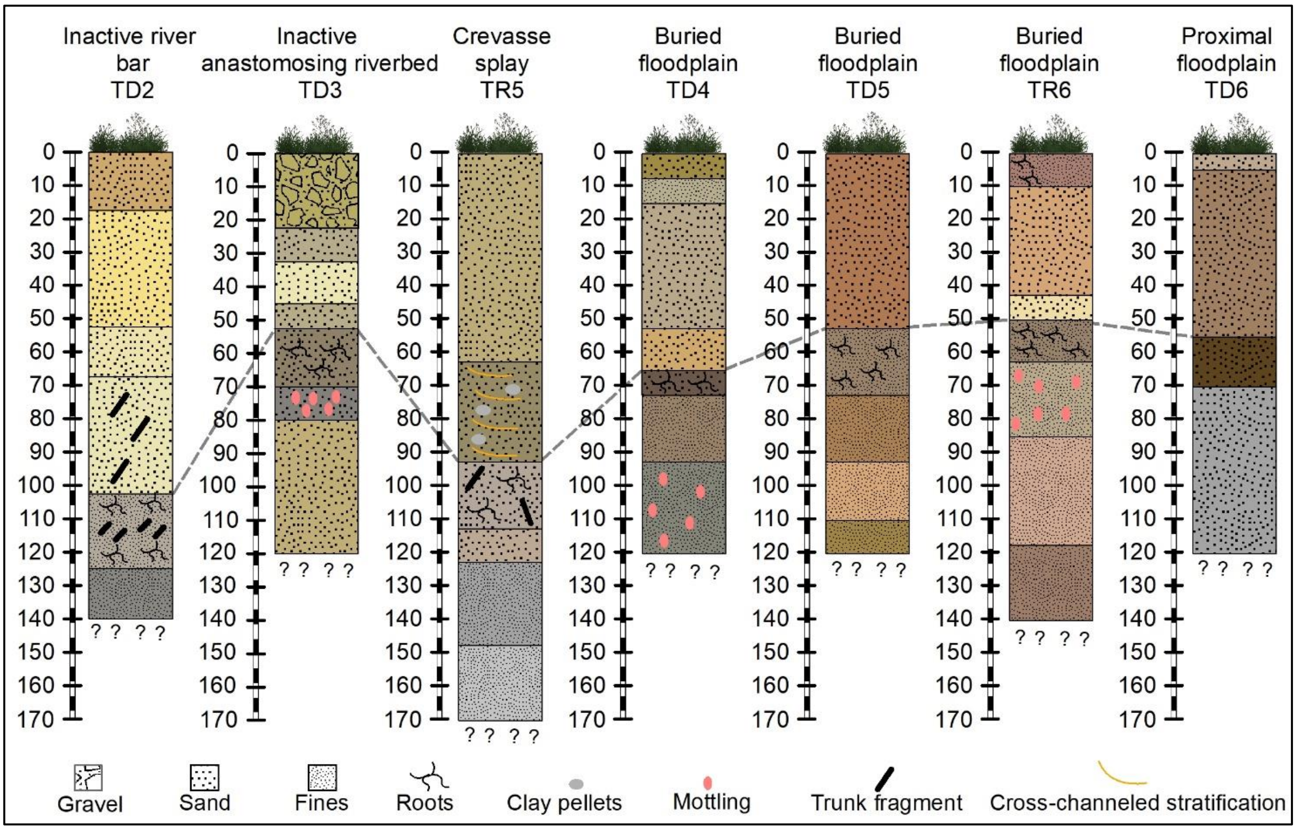



**Figure 13.** Sedimentary profiles of stratigraphic units formed by the 2011 event.

The high organic matter content in the facies following the sandy deposits formed by the 2011 event suggests that this facies is the A horizon of soils existing in the plain before 2011. Pedological mapping points to the existence of Fluvic Cambisols and Haplic Gleisols in the Jacareí River plain (PAULA, 2010; 2016). In a more detailed analysis, a typical Dystrophic Fluvic Cambisol was identified as buried by the 2011 event (PAZ; PAULA, 2021).

In trench 5, buried floodplain unit, in an area surrounded by arboreal vegetation, the first facies (Fr) can be interpreted as an A horizon being formed on top of the sandy material of the 2011 event. This facies is 10 cm thick, which may indicate the beginning of a pedogenetic process in the area. From the characteristics observed in the field, it appears that from a pedological point of view this trench portrays a Fluvic Cambisol (pre-event) overlaid by a Quartzarenic Neosol in the process of formation (post-event).

Previous studies on the alluvial plain of the Jacareí River have documented the occurrence of debris flows in the intra-mountain channels, and in the mouths and mud flows in the floodplain (PINTO; PASSOS; CANEPARO, 2012; SILVEIRA et al., 2014). Thus, considering the definitions in the literature regarding the granulometry of these processes (COSTA, 1984b; HUNGR, 2005), gravelly facies of the event are associated with debris flows, while sandy facies are associated with deposition by mud flows. However, in the sedimentary profile of trench 6 (proximal floodplain unit) massive sandy facies on gravel (mostly pebbles) were observed, which may indicate the interaction between both types of flows.

Prior to the 2011 event, sandy and fine material facies have their genesis linked to the processes of erosion and fluvial deposition of the Jacareí River. Grayish Fsm facies are commonly associated with marginal environments along the channel with the presence of water, such as proximal floodplains, floodplains, abandoned meanders, and backswamps (SUGUIO; BIGARELLA, 1990; MIALL, 2016b). On the other hand, sandy facies can be associated with landforms including river bars, marginal dykes, frontal or lateral accretion deposits, rupture deposits (crevasse splay), and even riverbed deposits, especially when cross laminations are present (SUGUIO; BIGARELLA, 1990; CHARLTON, 2007; MIALL, 2016b).

Furthermore, in terms of interaction, field evidence suggests that stretch 1 of the proximal floodplain unit was established after 2011 on debris flow deposits formed in 2011. This may be a distinct morphostratigraphic unit originating from the 2011 event that cannot be identified through mapping due to its complete coverage by the proximal floodplain unit.

As for the deposit formed, the alluvial plain grew significantly in height due to burial by the mud and debris flows of 2011, thus increasing the average elevation of the plain and certainly affecting fluvial processes in the area. The average depth of the deposits in the mapped landforms is 0.5 m, except for the inactive fluvial bar and crevasse splay units, with depths ranging from 0.9 to 1 m. Considering the criteria for distinguishing between sediments before and after the 2011 event mentioned above, further studies should be conducted to estimate the volume of this deposit, as well as explore its sedimentological characteristics.

Typical morphostratigraphic units of the fluvial landscape, such as terraces, proximal and distal floodplains, wetlands, and fans, were identified in the alluvial plain of the Jacareí River. On the other hand, the inactive anastomosing riverbed and buried floodplain units arose from the specificities of the interaction of gravitational and fluvial processes. Intense sedimentary input in the plain related to mass flows, to the point of destroying/burying the existing meandering channel and imposing an anastomosing channel, has been reported in other locations along the southern Brazilian coast, for example during the flood in the region of Tubarão, Santa Catarina State, in 1974 (BIGARELLA, 2003). In studies on Brazil, morphostratigraphic descriptions of a buried floodplain unit (or similar) were not identified, most likely due to the rarity and magnitude of its creation processes.

The mapped crevasse splay unit is also noteworthy, as it presented a morphogenesis distinct from the classic depositional model of meandering systems (CAHOON; WHITE; LYNCH, 2011; LI; BRISTOW, 2015; BURNS et al., 2017). A crevasse splay is understood as a margin rupture deposit due to the flooding of the channel, whether or not preceding a fluvial flood event (FRYIRS; BRIERLEY, 2013b). Previous studies have suggested that the observation of crevasse splay landforms in the Brazilian context is rare (MAGALHÃES JÚNIOR; BARROS, 2020c).

In the case of Jacareí, the crevasse splay was formed by the association of an increase in flow and sedimentary load and obstruction of the channel, resulting in its rupture. Water and sediment flows generate the conical shape, sometimes called a rupture fan (STEVAUX; LATRUBESSE, 2017a). In extreme cases, this landform precedes the fluvial avulsion process (KLEINHANS et al., 2013; YUILL et al., 2016). As mass flows are common from the Serra do Mar mountain range, crevasse splays formed in these events may instigate fluvial rearrangement processes in the coastal plain.

Finally, given the relative frequency (from a geological time perspective) of mass flows in the Serra do Mar and the impact of the 2011 event on the fluvial plain, it is important to highlight the particularities of the depositional cycle of fluvial plains throughout the mountain range. Previous studies have reported that after burial events by mass flows in floodplains in the coastal region, rivers tend to resume their meandering pattern, reworking the material in the anastomosing bed (BIGARELLA, 2003).

If there had been no anthropogenic interventions (desilting and channeling) in the channel in 2011, this would most likely be the scenario for the Jacareí River; the river would have continued to excavate the newly formed deposit until it created a new channel. Another fact that supports this hypothesis is the formation of a proximal plain after the 2011 event, indicating that lateral and vertical accretion processes are taking place. Furthermore, recent sandy facies were identified in the proximal floodplain, as well as sandy lenses over herbaceous/shrubby vegetation after extreme rainfall events. A recent study also indicates that after the extreme event of 2011 and despite human interventions, the Jacareí River is resuming a meandering path (PAZ; PAULA, 2021), suggesting that the lateral and vertical accretion processes typical of meandering rivers of the coastal plain are resuming.

## 5. Conclusions

Morphostratigraphic units were identified in three distinct contexts: those formed prior to 2011; those formed by the 2011 mud and debris flows; and units formed after 2011. There was a predominance of coarse material (rocks and pebbles) in stretch 1 and sandy material in stretches 2 and 3. Morphostratigraphic units specifically generated by the mud and debris flows in floodplains were identified.

The deposits formed by the 2011 event have sandy facies with a thickness between 0.5 and 1 m, and are marked by their granulometry, color, presence of roots, and organic matter content. In future studies, we recommend a more detailed analysis of the sedimentary structures throughout the buried floodplain unit, using non-destructive methods, such as ground penetrating radar or Uhland-type auger. The investigation of specific sedimentary structures in this unit can offer more information about the dynamics of internal water runoff and sedimentation during the burial process of the Jacareí River floodplain.

The results shed light on the evolutionary process of the Jacareí River coastal plain landscape, and the 2011 event may represent a phase of the sedimentary cycle of fluvial plains on the margins of the Serra do Mar mountain range. Further studies are recommended to test this hypothesis and its framework against deposition models in fluvial systems. The possible role of these events in local pedological transformations was also observed.

Finally, we emphasize that the landscape of the Jacareí River plain was totally transformed by the 2011 event. Thus, environmental dynamics that happened before 2011 may have been altered, and new processes may be occurring. The mapping of morphostratigraphic units presented here reveals a new substrate configuration, which can help inform land use studies and territorial planning in the area.

**Authors' Contributions:** Paz, O.L.S – Design, Data Curation, Formal Analysis, Investigation, Methodology, Conception, Writing – original draft and Writing – analysis and editing. Paula, E.V. – Design, Formal Analysis, Acquisition of Funding, Research, Methodology, Resources, Supervision, Validation and Conception. This research is part of the first author's PhD thesis, mentored by the second author.

**Financing:** Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001 – for granting the doctoral scholarship within the Academic Excellence Program (PROEX).

**Acknowledgements:** The authors thank the reviewers for their corrections, suggestions, and criticisms of the study. Thanks to the team of the *Brazilian Journal of Geomorphology* for conducting the editorial process. For the infrastructure and opportunities, we thank the Federal University of Paraná (UFPR) and its Graduate Program in Geography. For the laboratory equipment and analytical support, we acknowledge the Laboratory of Mineral and Rock Analysis (LAMIR/UFPR), the Laboratory of Sedimentological Studies and Sedimentary Petrology (LABESED/UFPR), and the Center for Applied Research in Geoinformation (CEPAG/UFPR). For resources, equipment, and support in the field, we thank the Laboratory of Geoprocessing and Environmental Studies (LAGEAMB/UFPR) and the Laboratory of Biogeography and Soils (LABS/UFPR). For support with field work and discussions, we thank Prof. Dr. Rodolfo Jose Angulo, Prof. Dr. Everton Passos, Prof. Dr. Fabiano Antonio de Oliveira, Prof. Dr. Leonardo José Cordeiro Santos, Prof. Dra. Monica dos Santos Marcal, Prof. Dr. Ricardo Michael Pinheiro Silveira and Prof. Dra. Maria Carolina Villaca Gomes.

**Conflict of interest:** The authors declare no conflict of interest.

## Referências

1. ANGULO, R. J. Mapa do Cenozoico do litoral do Estado do Paraná. **Boletim Paranaense de geociências**, v. 55, n. 1, p. 25–42, 2004. DOI: 10.5380/geo.v55i0.4281
2. BAYER, M.; ZANCOPÉ, M. H. C. AMBIENTES SEDIMENTARES DA PLANÍCIE ALUVIAL DO RIO ARAGUAIA. **Revista Brasileira de Geomorfologia**, v. 15, n. 2, p. 203–220, 2014. DOI: 10.20502/rbg.v15i2.414
3. BIGARELLA, J. J. Movimentos de massa. In: **Estrutura e origem das paisagens tropicais e subtropicais - Volume 3.** 1ª Ed. Florianópolis: Editora da UFSC, 2003. p. 1024–1098.
4. BRIDGE, J. S. **Rivers and floodplains: forms, processes, and sedimentary record**. 1ª Ed. Londres: John Wiley & Sons, 2009. 512p.
5. BRIDGLAND, D. R.; WESTAWAY, R. The use of fluvial archives in reconstructing landscape evolution: the value of sedimentary and morphostratigraphical evidence. **Netherlands Journal of Geosciences**, v. 91, n. 1–2, p. 5–24, 2012. DOI: 10.1017/S0016774600000536

6. BRIERLEY, G. J. Bar sedimentology of the Squamish River, British Columbia: definition and application of morphostratigraphic units. **Journal of Sedimentary Petrology**, v. 61, n. 2, p. 211–225, 1991. DOI: 10.1306/D42676D6-2B26-11D7-8648000102C1865D
7. BURNS, C. E.; MOUNTNEY, N. P.; HODGSON, D. M.; COLOMBERA, L. Anatomy and dimensions of fluvial crevasse-splay deposits: Examples from the Cretaceous Castlegate Sandstone and Neslen Formation, Utah, U.S.A. **Sedimentary Geology**, v. 351, p. 21–35, 2017. DOI: 10.1016/j.sedgeo.2017.02.003
8. CAHOON, D. R.; WHITE, D. A.; LYNCH, J. C. Sediment infilling and wetland formation dynamics in an active crevasse splay of the Mississippi River delta. **Geomorphology**, v. 131, n. 3, p. 57–68, 2011. DOI: 10.1016/j.geomorph.2010.12.002
9. CHARLTON, R. **Fundamentals of fluvial geomorphology**. 1ª Ed. London and New York: Taylor & Francis, 2007. 256p.
10. COSTA, J. E. Physical Geomorphology of Debris Flows. In: COSTA, J. E.; FLEISHER, P. J. (Eds.). **Developments and Applications of Geomorphology**. 1ª Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 1984. p. 268–317.
11. FRYIRS, K. A.; BRIERLEY, G. J. Floodplain forms and processes. In: **Geomorphic analysis of river systems: an approach to reading the landscape**. 1ª Ed. Backwell Publishing, 2013. p. 155–173.
12. GOLDIN, A. Reassessing the use of loss-on-ignition for estimating organic matter content in noncalcareous soils. **Communications in Soil Science and Plant Analysis**, v. 18, n. 10, p. 1111–1116, 1987. DOI: 10.1080/00103628709367886
13. HORN, B. K. P. Hill shading and the reflectance map. **Proceedings of the IEEE**, v. 69, n. 1, p. 14–47, 1981. DOI: 10.1109/PROC.1981.11918
14. HUNGR, O. Classification and terminology. In: JAKOB, M.; HUNGR, O. (Eds.). **Debris-flow Hazards and Related Phenomena**. 1ª Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005. p. 9–23.
15. KLEINHANS, M. G.; FERGUSON, R. I.; LANE, S. N.; HARDY, R. J. Splitting rivers at their seams: bifurcations and avulsion. **Earth Surface Processes and Landforms**, v. 38, n. 1, p. 47–61, 2013. DOI: 10.1002/esp.3268
16. LI, J.; BRISTOW, C. S. Crevasse splay morphodynamics in a dryland river terminus: Río Colorado in Salar de Uyuni Bolivia. **Quaternary International**, v. 377, p. 71–82, 2015. DOI: 10.1016/j.quaint.2014.11.066
17. MACHADO, R. **Vista em sobrevoo da comunidade de florestas após os movimentos de massa**. SECJ. 2011. 1 fotografia, color.
18. MAGALHÃES JÚNIOR, A. P.; BARROS, L. F. P. Estratigrafia, interpretação de fácies e reconstituição de paleoambientes deposicionais. In: MAGALHÃES JÚNIOR, A. P.; BARROS, L. F. P. (Eds.). **HIDROGEOMORFOLOGIA: Formas, processos e registros sedimentares fluviais**. 1ª Ed. Rio de Janeiro: Bertrand Brasil, 2020. p. 297–323.
19. MARÇAL, M. S.; RAMOS, R. R. C.; SESSA, J. C.; FEVRIER, P. V. R. SEDIMENTAÇÃO FLUVIAL QUATERNÁRIA NO VALE DO ALTO CURSO DO RIO MACAÉ, ESTADO DO RIO DE JANEIRO, BRASIL. **Revista Brasileira de Geomorfologia**, v. 16, n. 3, p. 449–467, 2015. DOI: 10.20502/rbg.v16i3.614
20. MIALL, A. The Facies and Architecture of Fluvial Systems. In: **Fluvial Depositional Systems**. 1ª Ed. Cham: Springer International Publishing, 2014. p. 9–68.
21. MIALL, A. D. The Geology of Fluvial Deposits: sedimentary facies, basin analysis and petroleum geology. 1ª Ed. Heidelberg: Springer-Verlag, 1996.
22. MIALL, A. D. Facies Models. In: **Stratigraphy: A Modern Synthesis**. 1ª Ed. Cham: Springer International Publishing, 2016a. p. 161–214.
23. MIALL, A. D. Facies Analysis. In: **Stratigraphy: A Modern Synthesis**. 1ª Ed. Cham: Springer International Publishing, 2016b. p. 77–159.
24. MINEROPAR. **MAPEAMENTO GEOLÓGICO-GEOTÉCNIICO DA PORÇÃO LESTE DA SERRA DO MAR DO ESTADO DO PARANÁ**. Curitiba: MINEROPAR, 2011. 102p.
25. MORAIS, E. S.; CREMON, É. H.; SANTOS, M. L.; ROCHA, P. C. Late Pleistocene-Holocene landscape evolution in the lower Peixe river, Brazil: A meandering river valley. **Journal of South American Earth Sciences**, v. 102, p. 102664, 2020. DOI: 10.1016/j.jsames.2020.102664
26. PAULA, E. V. **Análise da produção de sedimentos na área de drenagem da Baía de Antonina/PR : uma abordagem geopedológica**. Tese (Doutorado em Geografia) – Programa de Pós-Graduação em Geografia, Universidade Federal do Paraná, Curitiba. 2010. 220p.
27. PAULA, E. V. Análise da Produção de Sedimentos na Área de Drenagem da Baía de Antonina, Paraná: Contribuições ao planejamento do território. In: REIS, R. A. et al. (Eds.). **Litoral do Paraná: Território e Perspectivas**. 1ª. ed. Curitiba: Brazil Publishing, 2016. p. 11–35.
28. PAZ, O. L. S.; DAL PAI, M. O.; PAULA, E. V. Proposta metodológica para elaboração de base de dados geoespaciais como subsídio a estudos ambientais: aplicação em unidades de conservação do litoral norte do Paraná. **Revista Brasileira de Geografia Física**, v. 13, n. 02, p. 613–629, 2020. DOI: 10.26848/rbgf.v13.2.p613-629

29. PAZ, O. L. S.; PAULA, E. V. PLANÍCIE DO RIO JACAREÍ APÓS OS MOVIMENTOS DE MASSA DE 2011: CONSIDERAÇÕES A PARTIR DA ANÁLISE GRANULOMÉTRICA DE TRINCHEIRA E MUDANÇAS DO CANAL. **Revista Cerrados**, v. 19, n. 1, p. 83–99, 2021. DOI: 10.46551/rc24482692202106%20
30. PINTO, R. C.; PASSOS, E.; CANEPARO, S. C. Classificação dos movimentos de massa ocorridos em março de 2011 na Serra da Prata, Estado do Paraná. **Geoingá: Revista do Programa de Pós-Graduação em Geografia**, v. 4, n. 1, p. 3–27, 2012. DOI: 10.4025/geoinga.v4i1.49152
31. SANTOS, M. L.; STEVAUX, J. C.; GASPARETTO, N. V. L.; SOUZA FILHO, E. E. Geologia e Geomorfologia da Planície Aluvial do Rio Ivaí em seu Curso Inferior. **Revista Brasileira de Geomorfologia**, v. 9, n. 1, p. 23–34, 2008. DOI: 10.20502/rbg.v9i1.98
32. SILVEIRA, C. T.; FIORI, A. P.; SCHILIPACK, P.; DIAS, S. M. Mapeamento preliminar da suscetibilidade natural a movimentos de massa da Serra do Mar Paranaense apoiado na análise digital do relevo. **Revista Brasileira de Geomorfologia**, v. 15, n. 1, 2014. DOI: 10.20502/rbg.v15i1.366
33. STEVAUX, J. C.; LATRUBESSE, E. M. Planície de Inundação. In: **Geomorfologia fluvial**. 1. ed. São Paulo: Oficina de Textos, 2017. p. 197–225.
34. SUGUIO, K. **Introdução à sedimentologia**. 1ª Ed. São Paulo: Blücher, 1973. 317p.
35. SUGUIO, K.; BIGARELLA, J. J. **Ambiente fluvial**. 2ª Ed. Florianópolis: Editora da UFSC: Editora UFPR, 1990. 183p.
36. THAYER, J. B.; ASHMORE, P. Floodplain morphology, sedimentology, and development processes of a partially alluvial channel. **Geomorphology**, v. 269, p. 160–174, 2016. DOI: 10.1016/j.geomorph.2016.06.040
37. YUILL, B. T.; KHADKA, A. K.; PEREIRA, J.; ALLISON, M. A.; MESELHE, E. A. Morphodynamics of the erosional phase of crevasse-splay evolution and implications for river sediment diversion function. **Geomorphology**, v. 259, p. 12–29, 2016. DOI: 10.1016/j.geomorph.2016.02.005
38. ZAPATA, R.; SIMIANO, L. F.; PINHEIRO, E. G. O EVENTO ÁGUAS DE MARÇO E SUA AVALIAÇÃO DE DANOS E PERDAS. In: PINHEIRO, E. G.; PEDROSO, F. F. F. (Eds.). **CONSTRUINDO UM ESTADO RESILIENTE: O MODELO PARANAENSE PARA A GESTÃO DO RISCO DE DESASTRES**. 1ª Ed. Curitiba: CEPED/FUNESPAR, 2016. p. 34–51.

Esta obra está licenciada com uma Licença Creative Commons Atribuição 4.0 Internacional (http://creativecommons.org/licenses/by/4.0/) – CC BY. Esta licença permite que outros distribuam, remixem, adaptem e criem a partir do seu trabalho, mesmo para fins comerciais, desde que lhe atribuam o devido crédito pela criação original.