DIVISÃO 1 - SOLO NO ESPAÇO E NO TEMPO

Comissão 1.1 - Gênese e morfologia do solo

GENESIS OF TEXTURAL CONTRASTS IN SUBSURFACE SOIL HORIZONS IN THE NORTHERN PANTANAL-BRAZIL[1]

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SUMMARY

The Pantanal region can be characterized as a quaternary floodplain with predominant sedimentation in the form of alluvial fans. In the geomorphologic and sedimentary evolution, the avulsion process is inherent to this depositional system and its dynamics, together with surface water floods, influence soil sedimentation on this plain. The knowledge and differentiation of these two events can contribute to a better understanding of the variability of soil properties and distribution under the influence of these sedimentation processes. Therefore, this study investigated the genesis of soils in the Northern Pantanal with textural contrasts in deeper horizons and their relationship with the depositional system dynamics. We analyzed four soil profiles in the region of Barão de Melgaço, Mato Grosso State, Brazil (RPPN SESC Pantanal). Two profiles were sampled near the Rio Cuiabá (AP1 and AP4) and two near the Rio São Lourenço (AP10 and AP11). In AP11, the horizons contrast in particle size between the profile basis and the surface. In AP1, AP4 and AP10, the horizons overlaying the sand layer have similar particle size properties, mainly in terms of sand distribution. In the first case, floods (surface water) seem to have originated the horizons and layers with contrasting texture. In the second case, avulsion is the most pronounced process. Therefore, the two modes can form soils with contrasting texture that are discriminable by soil morphology, based on the distinct features associated to the specific sedimentation processes.

Index terms: alluvial soils, hydromorphic soils, fluvial deposition system, alluvial fans, avulsion.

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RESUMO: *ORIGEM DOS CONTRASTES TEXTURAIS DE HORIZONTES SUBSUPERFICIAIS EM SOLOS DO PANTANAL NORTE*

O Pantanal caracteriza-se por ser uma planície inundável quaternária, com sedimentação predominantemente na forma de leques aluviais. Na evolução geomorfológica e sedimentar, é inerente a esse sistema deposicional o processo de avulsão, cuja dinâmica, associada aos fluxos de águas superficiais de cheias, impõe diferenças sedimentares importantes nessa planície. O entendimento e a diferenciação desses dois eventos podem ajudar na compreensão da variabilidade dos atributos e da distribuição dos solos associados a esses processos sedimentares. Nesse sentido, o objetivo deste trabalho foi estudar a gênese de solos do Pantanal Norte que apresentam contrastes texturais em profundidade e sua relação com a dinâmica do sistema deposicional. Quatro perfis foram estudados na região de Barão de Melgaço, MT (RPPN SESC Pantanal), dois próximos ao rio Cuiabá (AP1 e AP4) e dois próximos ao rio São Lourenço (AP10 e AP11). No AP11, os horizontes apresentam contrastes granulométricos desde a base do perfil até a superfície. No AP1, AP4 e AP10, os horizontes sobrejacentes a uma camada arenosa possuem granulometria semelhante entre si, principalmente na distribuição de areia. No primeiro caso, os fluxos de cheias, ou seja, de águas superficiais, parecem ter originado os horizontes e as camadas contrastantes na textura; no segundo, a avulsão é o processo mais evidente. Dessa forma, as duas vias podem formar solos com contrastes texturais e é possível distingui-los no campo pela morfologia, pois possuem peculiaridades que estão associadas aos processos sedimentares responsáveis pelos depósitos.

Termos de indexação: solos aluviais, solos hidromórficos, sistema deposicional fluvial, leque aluvial, avulsão.

INTRODUCTION

The Pantanal is a huge sedimentary basin that comprises several depositional systems (lacustrines, alluvial fans and floodplains), which define the region as a depositional systems tract (Assine, 2003; Assine & Silva, 2009). Nevertheless, one of the most common depositional systems in this humid tropical region seems to be that of alluvial fans (Assine & Silva, 2009), in which sedimentation is mainly controlled by overbank flows on the floodplain (Bridge, 2006).

Although the term *pantanal* is derived from the Portuguese word pântano, i.e., swamp, this region consists of low plains affected by extensive and prolonged seasonal floods between January and June, with peak flood levels in distinct months, depending on the geographic features of the plain (Hamilton et al., 1996; Assine & Silva, 2009). Thus, the processes of transport and sedimentation in the Pantanal take place due to the river flooding, which takes water and sediments to areas that are not flooded during the dry season (Hamilton et al., 1996; Girard et al., 2010).

Aside from the overbank flows, which are common in this region, the peculiar dynamics of alluvial fans are characterized by the frequent construction and abandonment of a main river channel (Nichols & Fisher, 2007). This abandonment may occur due to a process known as avulsion, defined as a shift in the main channel bed of the river to a new course, causing the water course to flow through the former floodplain (Figure 1) (Mackey & Bridge, 1995; Slingerland & Smith, 1998; Assine, 2003; Stouthamer & Berendsen, 2007). During the avulsion process, firstly the levee of the river is breached and then sandy deposits are formed by the spreading of sediments transported through the channel (crevasse splay deposits) (Törnqvist & Bridge, 2002) (Figure 1).

The temporal and spatial distribution of different sedimentation processes in the Pantanal, associated to the dynamics of alluvial fans, directly influence the formation of their sedimentary architecture and, consequently, the soil distribution in the plain (Nascimento, 2012). Overbank flows and avulsion processes may directly affect the genesis of several soil properties, such as: a) the formation of a textural gradient, where fine sediments of floodplains are overlaid with sediments deposited in the avulsion process (Smith et al., 1989; Farrell, 2001); b) textural contrast in deeper layers formed due to the burial of avulsion sediments (Phillips, 2009); c) alternate horizons with different textures (fluvic characteristic - Embrapa, 2006; FAO, 2006), formed from overbank flows caused by floods (Cazanacli & Smith, 1998), among other combinations of sediment deposition.

Therefore, in soils and sediments in the Pantanal one can find horizons and layers influenced by the overbank flow. Soils with evidence of the avulsion process also occur, with peculiarities of sedimentation that distinguish them. In this sense, the aim of this work was to study the genesis of soils with textural contrasts in deeper horizons in the Northern Pantanal and their relationship with the dynamics of the depositional system.

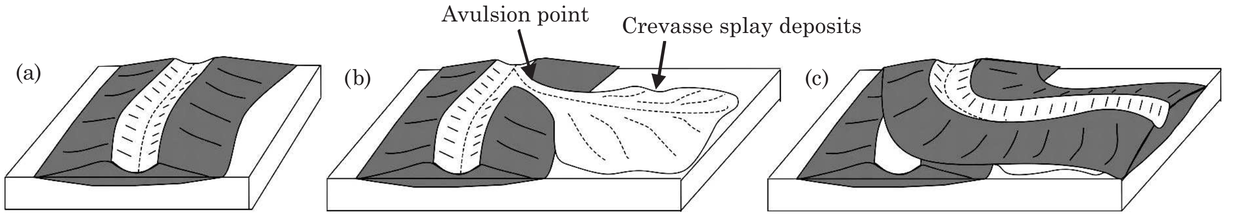

Figure 1. In the avulsion system, the levee of the river is breached (a), and water carrying sediments flows out onto the floodplain, forming crevasse splay deposits (b). Subsequently, a new river channel can be formed; however, the spread sediments can remain in the floodplain (c). Adapted from Assine (2003).

MATERIAL AND METHODS

The study was carried out in the Northern Pantanal region, in part of the 106,000 ha of the Reserva Particular do Patrimônio Natural (RPPN) Pantanal (16º 32' - 16º 49' S and 56º 03' - 56º 26' W), in Barão de Melgaço, Mato Grosso (Figure 2). In the East, the study area borders the Rio São Lourenço and in the West, the Rio Cuiabá, considered the most important rivers in the region.

The climate of the study site is Aw (Köppen classification), humid tropical with average annual pluvial precipitation of approximately 1,200 mm, characterized by rainy summers, dry winters and monthly average temperatures between 22-32 ºC. The overbank flows, which reach their peaks in the months of March/April, are caused by local and regional rains related to high water levels of rivers that drain the plain, which may be reflected in different flooding patterns (Hamilton et al., 1996). Floods in the Northern Pantanal occur between December/January and May/June, while the draining season lasts from June/July to November/December (Junk & Nunes da Cunha, 2005; Girard et al., 2010).

The studied profiles were outlined based on previous boreholes and field observations of floods in each study site during the rainy season. During the dry season, trenches approximately 2 m deep were opened, described and sampled according to Santos et al. (2005). We analyzed four profiles near rivers: two near the Rio Cuiabá and two near the Rio São Lourenço (Figure 2), respectively, in an area of floodable plains and an area at the flooding limit.

The samples were collected from the trenches, air-dried and crumbled with a rubber hammer. In order to carry out the particle size, chemical and mineralogical analyses, we sieved the soil through 2 mm mesh sieves to obtain t he Air-Dried Fine Earth (ADFE). The hydrometer method was used for particle-size analysis (Embrapa, 1997) and the sands were classified into five fractions (very coarse sand 2-1 mm; coarse sand 1-0.5 mm; medium sand 0.5-0.250 mm; fine sand 0.25-0.10 mm and; very fine sand 0.10-0.05 mm). The pH was determined in water (potentiometer), using a soil:solution ratio 1:2.5 after shaking and 1-h rest. The contents of exchangeable aluminum (Al^{3+}), potential acidity (H+Al) and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were determined as described by Embrapa (1997). The Ca^{2+}, Mg^{2+} and Al^{3+} were extracted in the solution of 1 mol L^{-1} KCl; P, K^+ and Na^+ with 0.0125 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl; H+Al with 0.5 mol L^{-1} calcium acetate at pH 7.0. The contents of Ca^{2+} and Mg^{2+} were determined by spectroscopy of atomic absorption; K^+ and Na^+ by flame photometry; Al^{3+} and H+Al by complexometric titration and P by colorimetry. The results of the chemical analyses allowed the calculation of: the cation exchange capacity in the soil [$CEC=Ca^{2+}+Mg^{2+}+K^++Na^++(H+Al)$], base saturation ($V=Ca^{2+}+Mg^{2+}+K^++Na^+x100/T$) and aluminum saturation ($m=Al^{3+}x100/Ca^{2+}+Mg^{2+}+K^++Na^++Al^{3+}$) (Embrapa, 1997).

Total carbon (C), total nitrogen (N) and carbon isotope (^{13}C) were determined in the laboratory of isotopic ecology of CENA/USP, in Piracicaba, São Paulo State, Brazil, using a dry combustion element analyzer (LECO® CN-2000) coupled to a mass spectrometer (Carlo Elba®, Delta Plus). Soil samples were collected from the trenches at intervals of 5 cm from the surface down to 20 cm depth and below this depth, pedogenetic/sedimentary horizons samples were collected and sent to a laboratory for analysis, Based on these results, the C/N ratio in the samples was established.

Undisturbed soil samples were collected from transitional horizons for micromorphological studies. The samples were collected, prepared and described according to Bullock et al. (1985) and Castro et al. (2003).

For sandy soils, samples were collected in PVC tubes (diameter 50 mm x length 200 mm), which were identified and stored according to Sallun et al. (2007). The samples were dated using optically stimulated luminescence (OSL) at the Laboratório de Datação, Comércio e Prestação de Serviços LTDA, in São Paulo City, São Paulo State, Brazil.

Samples of 13 horizons were analyzed by x-ray diffraction (XRD), according to Jackson (1979). About 30 g of each sample were weighed and subjected to elimination of organic matter and iron oxide. The samples were sieved through 0.053 mm mesh to separate the sand fraction from the silt+clay fraction. The total silt and clay were then separated by

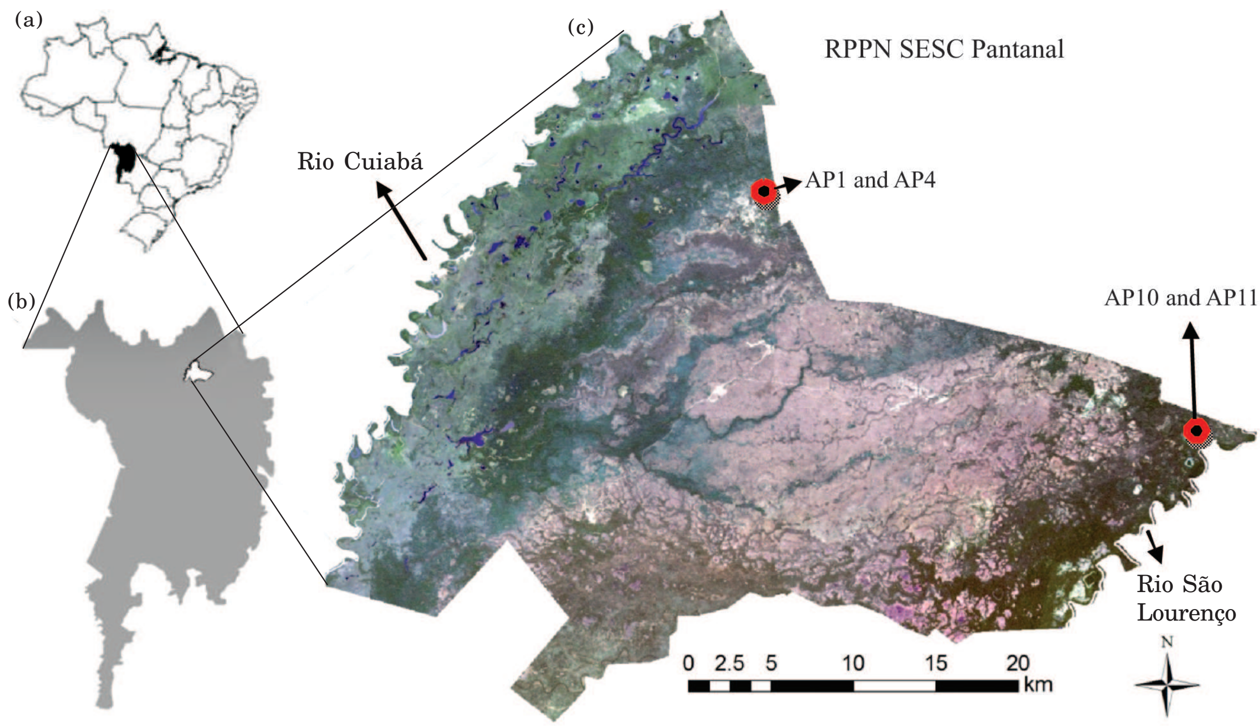

Figure 2. Study site in the Northern Pantanal. (a) location of the Pantanal region in Brazil; (b) study site in the Pantanal; (c) location of soil profiles in RPPN SESC Pantanal - SPOT imaging.

sedimentation according to Stokes' Law. Glass slides with oriented clay were subjected to the following treatments: Mg^{2+} at room temperature (25 °C); Mg^{2+} solvated with ethylene glycol (EG); K^+ at room temperature (25 °C); K^+ heated to 300 °C; K^+ heated to 500 °C.

These samples were irradiated at 3-35 °2θ in an x-ray diffractometer, using a step size of 0.02 °2θ and a counting time of 1 s per step, at tension 35 kV and current 15 mA. The sand and silt powder samples were irradiated at 5-70 °2θ, under the same conditions of step size, counting time, tension and current. The x-ray device Rigaku MiniFlex II was used, with copper (CuKα) radiation and a graphite crystal monochromator.

The mineralogy of the fine clay (<0.2 µm) fraction was also analyzed. The fine clay was separated by repeated centrifugation for 23 min at 4,100 rpm (refrigerated Sorvall centrifuge with 750 mL tubes). The supernatant was collected until limpid, indicating the absence of minerals <0.2 µm in suspension. The time required to obtain the supernatant contained in fine clay was calculated by equation 1:

$$t = \frac{[(63x10^8) \text{ x } n \text{ x } \log R/S]}{N^2 \text{ x } d \text{ x } \Delta S} \quad (1)$$

where: t = time in min; n = viscosity of the medium in poises; R = radius from the center of the centrifuge to the lower extremity of the tube in horizontal position (in cm); S = radius from the center of the centrifuge to the superior extremity of the tube in horizontal position (in cm); N = rotation speed (in rpm); d = maximum diameter of the particles in suspension (0.2 µm); ΔS = difference of the specific weight of material (silicates 2.653 Mg m^{-3} approximately) and liquid (water 1.0 Mg m^{-3}) (Jackson, 1979). After separation, the fine clay was subjected to the same procedures as total clay.

All mineralogical analyses were carried out in the mineralogy laboratory of soils of ESALQ/USP, Piracicaba, São Paulo State, Brazil.

RESULTS

Four soil profiles, two from near the Rio Cuiabá (AP1 and AP4) and two from near the Rio São Lourenço (AP10 and AP11), were sampled in floodable areas or at the limit with non-floodable areas. In the samples collected from the Rio Cuiabá, we observed floods up to 50 cm in AP1 and 5-10 cm in AP4 in March 2011. In the profiles from sites near the Rio São Lourenço, floods reached 80 cm in AP10 and 10 cm in AP11 in the same period. At both sites, the vegetation cover is composed of Cambará (*Vochysia divergens*) and shrubby and herbaceous understory.

The soil morphology, particle size and chemical analyses showed that, in deeper layers, the texture contrasts greatly between the profiles (Table 1). These patterns seem similar in the profiles AP1, AP4 and

Table 1. Particle size and main morphological and chemical properties of the profiles studied

Horizon	Depth	Color(1)		Str.(2)	Clay	Silt	Sand	pH(3)	CEC	V	m	C
		Matrix	Mottle									
	cm				g kg-1				cmol$_c$ kg-1	%		
AP1 - Plinthic Gleysol (Dystric)(4)												
A	0-5	10YR 4/1		GR	270	540	190	4.8	8.7	28	36	2.1
AB	5-15	2.5Y 6/1	10YR 6/8	SA	290	550	160	4.9	6.0	37	36	0.7
Btg1	15-30	2.5Y 6/1	10YR 6/8	AB-SA	420	530	50	5.1	8.2	40	33	0.7
Btg2	30-75	2.5Y 6/1	10YR 5/8	PR-SA	400	520	80	5.2	10.1	39	44	0.4
C	75-80	10YR 7/1		SG	30	100	870	5.2	1.4	33	23	0.1
2Cr1	80-90	10YR 4/1	10YR 7/8	MC-SA	280	430	290	5.1	6.8	46	30	0.3
2Cr2	90-110	10YR 5/1	10YR 7/8	MC-SA	250	310	440	5.2	5.5	48	27	0.2
2Crv1	110-145	10YR 5/1	10YR 6/8	MC-SA	400	250	350	5.5	7.8	42	26	0.2
2Crv2	145-200+	10YR 5/1	10YR 4/8	MC-SA	360	350	290	5.7	6.6	56	13	0.2
AP4 - Haplic Stagnosol (Alumic, Siltic)												
A	0-10	10YR 3/2		SA-GR	110	400	490	4.6	4.1	21	50	0.7
Ev	10-20	10YR 7/1	7.5YR 5/6	SA	190	490	320	4.8	5.2	14	75	0.4
Btg1	20-45	10YR 7/1	5YR 4/4	SA	330	520	150	5.0	8.9	21	72	0.2
Btg2	45-130	10YR 6/1	5YR 5/8	PR-SA	310	570	120	5.2	10.0	42	36	0.2
2Btg3	130-140	10YR 6/2	10YR 6/8	PR-SA	580	330	90	5.7	12.7	49	35	0.3
2Cr1	140-150	10YR 6/2		MC-SA	250	120	630	na	na	na	na	na
2Cr2	150-190+	10YR 7/1		MC-SA	380	250	370	6.0	8.5	47	37	0.1
AP10 - Haplic Gleysol (Alumic, Clayic)												
A	0-30	2.5Y 2,5/1		SA	690	260	50	4.7	21.4	29	36	3.2
E	30-50	10YR 4/1	10YR 7/8	SA	440	490	70	4.4	11.2	11	81	0.8
Btgc1	50-105	10YR 4/1	2YR 6/8	PR-SA	660	320	20	4.7	16.7	10	87	0.6
Btgc2	105-150	2Y 4/1	2YR 6/8	PR-SA	630	310	60	4.9	14.7	17	78	0.5
Cr1	150-157	10YR 5/1		MC	230	100	670	5.0	5.0	18	74	0.2
2Cr2	157-170	10YR 5/1	2.5YR 5/8	MC	360	400	240	4.9	9.8	20	70	0.3
3Cr3	170-200+	2.5YR 5/1		MC	150	80	770	5.0	3.2	24	58	0.1
AP11 - Fluvic Cambisol (Ruptic, Alumic)												
A	0-10	10YR 3/1		SA	440	240	320	4.6	14.5	28	36	1.7
Bg1	10-65	10YR 5/1	10YR 8/6	SA	250	250	500	4.7	6.2	14	73	0.4
2Bg2	40-65	2.5Y 4/1	2.5YR 5/8	SA	440	260	300	4.8	10.7	15	78	0.6
3Bg3	65-85	10YR 5/2	10R 4/8	SA	230	110	660	4.9	5.2	17	71	0.3
4Cl	85-165	2.5Y 5/1	2.5YR 5/8	SA	680	260	60	5.0	15.6	19	76	0.6
5Cli	165-200+	2.5Y 6/1	2.5YR 5/8	SA	850	120	30	5.0	18.2	22	70	0.6

CEC: cation exchange capacity; V: base saturation; m: aluminum saturation; C: total carbon. (1) Moist soil; (2) Structure: GR=granular; SA= subangular blocky; AB= angular blocky; PR=prismatic; SG=single grain; MC= massive coherent; (3) pH in water; (4) Soil classification according to FAO (2006). na=not analyzed.

AP10 and different in AP11. In AP11, particle size variations are observed from one horizon to another from the soil surface to a depth of 2 m. On the other hand, in the other profiles, we observe that above a sandier horizon or layer (AP1 - C 75-80 cm; AP4 - 2Cr1 140-150 cm; AP10 - Cr1 150-157 cm), the particle size distribution of the other horizons is relative homogenous up to the surface, without the variations observed in AP11.

The sand fraction distribution showed that the sandy layers/horizons in AP1 (C 75-80 cm), AP4 (2Cr1 140-150 cm) and AP10 (Cr1 150-157 cm) differ from the horizons above and below in terms of sand distribution and content (Figure 3). In AP11, nearly all horizons differ in the total sand content, whereas the distribution of the different sand fractions seems similar in all horizons (Figure 3). Moreover, in AP1, where we observe a sandy layer closer to the surface (75-80 cm), the overlaying horizons show basically the same sand fraction distribution as observed in the horizons underneath the sandy layer, although with a lower total sand content (Figure 3 a).

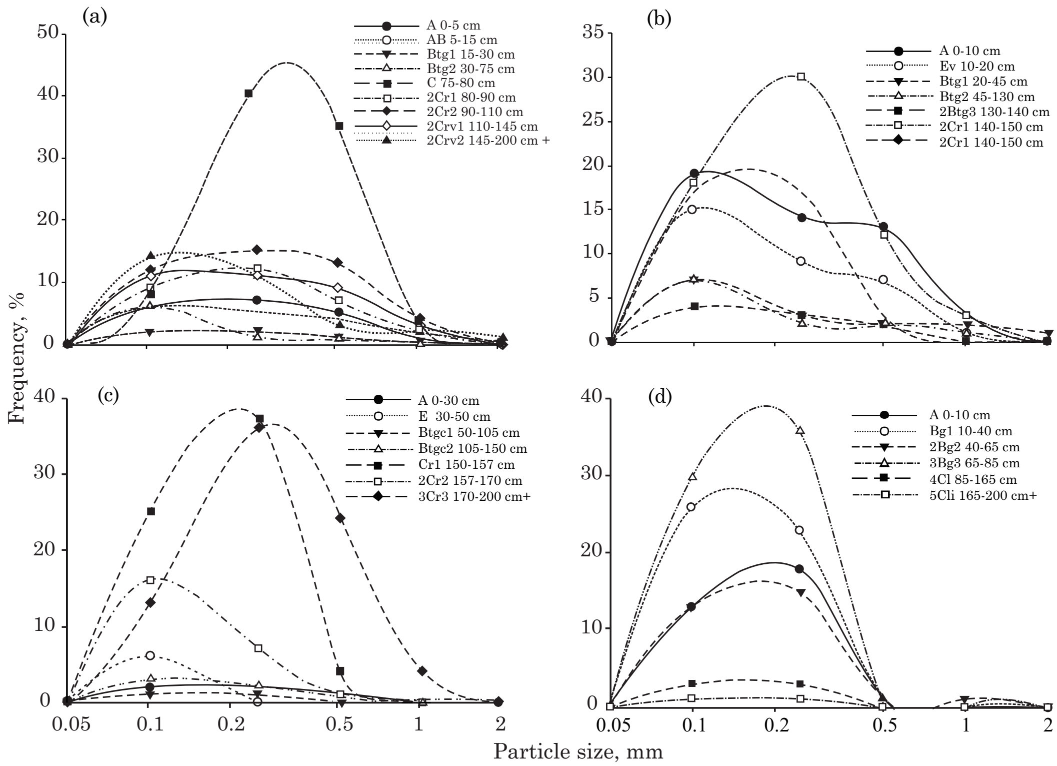

Figure 3. Sand fraction distribution (0.05-0.1 mm - very fine; 0.1-0.25 mm - fine; 0.25-0.5 mm - medium; 0.5-1 mm - coarse; 1-2 mm - very coarse) of AP1(a), AP4 (b), AP10 (c) and AP11 (d).

These textural differences are reflected, in some ways, in the morphological properties of these soils. In AP11, where the particle size variation between horizons is high, other soil properties vary similarly, mainly soil color, CEC and total C content. On the other hand, the horizons above the sandy layer in the other profiles (AP1, AP4 and AP10) were mainly similar in color and structure (prismatic), while the total C increased toward the surface (Table 1). In AP11, where the properties vary from horizon to horizon, the deposition process due to overbank flow seems to have formed these soils. In the second case, (AP1, AP4 and AP10), avulsion may be involved in the soil formation.

The profiles with evidence of an avulsion process show a clear reduction of total C content in the sandy layer (AP1 - C 75-80 cm; AP10 - Cr1 150-157 cm), compared to the total C content in the over- and underlying horizons. In AP1, for example, where there is only one sandy layer in the middle of horizons with predominant fine sediments, the total C content increases from the deeper layer to this sandy layer, decreasing in the sand layer itself and increasing again toward the surface. This shows strong evidence of soils that underwent an avulsion process, which is a rarer event, but with greater energy and capacity of sediment transport and deposition. This does not occur in soils derived from overbank flow deposits, a more frequent event on the compartment of the fluvial system and with less energy (Nichols, 2009).

The pH, V and m show little influence of these sedimentary variations. We observe a slight increase of V and pH, and decrease of m values in the horizons or layers underlying the sand layer originated from avulsion systems. In the overlying horizons, the results are the opposite. There is a slight decrease of V and pH and increase of m (Table 1). Furthermore, the structure of horizons over- and underlying the sandy layer is clear, once the underlying horizons are massive with some subangular blocks, and the overlying horizons show prismatic aggregates while the sandy layer may have a single grain or massive structure (Table 1).

The micromorphological analyses of the boundaries in these horizons with evidence of an avulsion process corroborated the hypothesis of textural discontinuity shown by the soil morphology, particle size and chemical data, in view of the abrupt limits between horizons with coarser particles and other fine-particle-sized horizons, as seen mainly in AP1 and AP4 (Figure 4 a,d).

The dating using optical stimulated luminescence (OSL) in horizon C (75-80 cm) in AP1, since only in this horizon a great quantity of pure quartz was observed, estimated an age of 12 ka BP (±4.7 ka). This means that the last time these sediments received solar radiation was around 12 ka ago, indicating that all overlying horizons were deposited and subjected to pedogenetic processes since the end of Pleistocene and beginning of the Holocene.

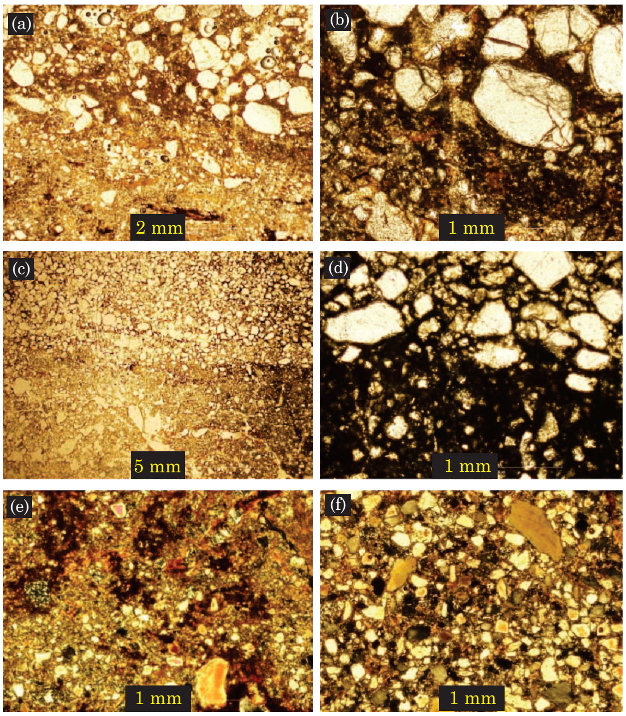

Figure 4. Photomicrograph of profiles AP1 (a and b: 78-88 cm), AP4 (c and d: 143-153 cm) and AP10 (e and f: 148-157 cm) that show coarse over finer sediments, evidencing the abrupt texture discontinuity.

In addition to the above differences, sedimentary variations provided differences of carbon isotopic fractionation. In the four profiles, the carbon isotopic fractionation from the deeper horizons to soil surface showed, in general, an isotopic signal of enriched carbon from the profile basis up to 30-20 cm, with a pronounced signal between -20 and -16 ‰ (Figure 5). In the horizons or layers of the profiles AP1, AP4 and AP10, where sedimentary variations seem to be associated to the avulsion process, there is abrupt impoverishment in the isotopic signal in the sandy layer of each profile (AP1 80 cm; AP4 140 cm; AP11 160 cm), exactly where changes in C contents occur. On the other hand, despite the variations in the total C content in AP11, the carbon isotopic signal does not abruptly vary according to the textural contrast or C content. Moreover, the C/N ratio also follows the carbon isotopic signal observed for AP1, AP4 and AP10 (Figure 5 b,d).

The mineralogical matrix of total clay before and after the layers or horizons formed by avulsion processes in AP1, AP4 and AP10, is similar, and is basically kaolinitic with mica and smectite in small amounts (Figure 6). Similarly, the under and overlying horizons to layers formed by avulsion processes show the same mineralogical fine clay matrix; however, in this fraction, the intensity of the smectite peaks increased in all samples analyzed (Figure 7). The relative amount of smectite in the fine clay of the horizons overlying the sandy layer seems greater than in the underlying horizons.

Similar to total and fine clay, in the sand and silt fractions of the horizons before and after the avulsion process, the same mineralogy was observed, with mainly quartz with mica and anatase in small amounts (Figure 8).

DISCUSSION

The results suggest that the textural contrasts in deeper layers and horizons in the soils studied in Northern Pantanal are related to two processes correlated with a fluvial system responsible for sediment deposition: avulsion and overbank flows.

The overlapping of layers, as seen in AP11, result from the overbank flows that, in the rainy season, overpass the river levees and carry sediments, resulting in the deposition of fine and coarse layers (Cazanacli & Smith, 1998; Nichols, 2009). Although this type of sediment deposition provides important particle size differences that are reflected in the soil morphology and C content, it does not influence the carbon isotopic signal and its C/N ratio, indicating homogenous vegetation in this depositional environment (Hall et al., 2012). On the other hand, in soils with textural differences connected to the avulsion process, as in AP1, AP4 and AP10, there is variation of the profile morphology and particle size, with a concomitant abrupt impoverishment of the carbon signal followed by a decrease in the C/N ratio.

The abrupt change in the carbon isotopic signal and C/N ratio in the sediments related to the avulsion process may be attributed to a greater contribution of C3 plants or algae, both with impoverished isotopic signal (Talbot & Johannessen, 1992; Meyers & Lallier-Vergès, 1999). During the avulsion process, the main river levee is breached first, and then sand deposits are formed due to the sediments carried by the channel (Törnqvist & Bridge, 2002). Therefore, the impoverishment of the carbon isotopic signal in these sandy layers may have been attributed to the sediments from the levees that were breached during the avulsion process, given that they are covered mainly by C3 plants (Nunes da Cunha & Junk, 2010), generating, therefore, an impoverished carbon signal in sediment deposits (Boutton et al., 1998). However, the isotopic signal analyzed together with the C/N ratio indicate that the signal impoverishment in these sandy layers may be related to a longer flooding period that allowed algal activity (Talbot & Johannessen, 1992; Meyers & Lallier-Vergès, 1999). This corroborates the fact the after the avulsion process, almost all water flow is deviated to these locations subjected to sediment deposits (Assine, 2003), forming an environment with shallow waters that may remain until a new river channel is formed (Smith et al., 1989; Stouthamer, 2001), favoring algal growth (Meyers & Lallier-Vergès, 1999).

The data of the profiles with evidence of the avulsion process suggest that these locations were initially environments with less energy, probably plains, which were subsequently influenced by the avulsion process in their proximity. Even afterwards, they continued to receive fine sediments, i.e., remained part of the floodable plain (Smith et al., 1989), becoming a fine-particle-size horizon below and above this sandy layer influenced by the avulsion process. Most likely, the locations that had a small sandy layer were close enough to the avulsion point to receive the sediments and far enough away to prevent the formation of a new river channel on its sediments (Smith et al., 1989; Mackey & Bridge, 1995).

The under and overlying horizons to the sandy layers differed from one another in terms of soil morphology and other properties. The wetting and drying processes of surface horizons together with the presence of high-activity clay (Figures 6 and 7) contributed to the formation of a prismatic soil structure, which was not observed in the horizons beneath the layer. This sandy layer impedes the alternation of wetting and drying processes in underlying layers because it interrupts the profile capillarity, keeping the underlying horizons wetter during the draining season in the Pantanal, resulting in the massive structure with low pedogenesis. The wetting and drying in the overlying horizons may also trigger ferrolysis (Brinkman, 1970), which would explain the high Al saturation in these horizons (Table 1). The post-avulsion horizons have greater clay contents, which favor CEC, as observed in AP1, AP4 and AP10.

In all soils with avulsion evidence, the horizons overlying the sand deposits have a finer texture (silt and clay). Regarding sedimentation, this is reasonable, since the overlying horizons are formed from an environment with less space for sedimentation (Muto & Steel, 2000), less energy (Nichols & Fisher, 2007), and lower capacity to transport coarse sediments such as sand (Nichols, 2009).

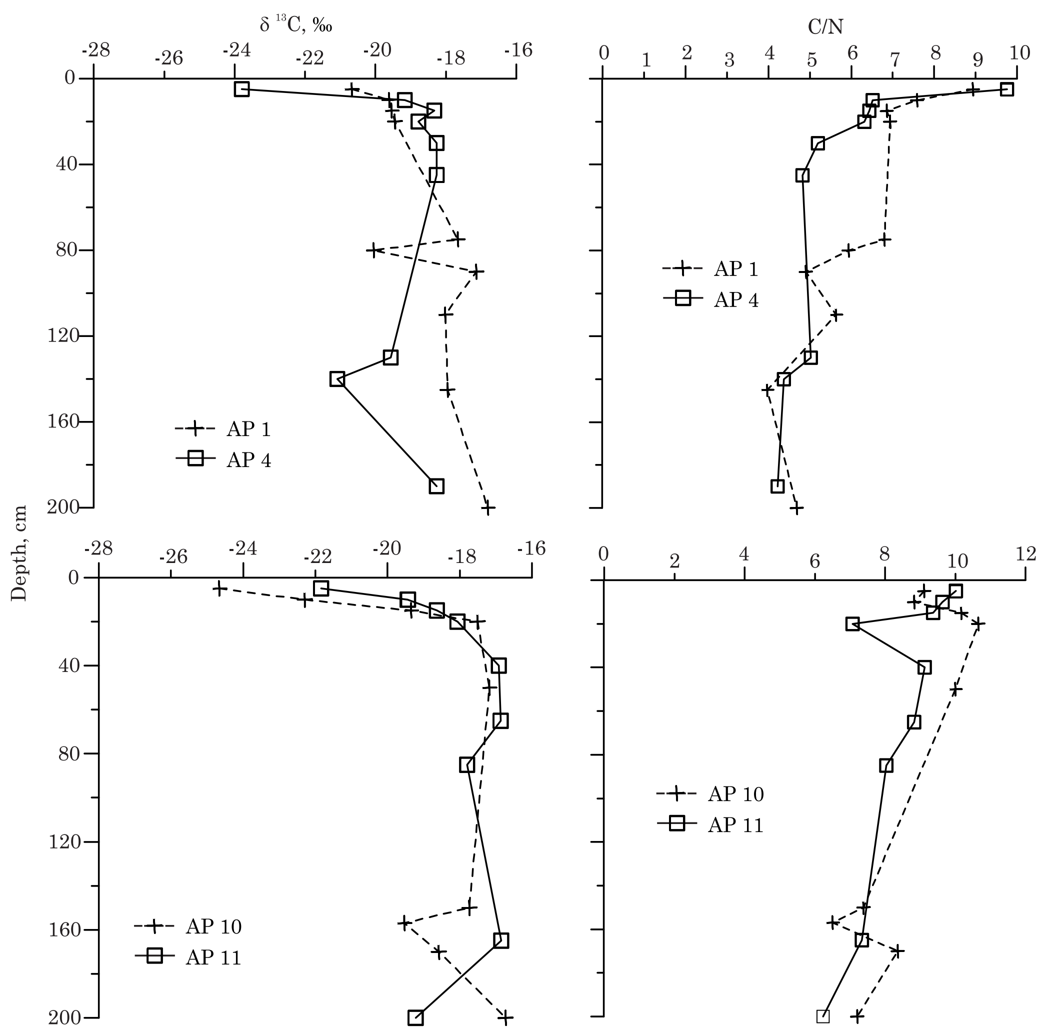

Figure 5. δ^{13}C and C/N ratio of horizons and layers in AP1, AP4, AP10 and AP11.

The establishment of the low-energy system after avulsions does not affect the mineralogical assemblage of the sand, silt and clay fractions. In the sand and silt fractions of the horizons before and after the avulsion process, the soil mineralogy is predominantly quartz and mica and in the fine and total clay kaolinite, with little mica and smectite. The only difference was observed in fine clay, where the relative

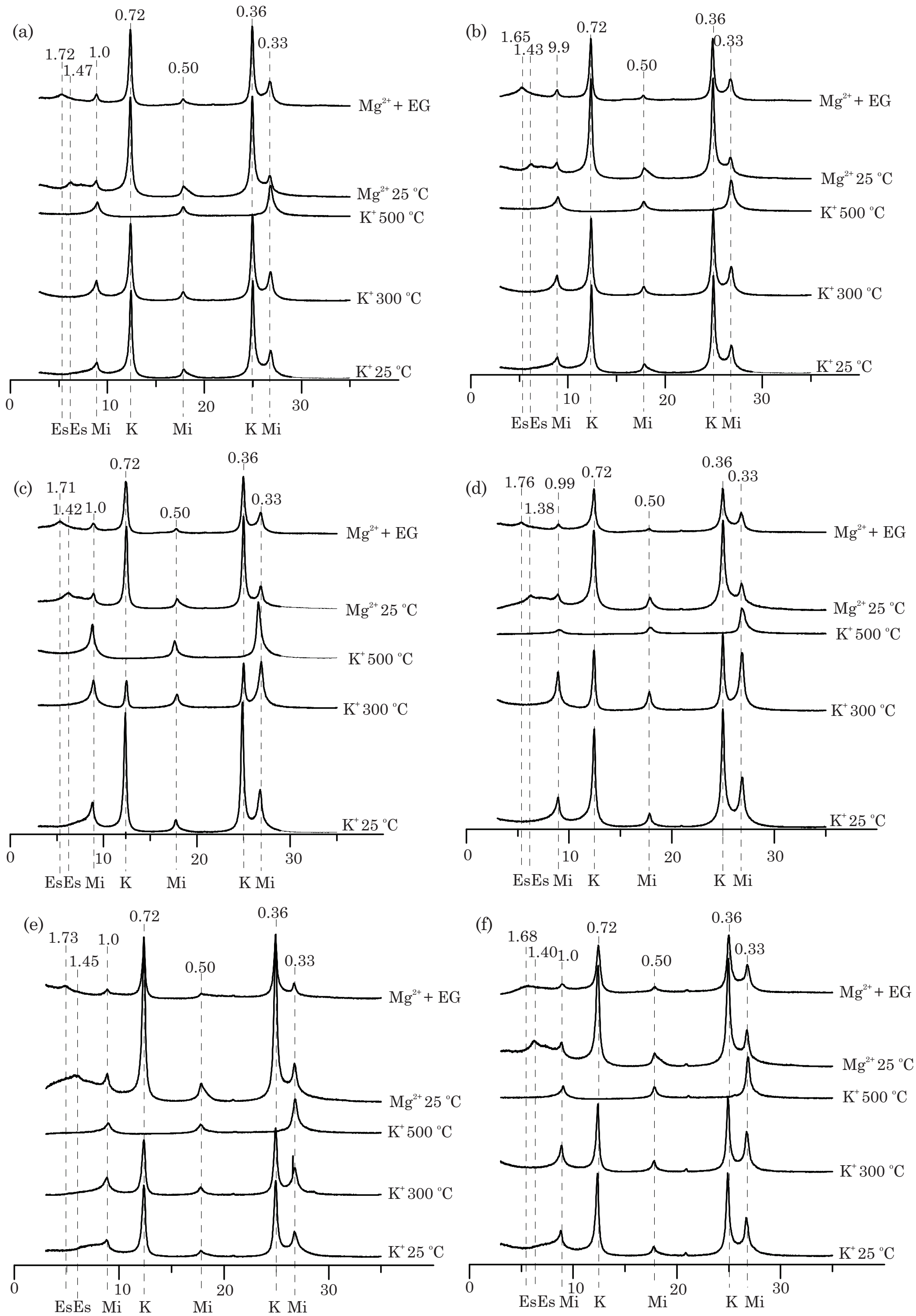

Figure 6. Diffractograms (°2θ CuKα) of total clay in horizons after (a, c, e) and before (b, d, f) the avulsion process in AP1: (a) 30-75 cm - post, (b) 145-200 cm - pre; AP4: (c) 30-45 cm - post, (d) 150-190 cm - pre; and AP10: (e) 105-150 cm - post. K=Kaolinite, Mi=Mica, Es=Smectite.

amount of smectite after avulsions was greater than in the horizons before avulsions. Since the depositional system after avulsions is characterized by low energy, a more concentrated environment may have been established, leading to the greater neoformation of smectite (Humphries et al., 2010). The same mineralogical assemblage in the sand and silt fractions before and after avulsion was probably related to the basin geology of the Rio Cuiabá and Rio São Lourenço that supply this region of the Pantanal (Franco & Pinheiro, 1982; Ross & Santos, 1982). In these catchment areas, the sediment sources are predominantly rocks of eolic sediments that contain great amounts of quartz (Barros et al., 1982; Del'Arco

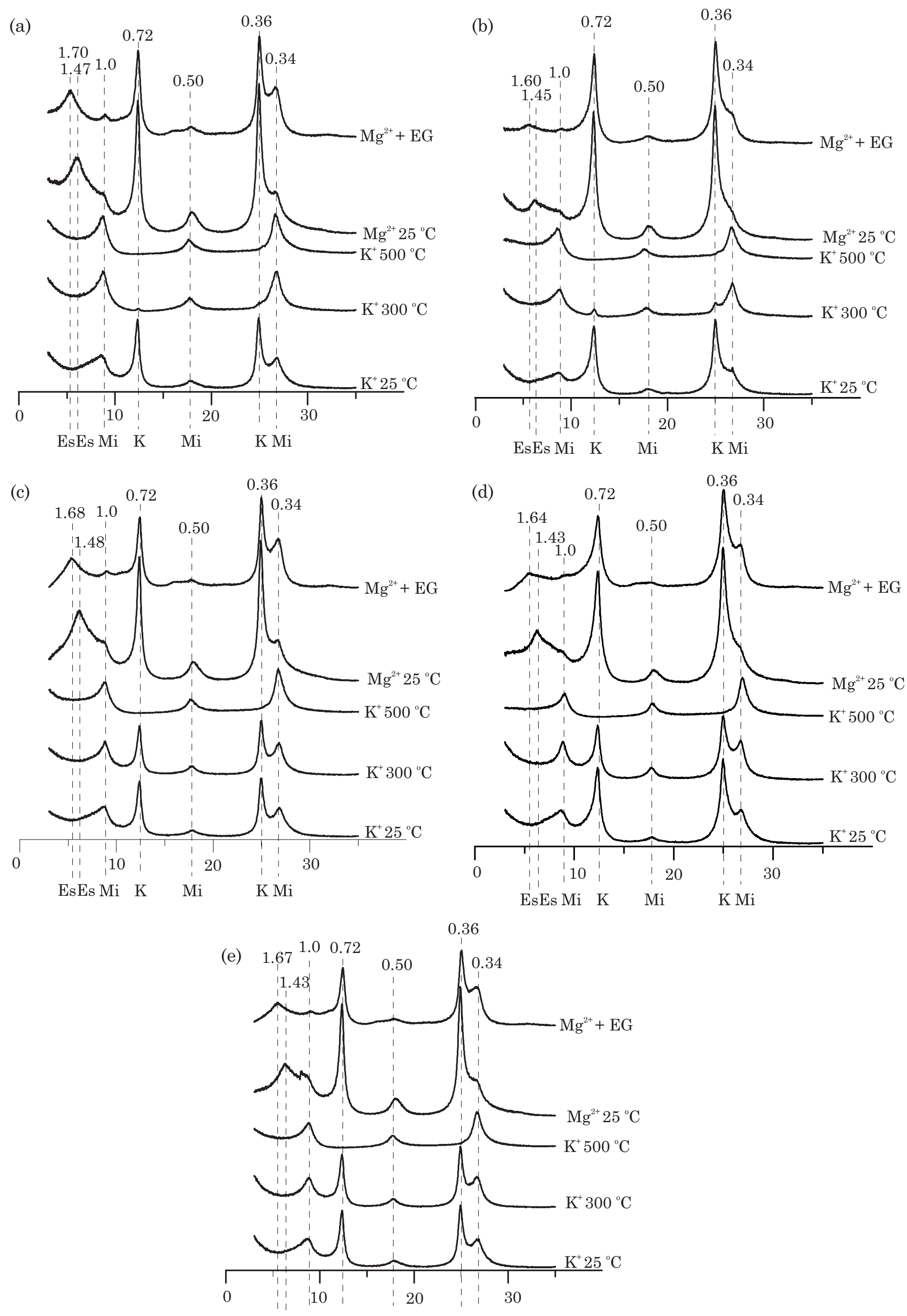

Figure 7. Diffractograms (°2θ CuKα) of fine clay in horizons after (a, c, e) and before (b, d) the avulsion process in AP1: (a) 30-75 cm - post; (b) 145-200 cm - pre); AP4: (c) 30-45 cm - post, (d) 150-190 cm - pre; and AP10: (e) 105-150 cm - post. K=Kaolinite, Mi=Mica, Es=Smectite.

et al., 1982), which explain the wide occurrence of this primary mineral in the sand and silt fraction in the soils studied.

The dating of the sand layer in AP1 (75-80 cm) indicates that these sediments last received solar radiation approximately at the end of the Pleistocene and at the beginning of the Holocene (ICS, 2010). Thus, their formation could be related to an environment dominated by winds, as in the Southern region of Pantanal (Soares et al., 2003), since at the end of the Pleistocene and at the beginning of the Holocene the climatic conditions for this were favorable (Almeida, 1945; Colinvaux et al., 2000; Stevaux, 2000; Clark et al., 2009). However, analyzing the thickness, particle size and frequency of the sand fraction in the layer, this seems unlikely, because the package and the selection degree of the sand grains would be greater (Nichols, 2009). Moreover, in the Northern Pantanal, no other evidence in the relief would corroborate the hypothesis of an eolic trait in this region (Colinvaux et al., 2000), even if the climatic conditions were favorable for this (Almeida, 1945; Stevaux, 2000). The formation of this layer may also be attributed to the role of soil genesis; however, given that sedimentation, morphological and micromorphological evidences show a great variation in the properties between the horizons, e.g., in sand frequency and the abrupt and submillimetric contact of fine sediments under coarse ones, this seems unlikely from the pedogenetic perspective (Schaetzl, 1998).

Questions regarding the eolic environments also arise when observing the silt content in the horizons after avulsions, mainly in AP1 and AP4, which surpasses 50 %. However, as mentioned above, in the catchment area there are eolic-origin sedimentary rocks, which are generally silt-rich (Barros et al., 1982; Del'Arco et al., 1982). Therefore, the large amount of silt in the catchment area together with the low energy of the fluvial system after avulsions are probably the factors that explain this increased amount of silt in these soils.

Based on the discussed evidences, on geomorphological data (Nascimento, 2012) and the literature (Smith et al., 1989; Mackey & Bridge, 1995; Cazanacli & Smith, 1998; Slingerland & Smith, 1998; Farrell, 2001; Törnqvist & Bridge, 2002; Assine, 2003; Nichols & Fisher, 2007; Stouthamer & Berendsen, 2007; Nichols, 2009), an illustrative model can be constructed to define how the fluvial evolution occurred, resulting in the genesis of the soils studied (Figure 9).

Firstly, in all soils, an active river channel (Figure 9a) underwent an avulsion process forming sediment deposits (Figure 9b) that buried the old surface and its related soils (Paleosols). In this stage (Figure 9b), which can last until a new channel is established, the presence of water seems frequent, provided the water that reaches this point is not canalized (Farrell, 2001). Furthermore, as the river brings sediments, small ephemeral channels may be formed, mainly near the avulsion point, which are easily eroded in rainy seasons (Smith et al., 1989; Farrell, 2001). The evolution of this avulsion process, with constant sediment transport by surface water flow reaching these sites, led to the formation of a new river channel (Figure 9c1,d1). After the new channel is formed, fine sediments start being carried to the floodplains, burying the sediment deposits

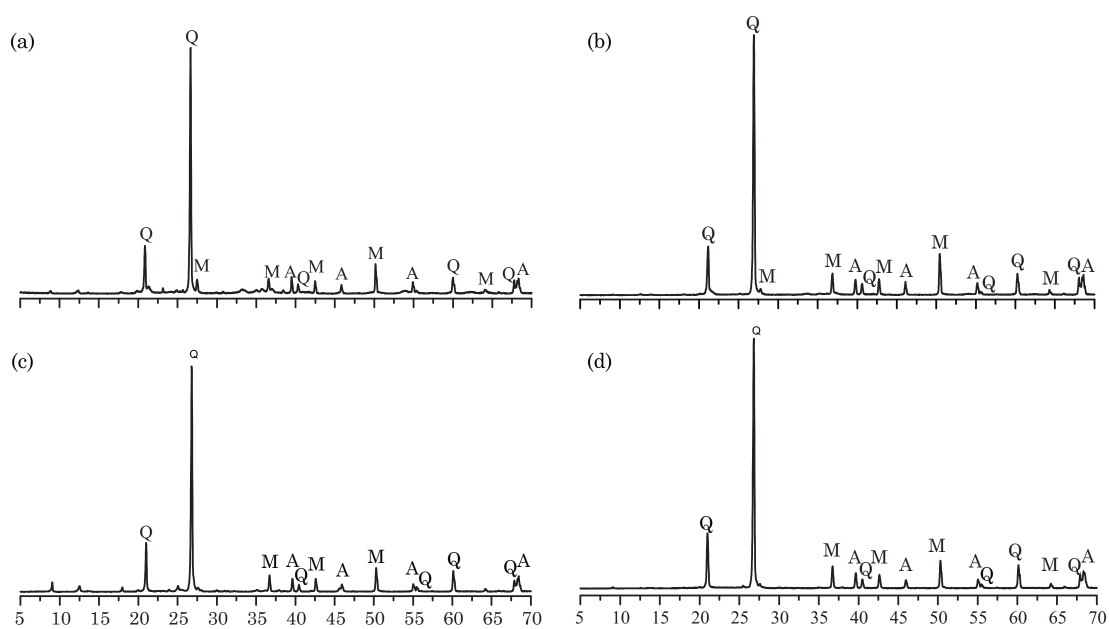

Figure 8. Diffractograms (°2θ CuKα) of sand in AP1: (a) 30-75 cm, (b) 145-200 cm), and silt in AP10: (c) 105-150 cm, (d) 170-200 cm, in horizons before (b, d) and after (a, c) the avulsion process. Q=Quartz, M=Mica, A=Anatase.

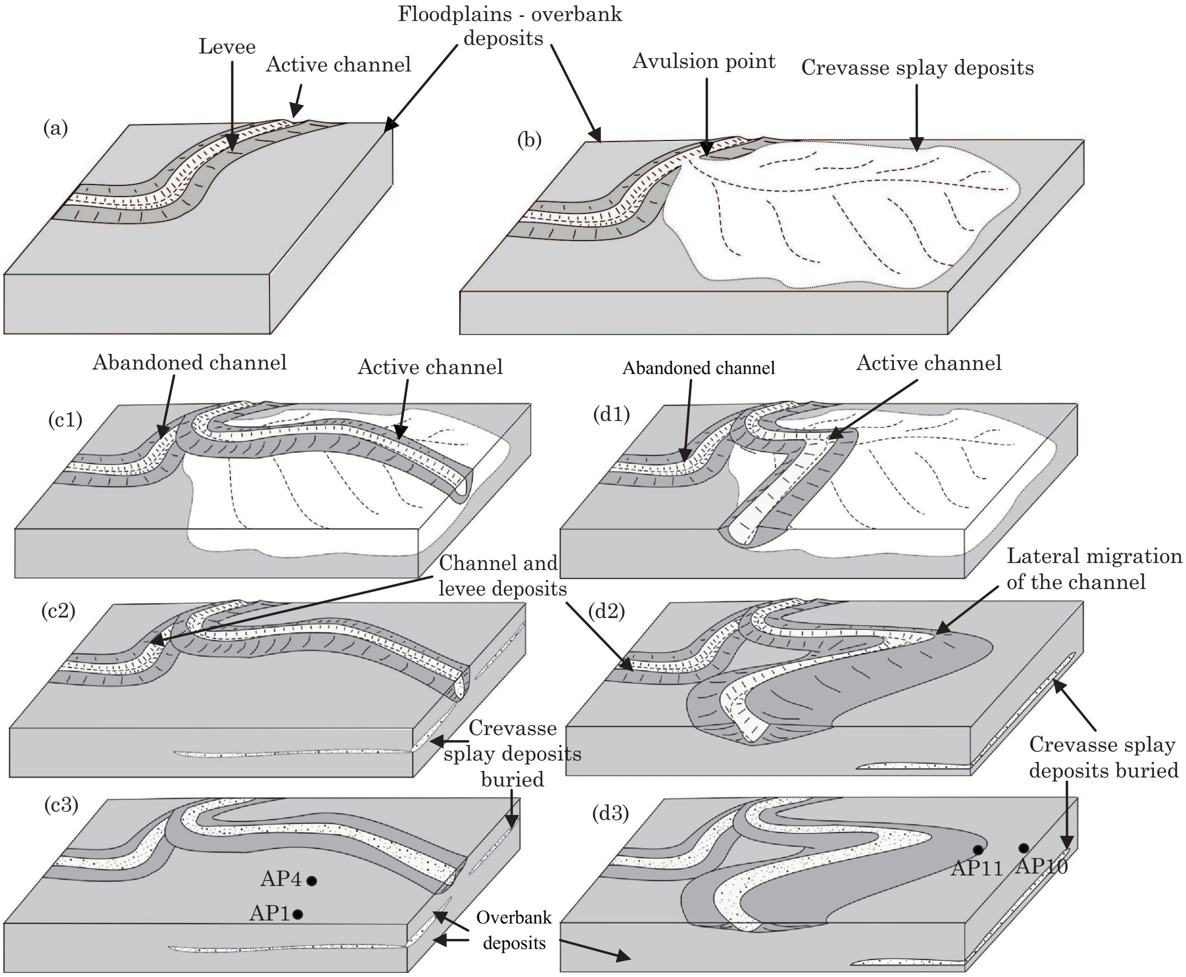

Figure 9. Evolution of the avulsion process and fluvial system that resulted in the formation of the soils studied.

(Figure 9c2,c3,d2,d3), which allowed this configuration with predominantly fine horizons that overlay the sandy sediments of avulsions.

The overlapping of layers in AP11 seems to be related to the influence of a marginal levee (Cazanacli & Smith, 1998), once the lateral migration of the channel resulted in a gradual dislocation of this channel from the fluvial system near the site where the profile was described (Figure 9d3). This determined the greater influence of overbank flows on the sediment depositions, as usually observed in places closer to levees (Cazanacli & Smith, 1998). On the other hand, during the evolution of the fluvial system after the avulsion process, the sites described in AP1, AP4 and AP10 remained farther away from the marginal levee, receiving predominantly fine and homogenous sediments (Cazanacli & Smith, 1998) after this process.

Nevertheless, when the deposit sediments are not overlaid by sediments from the activity of the fluvial system after the avulsion process, Smith et al. (1989) and Farrell (2001) observed in some sediment sections that this may result in the formation of a textural contrast widely observed in profiles with horizons with an increased clay content, denominated as B textural (Embrapa, 2006) or Argic horizon (FAO, 2006). However, in the case of the Pantanal, evidences of the avulsion process in the formation of horizons with increased clay content may be attenuated due to the intense biological activity, caused by vegetation, for instance, which often promote bioturbation of surface horizons (Buol et al., 2011) masking, hence, the evidences of abrupt changes in texture between the sediment deposits with the underlying horizons. Therefore, this issue should be further investigated with a focus on the formation of the B textural or Argic horizon, taking into account the influence of the depositional environments observed in the Pantanal.

In terms of soil classification, both processes, avulsion and overbank flows, may result in Fluvisols and Fluvic Cambisols (Embrapa, 2006; FAO, 2006). However, soils that have properties influenced by the avulsion process (i.e., a sandy layer contrasting in particle size, in the chemical properties, C content and origin, among several other properties of the over- and underlying horizons), were observed in the lower portions of the landscape that are more susceptible to flooding. This implies that these lower portions receive a larger amount of fine sediments during the flood season in the Pantanal, forming thick and homogeneous packages in the texture above this layer caused by the avulsion process, as observed in AP1 and AP10. Therefore, the thick horizons overlaying the sand layer of avulsion that occur in low portions, without textural variations and with hydromorphic traits, identify these soils as Gleysols (Gleissolos, by the Brazilian soil classification), as in AP10. Moreover, on plains where wetting and drying cycles were repeated more than twice (old floodplains), which favored the formation of plinthite, Plinthosols may occur (Buol et al., 2011).

The avulsion process results in the burying of surfaces, once the river may abruptly shift its bed to a new course, and start running in the floodplain (Smith et al., 1989). The distance from the levee crevasse, which determines the energy of this microenvironment and its erosive power (Stouthamer, 2001), may result in the burying of soils, characterizing paleosols (May et al., 2008), as suggested by the evidence found in this study. Thus, this characteristic, as observed in AP1, AP4 and AP10, may be used as basis for studies on paleoreconstruction and paleoclimate of the Quaternary (May & Veit, 2009), given that depositional environments are natural systems that react to changes of environmental variables in an attempt to return to balance conditions (Burkett & Kusler, 2000; Winter, 2000). Currently, this type of study is gaining more relevance because it answers questions related to the actual contribution of human intervention to environmental changes (Tooth & McCarthy, 2007).

CONCLUSIONS

1. The textural contrast in deeper layers in soils from Northern Pantanal originates from two processes associated to sediment deposition: avulsion and overbank flows.

2. Near the paleochannels, overbank flow may be responsible for the overlying horizons that contrast mainly in particle size and total carbon content.

3. In soils with evidence of the avulsion process, generally at the lower portion of the floodplain, the pre- and, mainly, post-avulsion horizons have similar particle sizes and increasing carbon contents towards the soil surface. Furthermore, in the layers affected by the avulsion process, abrupt variations in the carbon isotopic fractioning were observed, unlike in soils with contrasting horizons in the particle size analysis.

4. The old floodplain surfaces buried by the avulsion process constitute an object of study for the paleoclimatic and paleoenvironmental reconstruction, which may answer how this plain will respond to environmental changes.

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LITERATURE CITED

ALMEIDA, F.F.M. Geologia da Serra da Bodoquena (Mato Grosso). Rio de Janeiro, Divisão de Geologia e Mineralogia/ Departamento Nacional de Produção Mineral, 1945. (Boletim, 219)

ASSINE, M.L. & SILVA, A. Contrasting fluvial styles of the Paraguay river in the northwestern border of the Pantanal wetland, Brazil. Geomorphology, 113:189-199, 2009.

ASSINE, M.L. Sedimentação na bacia do Pantanal Mato-Grossense, Centro-Oeste do Brasil. Rio Claro, Universidade Estadual Paulista "Júlio de Mesquita Filho", 2003. 115p (Tese de Livre Docência)

BARROS, A.M.; SILVA, R.H.; CARDOSO, O.R.F.A.; FREIRE, F.A.; SOUZA JUNIOR, J.J.; RIVETTI, M.; LUZ, D.S.; PALMEIRA, R.C.B. & ASSINARI, C.C.G. Geologia da Folha SD.21 (Cuiabá). In: Projeto RADAMBRASIL. Rio de Janeiro, Ministério de Minas e Energia, 1982. p.25-192.

BOUTTON, T.W.; ARCHER, S.R.; MIDWOOD, A.J.; ZITZER, S.F. & BOL, R. ä^{13}C values of soil organic carbon and their use in documenting vegetation change in a subtropical savanna ecosystem. Geoderma, 82:5-41, 1998.

BRIDGE, J.S. Alluvium. In: GOUDIE, A.S., ed. Encyclopedia of geomorphology. London, Taylor & Francis, 2006. p.19-21.

BRINKMAN, R. Ferrolysis, a hydromorphic soil forming process. Geoderma, 3:199-206, 1970.

BULLOCK, P.; FEDEROFF, N.; JONGERIUS, A.; STOOPS, G. & TURSINA, T. Handbook for soil thin section description. London, Waine Research Publications, 1985. 152p.

BUOL, S.W.; SOUTHARD, R.J.; GRAHAM, R.C. & McDANIEL, P.A. Soil genesis and classification. 6.ed. Chichester, Willey-Blackwell, 2011. 543p.

BURKETT, V. & KUSLER, J. Climate change: Potential impacts and interactions in wetlands of the United States. J. Am. Water Res. Assoc., 36:313-320, 2000.

CASTRO, S.S.; COOPER, M.; SANTOS, M.C. & VIDAL-TORRADO, P. Micromorfologia do Solo: Bases e aplicações. In: CURI, N.; MARQUES, J.J.; GUILHERME, L.R.G.; LIMA, J.M.; LOPES, A.S. & ALVAREZ V., V.H., eds. Tópicos em ciência do solo. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2003. v.3. p.107-164.

CAZANACLI, D. & SMITH, N.D. A study of morphology and texture of natural levees - Cumberland Marshes, Saskatchewan, Canada. Geomorphology, 25:43-55, 1998.

CLARK, P.U.; DYKE, A.S.; SHAKUN, J.D.; CARLSON, A.E.; CLARK, J.; WOHLFARTH, B.; MITROVICA, J.X.; HOSTETLER, S.W. & McCABE, A.M. The Last Glacial Maximum. Sci., 325:710-714, 2009.

COLINVAUX, P.A.; OLIVEIRA, P.E. & BUSH, M.B. Amazonian and neotropical plant communities on glacial time-scales: The failure of the aridity and refuge hypotheses. Quater. Sci. Rev., 19:141-169, 2000.

DEL'ARCO, J.O.; DA SILVA, R.H.; TARAPANOFF, I.; FREIRE, F.A.; MOTA PEREIRA, L.G.; SOUZA, S.L.; PALMEIRAS, R.C.B. & TASSINARI, C.C.G. Geologia da Folhas SE. 20/21 (Corumbá). In: Projeto RADAMBRASIL. Rio de Janeiro, Ministério de Minas e Energia, 1982. p.25-160.

EMPRESA BRASILEIRA DE PESQUISA AGROCUPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa em Solos. Sistema Brasileiro de Classificação de Solos. 2.ed. Rio de Janeiro, 2006. 306p.

EMPRESA BRASILEIRA DE PESQUISA AGROCUPECUÁRIA - EMBRAPA. Centro Nacional de Pesquisa em Solos. Manual de métodos de análise de solo. 2.ed. Rio de Janeiro, 1997. 212p.

FARRELL, K.M. Geomorphology, facies architecture, and high-resolution, non-marine sequence stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan. Sedim. Geol., 139:93-150, 2001.

FOOD AND AGRICULTURE ORGANIZATION - FAO. World reference base for soil resources Rome, 2006. 132p. (WRB, 103)

FRANCO, M.S.M. & PINHEIRO, R. Geomorfologia da Folha SE.21 (Corumbá). In: Projeto RADAMBRASIL. Rio de Janeiro, Ministério de Minas e Energia, 1982. p.161-224.

GIRARD, P.; FANTIN-CRUZ, I.; OLIVEIRA, S.M.L. & HAMILTON, S.K. Small-scale spatial variation of inundation dynamics in a floodplain of the Pantanal (Brazil). Hydrobiologia, 638:223-233, 2010.

HALL, S.A.; BOUTTON, T.W.; LINTZ, C.R. & BAUGH, T.G. New correlation of stable carbon isotopes with changing late-Holocene fluvial environments in the Trinity River basin of Texas, USA. The Holocene, 22:541-549, 2012.

HAMILTON, S.K.; SIPPEL, S.J. & MELACK, J.M. Inundation patters in the Pantanal wetland of South America determined from passive microwave remote sensing. Arch. Hydrobiol., 137:1-23, 1996.

HUMPHRIES, M.S.; KINDNESS, A.; ELLERY, W.N. & HUGHES, J.C. Sediment geochemistry, mineral precipitation and clay neoformation on the Mkuze River floodplain, South Africa. Geoderma, 157:15-26, 2010.

INTERNATIONAL COMMISSION ON STRATIGRAPHY - ICS. International stratigraphic chart. 2010. Available at: <http://www.stratigraphy.org/column.php?id=Chart/Time%20Scale>. Acessed: Oct. 05, 2011.

JACKSON, M.L. Soil chemical analysis: Advanced course. Madison, 1979. 895p.

JUNK, W.J. & NUNES DA CUNHA, C. Pantanal: A large South American wetland at a crossroads. Ecol. Eng., 24:391-401, 2005.

MACKEY, S.D. & BRIDGE, J.S. Three-dimensional model of alluvial stratigraphy: Theory and application. J. Sediment. Res., 65:7-31, 1995.

MAY, J.H. & VEIT, H. Late Quaternary paleosols and their paleoenvironmental significance along the Andean piedmont, Eastern Bolivia. Catena, 78:100-116, 2009.

MAY, J.H.; ZECH, R. & VEIT, H. Late Quaternary paleosol-sediment-sequences and landscape evolution along the Andean piedmont, Bolivian Chaco. Geomorphology, 98:34-54, 2008.

MEYERS, P.A. & LALLIER-VERGÈS, E. Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. J. Paleolimnol., 2:345-372, 1999.

MUTO, T. & STEEL, R.J. The accommodation concept in sequence stratigraphy: some dimensional problems and possible redefinition. Sediment. Geol., 130:1-10, 2000.

NASCIMENTO, A.F. Relações pedologia-geomorfologia-sedimentologia no Pantanal Norte. Piracicaba, Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, 2012. 200p. (Tese de Doutorado). Available at: <http://www.teses.usp.br/teses/disponiveis/11/11140/tde-06072012-103745/en.php>.

NICHOLS, G. Sedimentology and Stratigraphy. 2.ed. United Kingdom, Wiley-Blackwell, 2009. 419p.

NICHOLS, G.J. & FISHER, J.A. Processes, facies and architecture of fluvial distributary system deposits. Sedim. Geol., 195:75-90, 2007.

NUNES DA CUNHA, C. & JUNK, W.J. A preliminary classification of habitats of the Pantanal of Mato Grosso and Mato Grosso do Sul, and its relation to national and international wetland classification systems. In: JUNK, W.J.; SILVA, C.J.; NUNES DA CUNHA, C. & WANTZEN, K.M., eds. The Pantanal: Ecology, biodiversity and sustainable management of a large neotropical seasonal wetland. Sofia, Pensoft, 2010. p.127-142.

PHILLIPS, J.D. Avulsion regimes in southeast Texas rivers. Earth Surf. Process. Landf., 34:75-87, 2009.

ROSS, J.L.S. & SANTOS, L.M. Geomorfologia da folha SD.21 (Cuiabá). In: Projeto RADAMBRASIL. Rio de Janeiro, Ministério de Minas e Energia, 1982. p.193-256.

SALLUN, A.E.M.; SUGUIO, K.; TATUMI, S.H.; YEE, M.; SANTOS, J. & BARRETO, A.M.F. Datação absoluta de depósitos quaternários brasileiros por luminescência. R. Bras. Geoci., 37:402-413, 2007.

SANTOS, R.D.; LEMOS, R.C.; SANTOS, H.G.; KER, J.C. & ANJOS, L.H.C. Manual de descrição e coleta de solo no campo. 5.ed. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2005. 100p.

SCHAETZL, R.J. Lithologic discontinuities in some soils on drumlins: Theory, detection, and application. Soil Sci., 163:570-590, 1998.

SLINGERLAND, R. & SMITH, N.D. Necessary conditions for a meandering-river avulsion. Geology, 26:435-438, 1998.

SMITH, N.D; CROSS, T.A.; DUFFICY, J.P. & CLOUGH, S.R. Anatomy of an avulsion. Sedimentology, 36:1-23, 1989.

SOARES, A.P.; SOARES, P.C. & ASSINE, M.L. Areiais e lagoas do Pantanal, Brasil: Herança paleoclimática? R. Bras. Geoci., 33:211-224, 2003.

STEVAUX, J.H. Climatic events during the Late Pleistocene and Holocene in the Upper Parana River: Correlation with NE Argentina and South-Central Brazil. Quatern. Int., 72:73-85, 2000.

STOUTHAMER, E. & BERENDSEN, H.J.A. Avulsion: The relative roles of autogenic and allogenic processes. Sediment. Geol., 198:309-325, 2007.

STOUTHAMER, E. Sedimentary products of avulsions in the Holocene Rhine-Meuse Delta, The Netherlands. Sedim. Geol., 145:73-92, 2001.

TALBOT, M.R. & JOHANNESSEN, T. A high resolution palaeoclimatic record for the last 27,500 years in tropical West Africa from the carbon and nitrogen isotopic composition of lacustrine organic matter. Earth Planet. Sci. Lett., 110:23-37, 1992.

TOOTH, S. & McCARTHY, T.S. Wetlands in drylands: Key geomorphological and sedimentological characteristics, with emphasis on examples from Southern Africa. Progres. Phys. Geogr., 31:3-41, 2007.

TÖRNQVIST, T.E. & BRIDGE, J.S. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. Sedimentology, 49:891-905, 2002.

WINTER, T.C. The vulnerability of wetlands to climate change: A hydrologic landscape perspective. J. Am. Water Res. Assoc., 36:305-311, 2000.