How Ground Penetrating Radar helps to understand the Nhecolândia lakes landscape in the Brazilian Pantanal wetland

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Abstract

The Pantanal wetland is an active sedimentary basin representing a relevant depositional setting for alluvial sedimentation studies. However, sedimentation homogeneity and the lack of outcrops makes sedimentary analysis more difficult. The Lower Nhecolândia is located at the Southern edge of the Taquari river megafan, whose genetic origin has been disputed as fluvial or eolian deposition. GPR analysis was used to characterize the subsurface stratigraphy and understand the region's geomorphic evolution. The 100 MHz GPR provided continuous good quality sections up to a depth of 8 m. Two continuous reflections are disconformities that bound three depositional sequences characterized by distinct radar facies. The lower facies presents an upper erosional truncation followed by reflections presenting ~1.5 m deep channelized forms and concave-up low amplitude reflections. The intermediate facies (~4 m thick) presents a base with erosional truncation followed by concave-upward forms, ~10 m wide, 1–3 m deep, separated by 1–2 m, and offlapping geometry. The upper facies has a flat base and thickness of 2–4 m, with parallel reflections; it shows a strong correlation between the radar facies and the forms preserved in the landscape, suggesting that channelized fluvial streams did not form them. The results obtained indicate that GPR use in the Pantanal is an important method to elucidate its geologic evolution.

KEYWORDS: Pantanal Basin; ground penetrating radar; Taquari megafan; radar facies; shallow stratigraphy.

INTRODUCTION

The Pantanal region, located in West Central Brazil, is one of the most important wetlands in the world (Por 1995, Junk *et al.* 2006), with large pristine alluvial plains (Assine 2015). It is an important depositional site where modern alluvial sedimentation can be studied (Assine and Soares 2004, Assine 2005, Assine *et al.* 2015b). The alluvial plain offers the opportunity to link the vertical sections of the subsurface with the depositional forms that are preserved in the landscape, allowing 3D analysis of the depositional architecture. However, facies analysis is extremely difficult due to the absence of natural outcrops and the homogeneity of sediments, which consists mainly of medium to fine-grained sand.

Considering the scarcity of outcrops, the ground penetrating radar (GPR) can be an important tool to help to understand the current and past depositional systems in the alluvial plain. The use of GPR enables the evaluation of geomorphic features

and helps to identify possible anomalies, discontinuities, buried anthropic artifacts and geological structures such as facies variations, thus optimizing the costs of surveys. GPR analysis in depositional river systems benefits from the variability of river systems and has been used in several large-scale studies (Bridge *et al.* 1995, Van Overmeeren 1998, Bristow and Jol 2003, Neal 2004, Smith *et al.* 2006, Smith *et al.* 2009, Tatum and Francke 2012, Lopes *et al.* 2013, Tamura *et al.* 2016). Subsurface investigations using GPR in modern deposition sites in the Pantanal were solely conducted in the modern Taquari river channel (Souza *et al.* 2002, Porsani *et al.* 2005).

To evaluate the applicability of GPR in characterizing the subsurface stratigraphy and in understanding the geomorphic evolution of the Pantanal wetland (Fig. 1), we have investigated the enigmatic landscape of the Lower Nhecolândia, in the Southern fringe of the Taquari fluvial megafan (Assine *et al.* 2015b, Assine *et al.* 2015c). The genetic origin of the Lower Nhecolândia landscape is disputed (Assine *et al.* 2015c), being interpreted as fluvial (e.g., Ab'Saber 1988, Colinvaux *et al.* 2000, Barbiéro *et al.* 2002, Furquim *et al.* 2010) or eolian relict landforms (e.g., Klammer 1982, Tricart 1982, Assine and Soares 2004, McGlue *et al.* 2017). Therefore, the imaging of the Nhecolândia subsurface characteristics can clarify these discussions, with a perspective of conclusive results concerning the pointed hypothesis.

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GEOLOGICAL SETTING

The Pantanal Basin is a subsiding sedimentary basin located in West Central Brazil. It is related to the hydrographic basin

of the upper Paraguay River (Ussami *et al.* 1999, Assine and Soares 2004). It is characterized by an extensive alluvial plain that is flooded annually and displays a relatively flat topography. Altitude values range from 80 to 190 m, and topographic gradient varies from 0.3 to 0.5 m/km (E—W) and 0.03 to 0.15 m/km (N—S) (Assine 2003). The Pantanal alluvial plain is characterized by a complex arrangement of different alluvial system tracts: distinct fluvial systems originated in the surrounding basement areas flow into the basin, where they develop different types of fluvial-fan (e.g., Negro River), mega-fan (e.g., Taquari River), interfan systems (e.g., Piquiri River), and a trunk-river system (i.e., the Paraguay River). The hydrologic regime and sedimentary dynamics of the Pantanal fluvial systems are determined by the geology and geomorphology of these systems' basement source-areas, which consists of both Precambrian crystalline rocks and Palaeozoic to Mesozoic rocks related to the Paraná Basin (Fig. 1; Assine *et al.* 2015a).

The Taquari Megafan (Assine 2005) is the largest megafan in the Pantanal plains, with approximately 50,000 km², about 37% of the Pantanal Basin total area (Assine 2003, Zani *et al.* 2012). It is composed of 4 geomorphologic components:

- the incised meander belt to the East;
- the modern depositional lobes to the West;
- the abandoned lobes to the North (Paiaguás);
- the abandoned lobes of the Nhecolândia to the South (Assine 2005, Assine *et al.* 2005).

The meander belt is confined in an incised valley in the upper portion of the megafan, which functions as a bypass for the water and sediment sourced from the Eastern plateau to the modern depositional lobes where the bulk of sedimentation is currently taking place. The Paiaguás and Nhecolândia paleolobes are not currently being fed by the Taquari River, and their runoffs have a pluvial origin (Assine *et al.* 2015a). The Paiaguás paleolobes are characterized by an intricate network of distributary paleochannels (Assine 2005) with distinct dimensions, superposing and cross-cutting planform patterns, similarly to those preserved in the São Lourenço Megafan (Assine *et al.* 2015b), a coalescing depositional system located to the North of the Taquari River and separated by the latter by the interfan plain of the Piquiri River (Assine *et al.* 2015b).
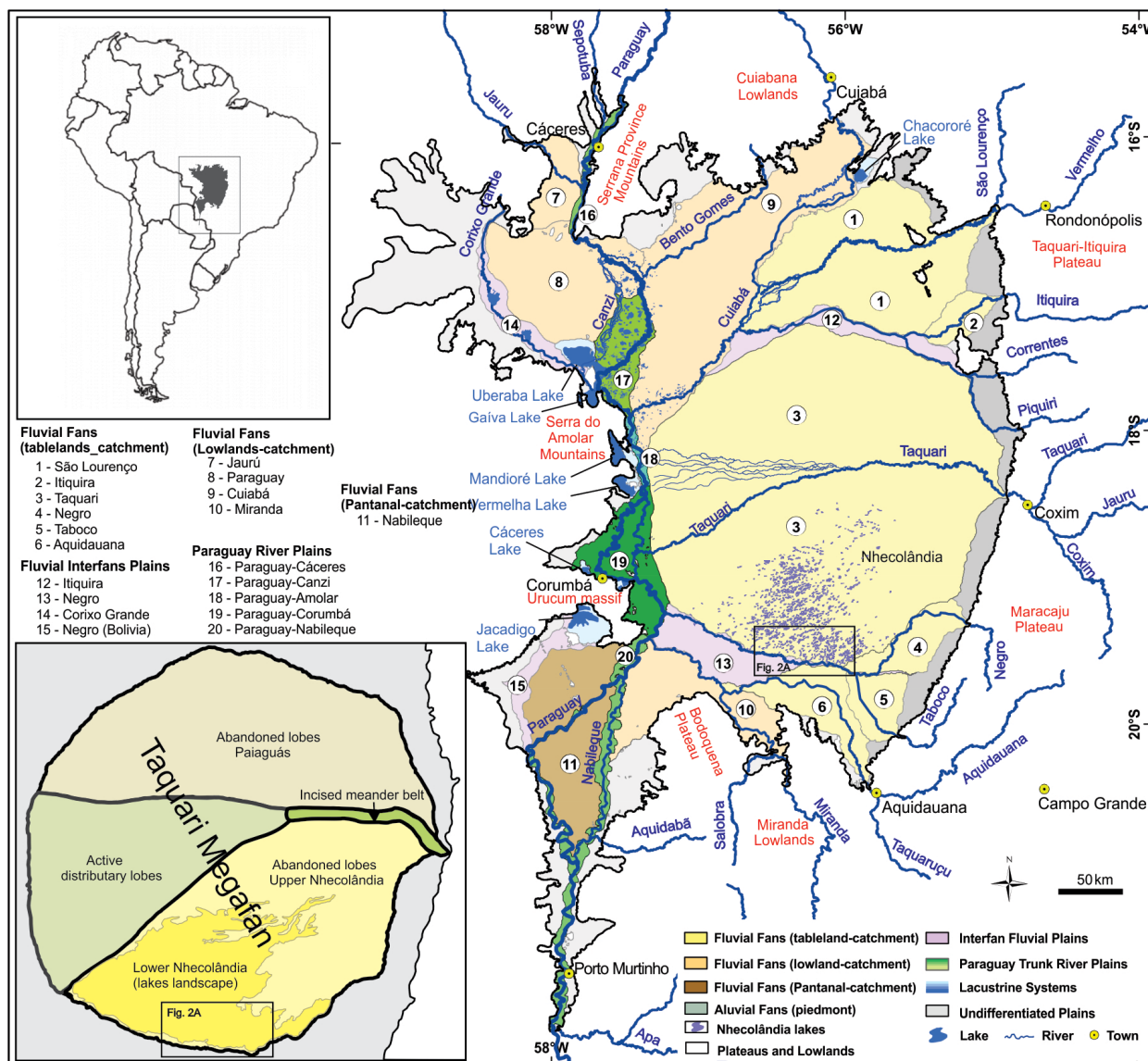

Figure 1. Depositional system tract of the Pantanal Basin (after Assine *et al.* 2015a) showing Figure 2 area. Lower-left square shows the incised meander belt, as well as the active and abandoned lobes of the Taquari megafan.

The Nhecolândia lobes are currently experiencing degradation through erosional tributary intermittent channels that drain floodwaters to the interfan system of the Negro River (Assine *et al.* 2015b). Two distinct geomorphologic zones characterize the Nhecolândia region: the upper Nhecolândia, characterized by distributary paleochannels with apexes on proximal areas of the megafan; and the myriads of ponds composing the Lower Nhecolândia (Assine and Soares 2004, Evans and Costa 2013) (Fig. 2).

The Lower Nhecolândia is a unique landscape in the wetland, characterized by aligned lakes bordered by sand ridges (locally named "*cordilheiras*"), which are only a few meters higher than the lake's bottom. Freshwater lakes ("*baías*") are interconnected by small intermittent stream ("*corixos*" or "*vazantes*") and reached by surface runoff during floods. Alkaline lakes ("*salinas*") make up for less than 10% of the Lower Nhecolândia and are rarely invaded by floodwaters; their waters are characterized by varied levels of salinity (Barbiéro *et al.* 2008, Furian *et al.* 2013, Bergier *et al.* 2014).

METHODS AND MATERIALS

Ground penetrating radar (GPR) is a near-surface geophysical technique based on the emission and reception of high frequency (10–1,000 MHz) electromagnetic waves in the subsurface. The electromagnetic wave reflections in the subsurface occur at the interfaces of materials with different dielectric properties. The physical property involved in this phenomenon is the dielectric permittivity, which is expressed by the dielectric constant (K) (Davis and Annan 1989). The higher the permittivity difference between the materials, the greater the reflected energy. The method works particularly well in dry materials with high electrical resistivity. Neal (2004) presents an excellent introduction to the GPR method, data processing, radar facies descriptions and interpretation.

GPR provides continuous sections in real-time (two-way travel time through a distance x) profiles performed in the field, and allows high-resolution imaging of the subsurface structures. The two-way travel time can be converted accurately into depth by running a particular sounding (wide-angle reflection
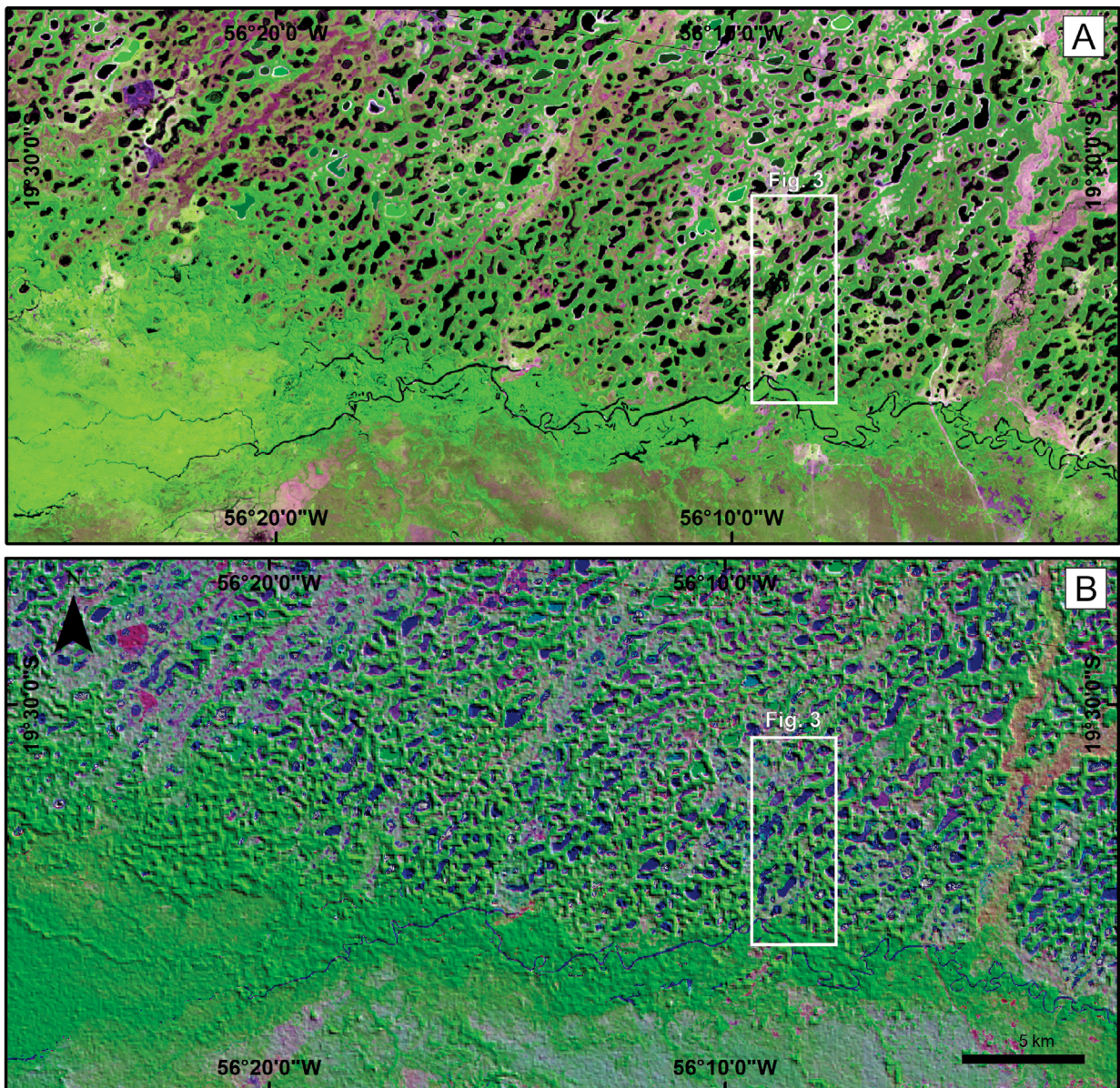

Figure 2. Lakes landscape of the lower Nhecolândia in the Southern fringe of the Taquari fluvial megafan, bordering the Negro River interfan system (Merino and Assine 2020). The white rectangle is the study area that is portrayed in Figure 3.

and refraction — WARR or Common Mid-Point — CMP). Permittivity values obtained from reliable literature with known study materials based on homogeneous lithology may also be used for the conversion of times to depths.

In this study, GPR equipment was used (from IDS *Ingegneria Dei Sistemi* SPA). The equipment is composed of two antennas (transmitter and receiver) with a coupled odometer, a control unit (DAD Control Unit) and a portable computer. The control unit (DAD) generates a pulse that is sent to the transmitting antenna. The signal then travels through the investigated substrate. Upon return, it is collected by the receiving antenna before it is scanned and displayed on the microcomputer monitor in the form of wave amplitude versus time plot. Accurate information of the traversal distance is given by a pulley (odometer), which generates a pulse at pre-set intervals, with each pulse corresponding to a data acquisition scan. The distance between scans was set to 4 cm in the software that manages all other data acquisition parameters, as well as the presentation of radargram (section time versus distance traveled). Antennas with a 100 MHz frequency were used due to their ability to allow relatively greater penetration in the geological environment while maintaining a vertical resolution of about 25 cm in the sandy lithology. The configuration used in this environment allows one to investigate depths of up to 8 m.

Although GPR data interpretation is based on electromagnetic waves, the sections' processing is similar to that applied to seismic reflection data when using the common offset technique. A software (GRED) was used for the conventional data processing and involved the following steps:

- zero-time correction (zero-drift time): to eliminate the wave travel time in the interface space between the antennas and the topsoil;
- Signal saturation correction by removing low frequencies (dewow): a low-pass filter that eliminates the wave interference propagated through the air;
- application gains for attenuated signals: to apply a gain curve which essentially compensates the natural spherical decay suffered by the signal;
- application of a frequency filter (band pass vertical): used in the attenuation of high-frequency noise inherent to the device;
- application of spatial filters (2D) for smoothing the reflections.

The generated section was then exported to another software (Reflex), in which topographic correction was applied and the final section was created. The propagation speed was measured by setting several diffraction hyperboles present in the section, reaching an average speed of 0.100 m/s (a number used to convert two-way travel time to depth). This value is consistent with the literature (e.g., Neal 2004, Jol and Bristow 2003).

Altitudes in the study area vary slightly (between 114 and 118 m). As such, there is a need for topographic corrections particularly in the study of depositional systems, where subtle variations in inclination may result in misinterpretation. This process helps to adjust the reflections to become more reliable in the section. A Trimble DGPS was used for the correct spatial positioning in both coordinates and altitude, allowing better precision than 5 cm in height. Points were collected every 5 meters and were used in the GPR data processing.

According to Neal (2004), although much of the terminology associated with seismic stratigraphy can be applied directly to the radar stratigraphy, it is recommended that the approach be changed. This is because interpretations tend to mix descriptive and interpretative terms, especially regarding the definition of facies, which may not be correct if the context in which the terms are used is not specified. Furthermore, where the descriptive terms have been used, they are often poorly defined. Thus, for each reflection, or each radar facies, or each reflection's package, the ideal situation is to consider the shape, dip, continuity, amplitude and relationship between the reflections.

Radar facies are interpreted to record depositional sedimentary structures. As such, a sequence stratigraphic analysis was applied to interpret different depositional sequences similarly to those used in seismic interpretation. Depositional sequences record sedimentary cycles (Vail *et al.* 1977) and are defined as genetically related sediment bodies that are bounded by unconformities or correlative conformities (Posamentier and Vail 1988, Van Wagoner *et al.* 1988). Thus, the methodology applied to siliciclastic sequence stratigraphy (e.g. Posamentier and Allen 1999) was used and adapted to the continental environment.

RESULTS

Two sites were investigated in the Barranco Alto farm, in the Southernmost part of the Nhecolândia (Fig. 3). In both areas, GPR sections were surveyed approximately in the directions NE-SW and NW-SE, respectively parallel and perpendicular to the surface runoff which flows to the South of the Negro River. The GPR technique applied to the sedimentation study in the Taquari megafan provided continuous sections. Due to the lithologic composition of the sediments, it was possible to reach depths of up to 8 meters with a vertical resolution of about 25 cm and horizontal resolution of 5 cm using 100 MHz antennas. This allowed the characterization of the reflections' architecture (in radargrams) and the identification of sedimentation patterns that a direct method of geological research would hardly demonstrate. The data were generally of good quality. Despite the good penetration considering the study´s goal, it might be jeopardized by the electrical conductivity of the groundwater, which can reach more than 10,000 µS/cm and have pH > 9 (Almeida *et al.* 2011).

Five sections were surveyed near the Barranco Alto farm headquarters (approximate coordinates: 19º34'10" S 56º08'40" W), and other three approximately 8 km to its North (approximate coordinates: 19º31''40" S and 56º08'40" W). Sections 1, 2 and 3 (Fig. 3B) are perpendicular to the surface-runoff direction (NW-SE), whereas sections 4 and 5 are parallel to the surface-runoff direction (NE-SW). It forms a grid covering a total length of 1,875 m. The radar facies classification was written according to previous research proposed by Neal (2004). The stratigraphic interpretation of the processed sections shows two disconformities, recognized in all sections. Three sedimentary units (Figs. 4 and 5) were also recognized. Local relief is characterized by the presence of sand ridges between the lakes; as such, topographic

corrections were applied during the GPR data processing of the NW-SE sections (low-pass filter). However, this procedure introduced a slightly high-frequency noise that could not be extracted and was important during the verification of the continuity between both disconformities, as shown in Figure 4.

The disconformities individualized three different depositional sequences (Table 1), which were named Unit 1, 2 and 3, from the oldest to the most recent one, respectively. It was impossible to identify the base of Unit 1 (lowest) due to limitations in the GPR signal-penetration. The radar facies of the upper limit in Unit 1 are characterized by erosional truncation with concave-up geometries. The resolution decreases with depth (most likely due to humidity increase). Internal reflections of Unit 1 are mainly characterized by a chaotic pattern, with some concave-up and channelized forms. The sedimentological interpretation of Unit 1 is limited by low resolution as a greater depth is achieved, as well as a considerable amount of noise (most likely due to humidity increase). Although geologic reflections are chaotic and have a short lateral extent (discontinuous), the identified concave-up erosional features and channelized forms are filled with relatively flat-lying deposits. This suggests fluvial deposition, with preservation of both horizontal stratification and cross-stratification, along with the fan's overall depositional environment.

The base of Unit 2 (intermediate) is very irregular and characterized by various concave-up geometries. This suggests deposition by rivers characterized by braided channels, contrasting with current characteristics of active channels in the megafan. The unit is approximately 1m thick, but can be up to 4m deep depending on its location. Radar facies of various types were characterized by subparallel, oblique, concave-upward forms, approximately 10m wide and 1–3m deep, separated from each other by 1– 2m, and offlapping geometries. The upper boundary is concordant and nearly parallel with the pattern of Unit 3. The reflections' configurations suggest a stratigraphy composed of channels, ranging between 15–40m wide, filled with fluvial bar sets (Figs. 4 and 7).

Figure 3. Location of the GPR sections. (A) Overview of the study area in the Nhecolândia region, showing the Negro River in the southern part of the image as well as the location of (B) and (C). (B) Location of sections 6 – 8. (C) Location of sections 1 – 5, showing the Lindóia Saline. The red star indicates the location of the pit excavation site (sediment profile as shown in Figure 8).
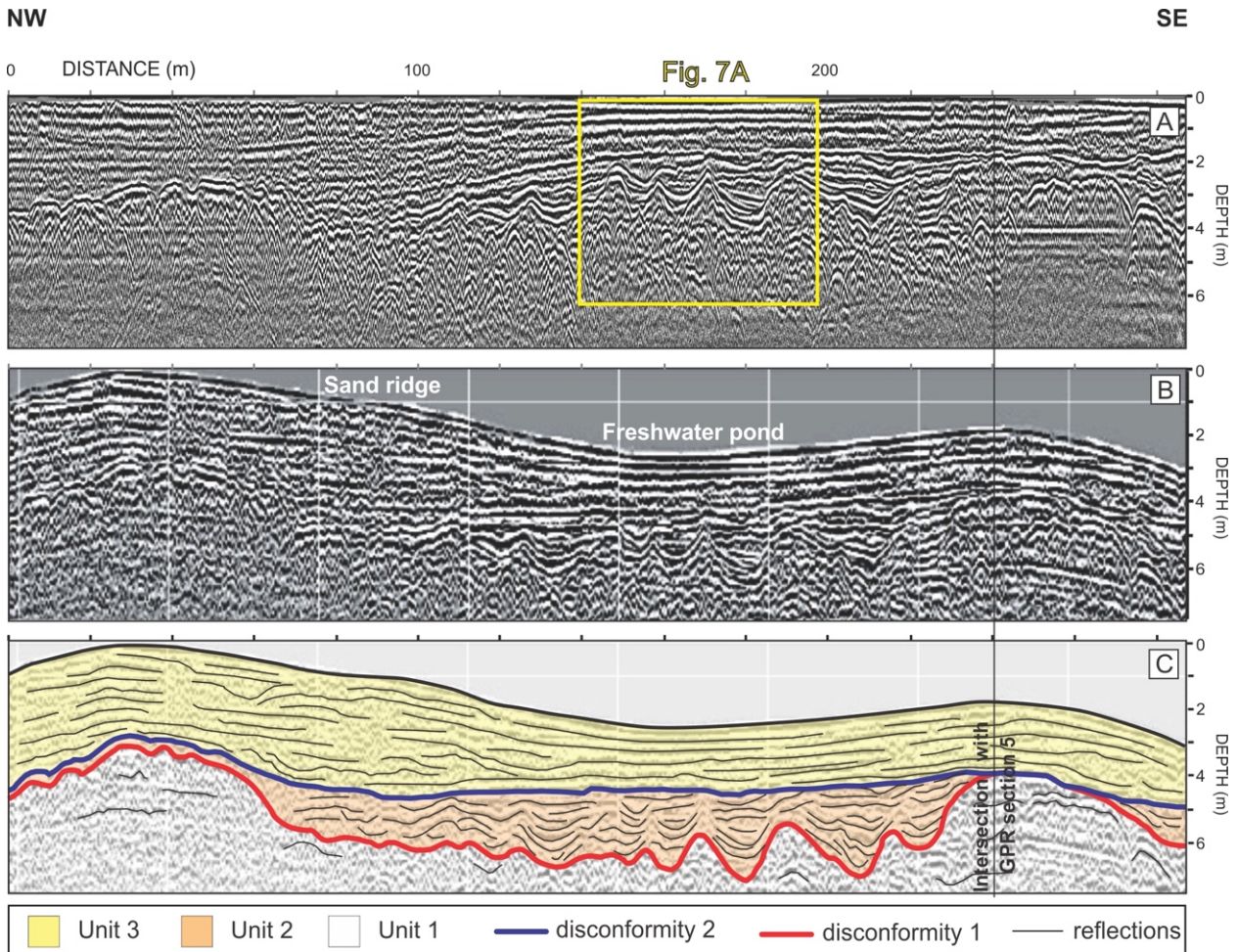
Figure 4. GPR section 2 near the Lindóia Saline (see Figure 3C for location). The GPR section is presented (A) without and (B) with topographic correction. The section is perpendicular to the surface runoff and runs from one sand ridge to another while crossing a small freshwater pond. The irregular nature of disconformity 1 can be observed through multiple concave-up sections which might indicate deposition by multi-channel fluvial planform. The yellow square indicates the location of the section in Figure 7A.
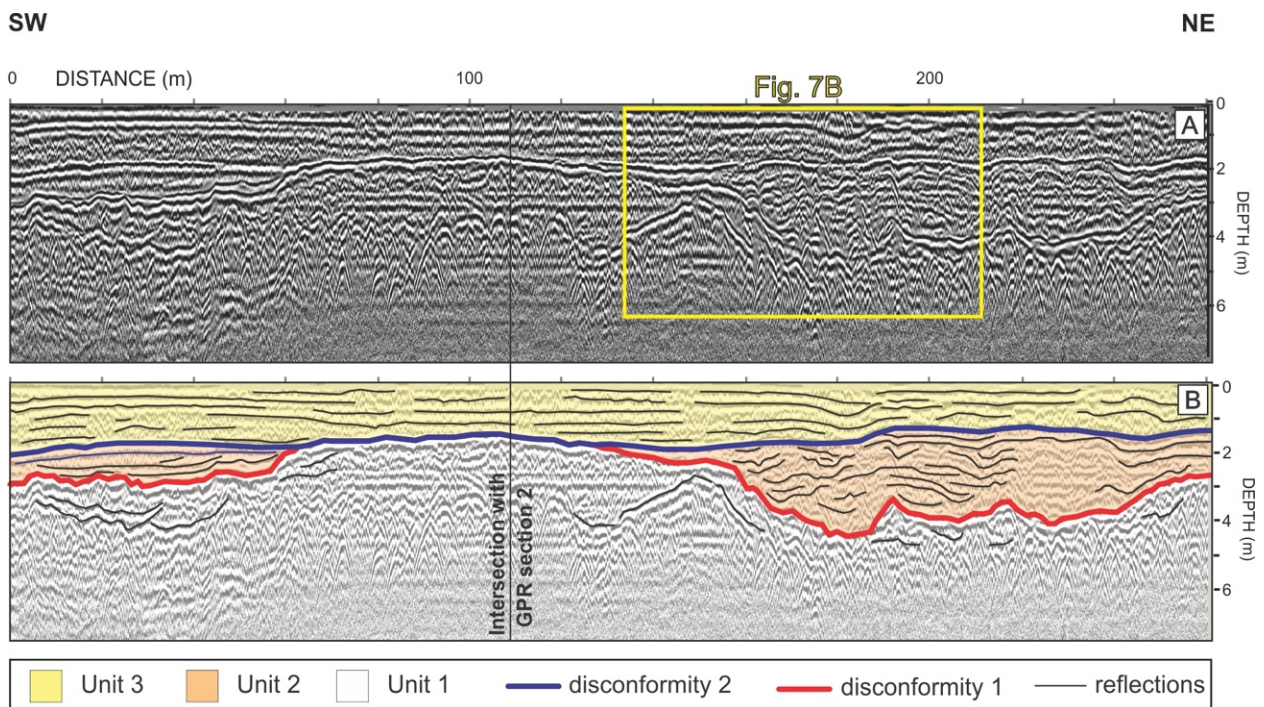
Figure 5. GPR section 5, acquired parallel to the Lindóia Salina and the surface runoff (see Figure 3C for location). The topographic surface is flat and no elevation corrections were applied. Disconformity 1 shows an incision of up to 3 meters and a concave-up profile, while disconformity 2 is characterized by a relatively flat geometry, concordant with the overlying reflections. The yellow square indicates the location of the section in Figure 7B.

Unit 3 (upper facies) has a flat and slightly irregular base and comprises the most recent deposits of Nhecolândia. The unit is approximately 2–4 m thick, and the radar facies are characterized by roughly parallel internal reflections that can laterally present divergent and convergent configurations. Radar facies geometry also indicates vertical aggradation in the lower units. Stratigraphically, the reflections exhibit low-angle convex-upward geometry beneath the sand ridges (*cordilheiras*), but pinch out laterally towards the ponds where they are mostly near horizontal.

In contrast with the morphology of ponds and sand ridges that characterize the site near the farm headquarters, the site situated 8 km to the North is a flat area where the lake landscape is being obliterated by sheet-flowing waters (Fig. 3C).

Relict-ponds morphology can be seen during the dry season, but they are connected by surface runoff waters during floods. Due to this flatness, no topographic correction was necessary during the GPR data processing, and the three sections (4, 5 and 6) are of good quality. In the surveyed sections, the two disconformities were easily recognized, and units 2 and 3 present the same patterns observed in the Southernmost sections (Fig. 6).

DISCUSSION

The GPR technique has been successfully used in the emerged areas of the Pantanal Basin to investigate shallow stratigraphy and sedimentation patterns. The data presented
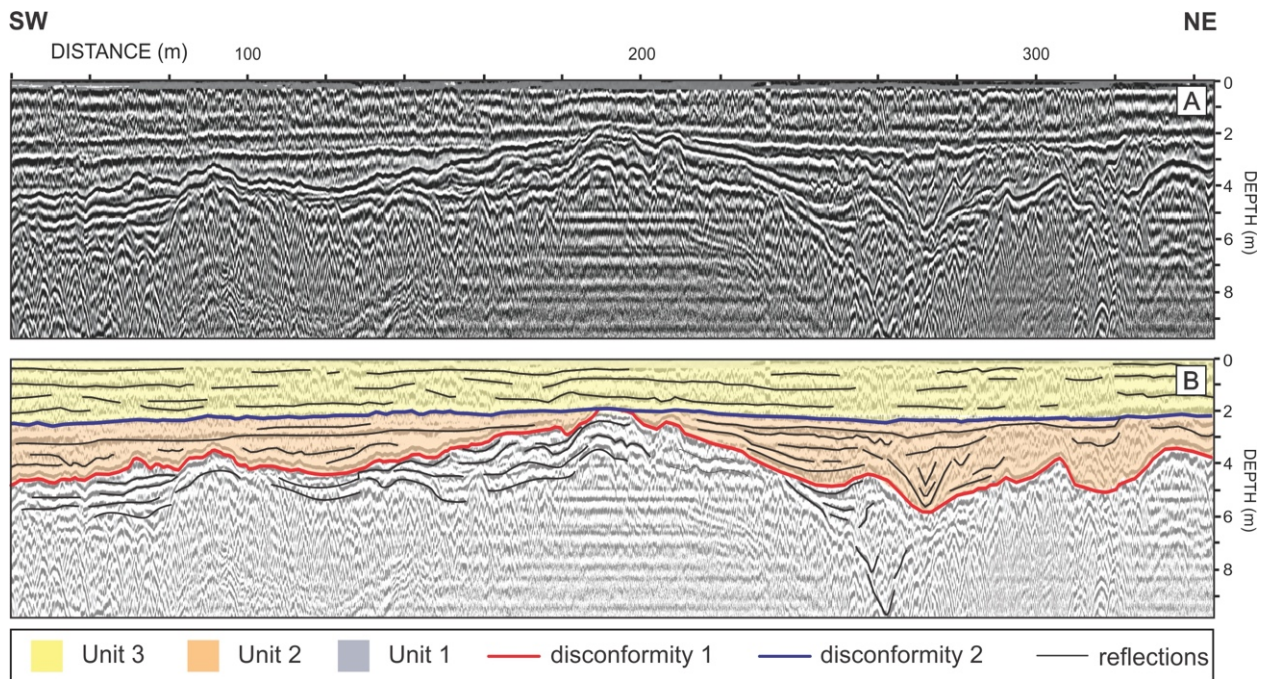

Figure 6. GPR section 6 (see Figure 3B for location), acquired perpendicularly to the surface runoff, in a flat surface (no elevation corrections were made). Disconformity 1 shows two distinct concave-up sections with up to 3 m-deep incisions.
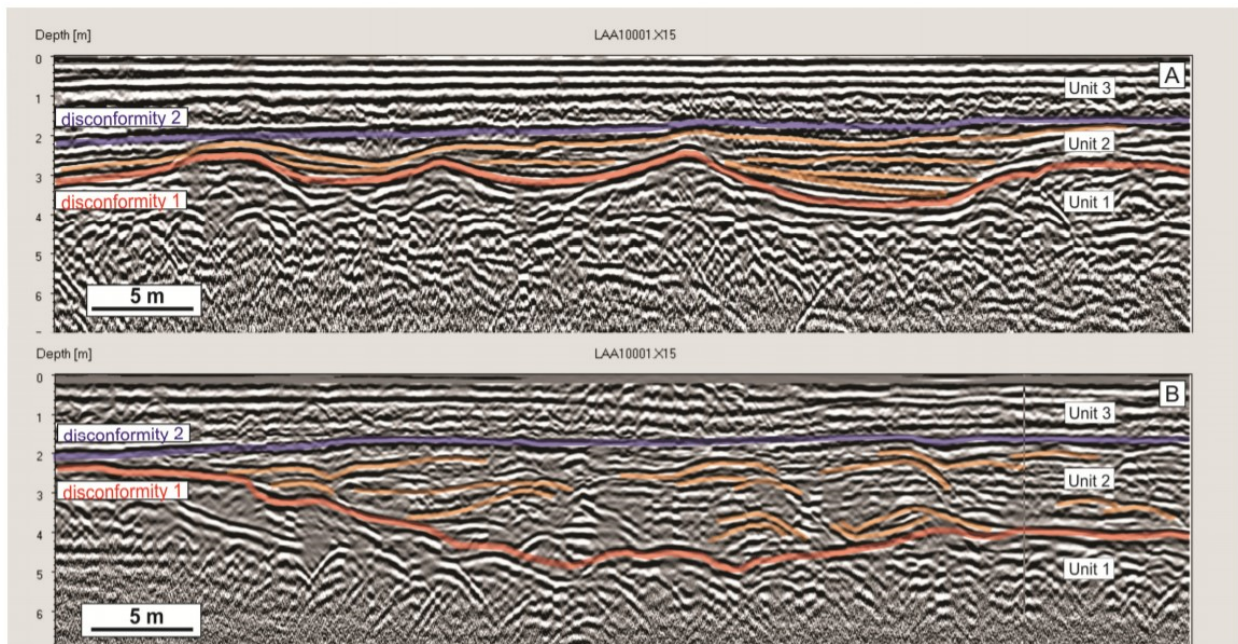

Figure 7. Fluvial channel-fill architectural elements: (A) Bar set perpendicularly to paleoflow in section 2 (location as shown in Figure 4); (B) Bar set parallel to paleoflow in section 5 (see Figure 5 for location). See Figure 3C for location.
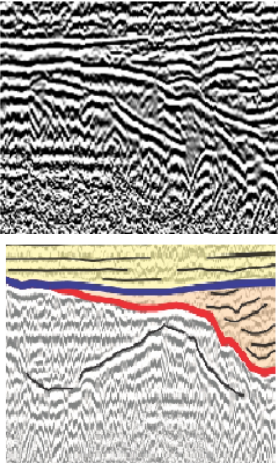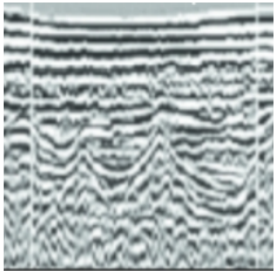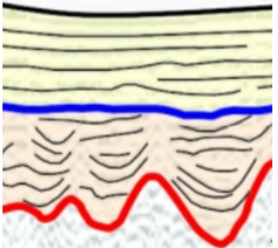
herein provides crucial information on the depositional history of the Taquari megafan, allowing the interpretation of river regimes that prevailed in the region in the past. This pioneering approach of the Taquari region allows for considerable progress in understanding the past dynamics of the alluvial rivers of the Pantanal. It enabled the identification and recognition of a number of depositional environments, ranging from distinct fluvial styles in the lowermost successions and eolian deposition and re-working at the uppermost succession.

Analyses on GPR profiles allowed the identification of two main discontinuities separating three depositional units. Unit 1 is characterized by a somewhat chaotic pattern of reflections that are commonly truncated and locally characterized by concave-up geometries. Some of the reflections are relatively continuous laterally and characterized by irregularities, with concave-up geometry locally. This unit´s collective characteristics are indicative of fluvial deposition, even though the quality of the section in this particular stratum decreases with depth.

Reflections of Unit 2 (intermediate) exhibit erosive bases and aggrading geometries, with some reflections truncated by each other and others characterized by horizontal-parallel geometry. The basal reflection of this unit is irregular, presenting troughs and ridges, as opposed to the upper reflection, which is mostly horizontal; locally, the upper reflection drapes the ridges formed by the lower bounding surface. The characteristics observed in Unit 2 indicate fluvial-system deposition preserved in the subsurface of the Nhecolândia landscape (section 2, Fig. 7A), indicating a long-term history of fluvial deposition when combined with the underlying Unit 1. Numerous, laterally related concave-up geometries of the basal surface indicate multiple and narrow channels of possible braided-channel planform; the geometries are interpreted as bar-set growth within the channel (section 5, Fig. 7B).

The radar facies in Unit 3 have a distinct pattern and present characteristics other than the strictly fluvial facies. In the lower areas, where freshwater lakes are connected during the flood seasons, the reflections are nearly horizontal, continuous and concordant. This pattern can be attributed to deposition by

Table 1. Radar facies descriptions and respective interpretations.

Radar facies	Description	Interpretation
	Unit 1 (beneath the red line) is mainly represented by a chaotic pattern (1 to 1.5 m deep) with horizontal filling; basal reflections show low-amplitude (decimetric), concave-up shape.	These features indicate possible channel deposition of markedly varying flow regimes resulting in channel fill by alternating upper and lower flow regime. Concave-up surfaces at the base of this succession indicate significant base-level drop and incision of fluvial channels into older sediments.
	The base of Unit 2 (intermediate - between blue and red lines) is very irregular and characterized by concave-up geometries. Its thickness varies from approximately less than 1 m up to 4 m; base shows erosional truncation. The radar facies present subparallel, oblique, concave-upward forms, approximately 10 m wide and from 1 to 3 m deep, separated from each other by 1 m to 2 m, and offlap geometries.	Reflections of Unit 2 (intermediate) exhibit erosive bases and aggrading geometry; recording deposits of fluvial systems. Concave-up forms record multiple and narrow channels of possibly braided-channel planform, and the geometries are interpreted as bar-set growth within channels.
	Unit 3 (above the blue line) is approximately 2 m to 4 m thick, and is characterized by a flat and slightly sinuous base. Radar facies are characterized by a moderately continuous and roughly parallel internal decimetric reflections that can laterally present divergent and/or convergent configurations. Radar facies geometries also indicate vertical aggradation in the lower units.	Radar facies of Unit 3 present distinct characteristics from the underlying fluvial facies. In the lower areas where freshwater lakes are connected during the flood seasons, the reflections are near horizontal, continuous and concordant. This pattern can be attributed to deposition by unconfined sheet-flow processes during flooding. Reflections of Unit 3 are slightly convex upward in the studied sections, and are perpendicular to the sand ridge in the Eastern border of the Lindoia saline.
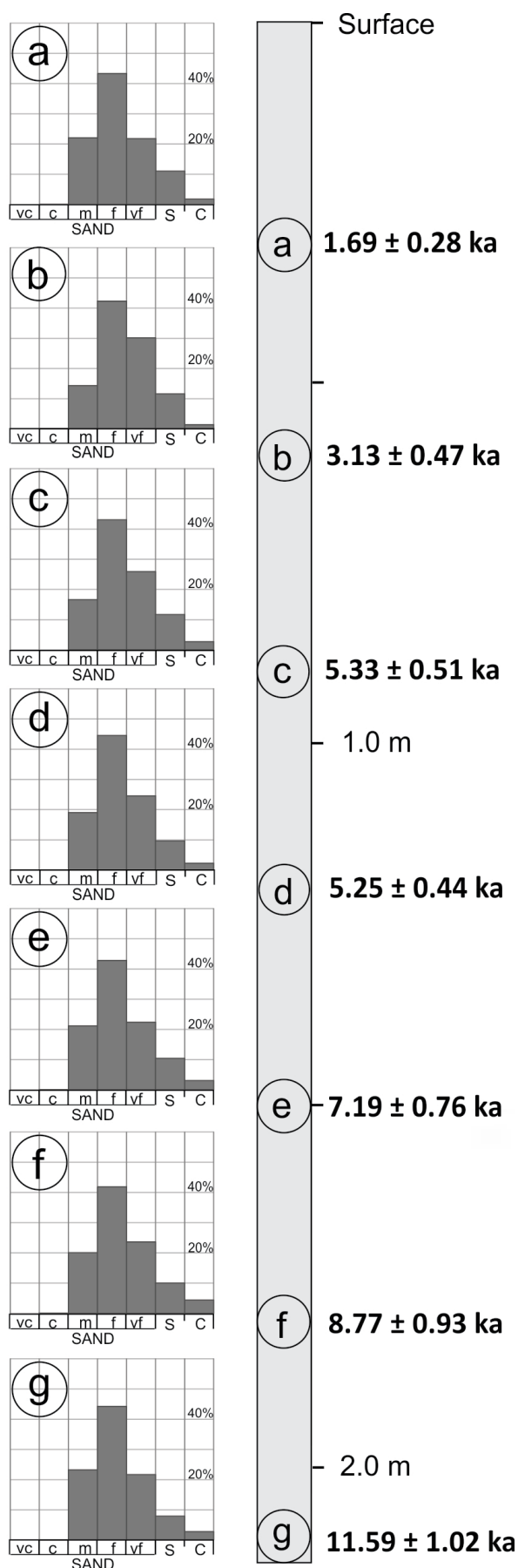
Source: modified from Mendes (2015).

Figure 8. OSD dating of samples (a-g) collected from a 2.1 m deep pit excavated in the sand ridge (Unit 3; location as shown in Figure 3). The profile is composed of average diameter sediments from fine to very fine sands (histograms of particle size distribution on the left). The ages indicate continuous accumulation during the Holocene.

unconfined sheet-flow processes during flooding. Locally, the reflections of Unit 3 are slightly convex upward in the sections, and they are perpendicular to the sand ridge on the eastern border of the Lindoia saline (Fig. 4). Sedimentological analyses on such sediments show moderate to well-sorted fine- and medium-grained sands (Soares *et al.* 2003, Mendes 2015).

An eolian origin during the Late Pleistocene maximum and glacial maximum was previously proposed by many publications in order to explain the sand ridges (Almeida 1945, 1959, Klammer 1982, Tricart 1982, Soares *et al.* 2003). Based on seven OSL dating of sand samples collected in a 2.1 meters deep pit (Fig. 8), Mendes (2015) interpreted that sand ridges were formed by eolian sand accumulation during the Holocene. A significant period of eolian deflation during the early and middle Holocene is considered to have occurred before establishing the perennial lakes in the Nhecolândia around 3,300–3,200 cal yrs BP (McGlue *et al.* 2017, Guerreiro *et al.* 2018). While our data clearly demonstrates the non-channelized nature of the processes responsible for the deposition of Unit 3, it is yet unclear if it was deposited by sheet-flow or eolian processes, or indeed a combination of both.

CONCLUSION

The GPR technique applied to the sedimentation study in the Taquari megafan provided continuous sections of good quality in both directions (parallel and perpendicular to the main channel flow). Using a frequency of 100 MHz was a good compromise between depth of investigation and resolution, reaching depths of up to 8 m and decimetric vertical detail. Therefore, the GPR technique has been successfully used in the sand-prone emersed areas of the Pantanal Basin to study shallow sedimentation structures.

The identification of two disconformities allowed the recognition of three high-frequency depositional sequences. The two older sequences record channelized forms and similar radar facies, which are related to laterally migrating channel and barform deposits.

The younger depositional sequence presents continuous and parallel reflections that indicate vertical aggradation, initiated by the end of the Pleistocene and continued throughout the Holocene. There is a strong correlation between the younger sequence´s radar facies and the depositional forms preserved in the landscape. This suggests that these features were not formed by channelized fluvial streams, but rather by sheet-flood and/or eolian processes.

ACKNOWLEDGMENTS

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