PERGAMON

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Quaternary of the Pantanal, west-central Brazil

Mario Luis Assine[a,*], Paulo César Soares[b]

[a] *Departamento de Geologia Aplicada, UNESP—Universidade Estadual Paulista, Avenida 24A, 1515, Rio Claro SP 13.506-900, Brazil*
[b] *Departamento de Geologia, UFPR—Universidade Federal do Paraná, Caixa Postal 19011, Curitiba PR 81.531-990, Brazil*

Abstract

The Pantanal is a tectonic depression located at the left margin of the Upper Paraguay River. The Paraguay is the trunk river of an alluvial depositional tract composed by several large marginal alluvial fans, the Taquari fan being the largest one. The present landscape is a complex tropical wetland characterized by month-long floods every year, with geomorphic features derived from the present conditions and others inherited from successive Pleistocene and Holocene climates. Some areas containing ponds are landscape relicts generated by eolian deflation during the Last Glacial Maximum. Many ponds, closed depressions isolated from the superficial waters by vegetated crescent ridges of fine sands, were interpreted as salt pans bordered by lunette sand dunes. Initiation of the modern wetland has occurred during the Pleistocene/Holocene transition, with the change to a more humid climate and the individualization of lacustrine systems. Active tectonics has been playing an important role in the development of the Pantanal landscape. Nowadays, the Paraguay River meanders in a large flood plain with extensive swamp surfaces, being structurally constrained by faults in the west border of the basin. Sedimentation within the Pantanal wetland is also affected by tectonic activity, especially along faults associated with the Transbrasiliano Lineament.

1. Introduction

The Pantanal wetland concentrates the headwaters of the Paraguay River, a major tributary of the La Plata River (Fig. 1). Located in west central Brazil, the Pantanal covers about 135,000 km^2 of the Upper Paraguay drainage basin and ranges in altitude from 80 to 180 m above sea level. Human occupation is of low density and economic activities are restricted to cattle ranching.

Being a prototype of tropical wetlands (see Iriondo, this volume), the Pantanal is a vast expanse of poorly drained lowlands that experiences annual flooding from summer to fall months (January–May). Drainage patterns and flooding characteristics allow the wetlands to be subdivided into 9 different Pantanal geomorphological compartments (Fig. 2).

Flowing from north to south, the Paraguay is the trunk river of an alluvial depositional tract composed by several large marginal alluvial fans. The Taquari fan is the most remarkable of these (Braun, 1977; Soares et al., 1996; Assine and Soares, 1997), being a geological feature easily visible in satellite images (Fig. 3).

Although the Pantanal is a well-known wetland because of its biodiversity-rich ecosystems, knowledge of its geology is still poor. In fact, the Pantanal is an active sedimentary basin filled up with a thick sequence of Quaternary sediments. Many of its present-day geomorphological features are relicts of a complex history of paleoclimatic and paleogeographic changes that have been occurring since the Late Pleistocene. The aim of this paper is to present the main aspects of its geology and geomorphology, emphasizing the attempt to reconstruct the succession of Quaternary events and their morphologic and sedimentary products.

2. Geological setting

The Pantanal basin is a tectonic depression located at the left margin of the Paraguay River. According to Ussami et al. (1999), the origin of the Pantanal basin was a consequence of tectonic reactivation of the forebulge during the last Andean compressive event at ~2.5 Ma (Fig. 4).

The depocenter is roughly parallel to the forebulge elongation and subsidence has been controlled by faults.

*Corresponding author.
E-mail addresses: assine@rc.unesp.br (M.L. Assine), soares@geologia.ufpr.br (P.C. Soares).

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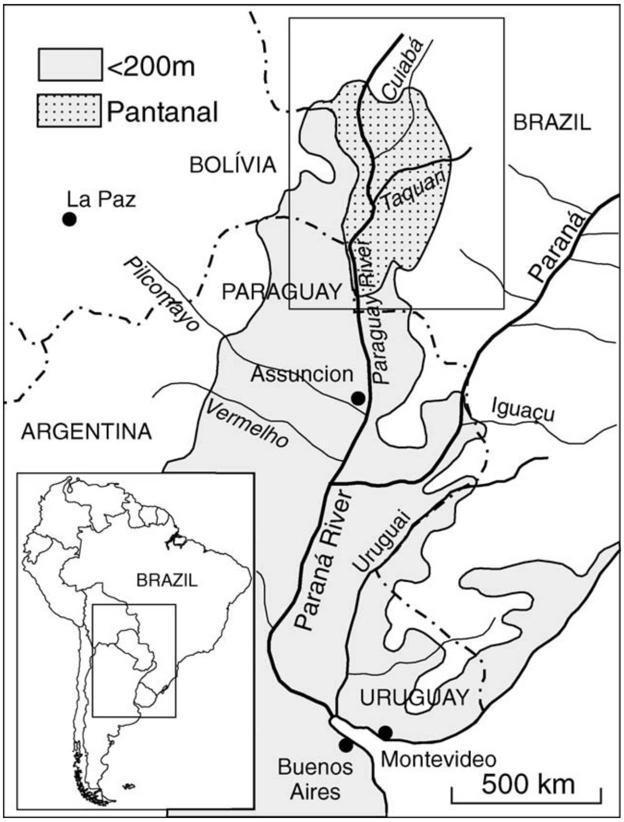

Fig. 1. Location map of the Brazilian Pantanal wetlands.

The basement is mainly composed by low-grade metamorphic rocks of the Neoproterozoic Alto Paraguay folded belt.

The collapse of the forebulge occurred after the generation of the South American peneplain, which was delineated in Miocene times according to Soares and Landim (1976). Remnants of this paleosurface can be found from 500 to 1000 m above present sea level in neighboring plateau areas. The same paleosurface constitutes the basin floor now buried by alluvial deposits of the Quaternary Pantanal Formation, with a maximum sediment thickness of about 550 m (Fig. 5) inferred from seismic data.

Subsurface information is restricted to 11 wells drilled in the beginning of the 1960s by Petrobrás (Brazilian oil state company). The deepest one (SB-1A) through 412.5 m of the Pantanal formation, did not reach the basement as shown in Table 1. In consequence, and as chronostratigraphic data are not available, there is no precise information about the beginning of sedimentation in the Pantanal basin. Sedimentation possibly started at the Pliocene, after uplift of the Miocene South American peneplain and fragmentation of forebulge.

Basin infilling was mainly by siliciclastic sediments (Weyler, 1962). The overall section shows fining upward, from conglomerates and coarse–grained sandstones in the lower portion to fine/medium quartz sands, locally coarse–grained, in the upper portion. Reddish sands occur in several levels and are characterized by the presence of iron oxide cements, sometimes true lateritic beds.

The framework of the Pantanal basin is not known in detail, but a N–S graben-like structure can be outlined. Eastern border faults are covered by modern alluvial sediments that onlap basement towards the east with the regression of fault-line escarpments. The basin floor is slightly tilted to the west and the western border is defined by a trend of N–S faults, segmented by E–W faults.

The main sites of deposition are controlled by local tectonic base level placed in the southern portion of the Pantanal wetland. The rate of subsidence was lower in the Paraguay–Nabileque area, as indicated by the fact that the thickness of Quaternary sediments does not reach 100 m (data from Aq-1 and PM-1 wells in Table 1). Basement rocks crop out in the locality of Fecho dos Morros and erosive processes become dominant south of the confluence with the Apa River (Almeida, 1945).

3. Late Pleistocene

Reddish sediments with common laterite horizons characterize the oldest sedimentary facies exposed on the surface of the Pantanal lowlands. In the ramps of pediments associated with marginal escarpments, which are the natural geomorphic transition to adjacent plateaus, these facies are represented by coarse–grained sands and debris flow facies. In the Pantanal lowland they are represented by sands, locally cemented by iron oxides. These reddish facies are suggestive of past warm climates.

Based on palynological data, Ferraz-Vicentini and Salgado-Labouriau (1996) suggested warm semi-humid climatic conditions before 32,400 years B.P. in the Central Brazil area, located at the same latitude as the Pantanal, 500 km east. It is possible, therefore, that the reddish facies in the Pantanal could be of this age, but it is also possible that they could encompass older deposits generated during warmer times at about 120,000 years ago (Eemian interglacial).

The succession of climatic events reported for the Quaternary might have left a sedimentary signal in the Pantanal area as a whole, but deposits are most easily observed in the Taquari fan, where a few meters of fine/medium white sands cover unconformably the reddish sand facies. The mantle of sands was deposited by braided alluvial fans, the original geometry of which is preserved as relict forms, permitting remarkable patterns of distributary paleochannels to be easily recognized in satellite images (Fig. 6).

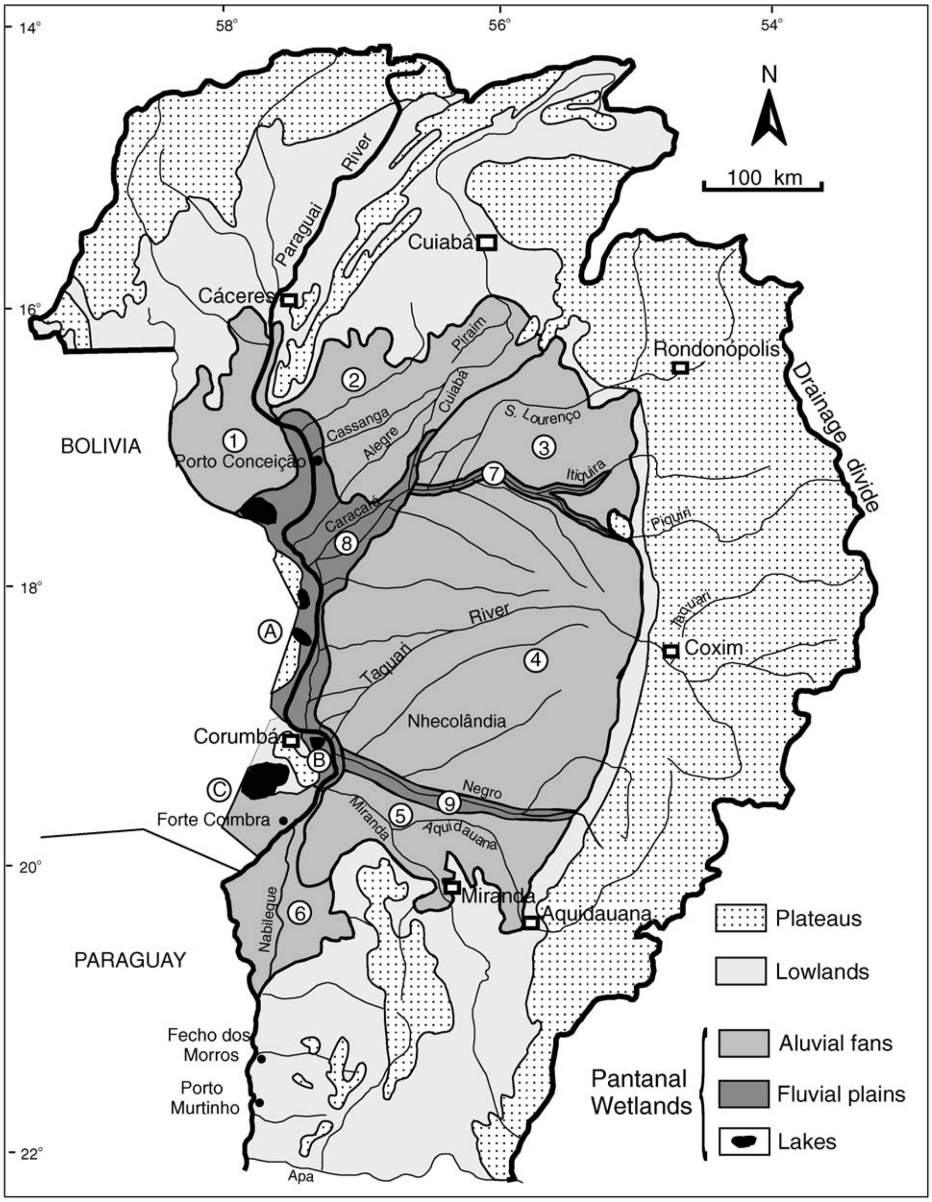

Fig. 2. Map of the Upper Paraguay River drainage basin (modified from Brasil and Alvarenga, 1988). Watersheds are located in the eastern and northern plateaus. Lowlands are almost flat, but they are non-inundating areas. Pantanal wetlands experience weak to strong flooding and include alluvial fans (1 = Paraguay–Corixo Grande; 2 = Cuiabá; 3 = São Lourenço; 4 = Taquari; 5 = Aquidauana; 6 = Paraguay Nabileque) fluvial plains (7 = Piquiri; 8 = Paraguay–Paiaguás: 9 = Negro) and permanent lakes (A = Castelo; B = Negra; C = Jacadigo).

Many researchers have attributed the fan deposition to a semi-arid climate during the Late Pleistocene (Braun, 1977; Tricart, 1982; Klammer, 1982; Ab'Sáber, 1986). Clapperton (1993, p. 196) wrote: "the features presently visible may have formed only during the last interval of aridity, presumably corresponding to the Last Glaciation".

The assumption of a prevalent arid climate during the Late Pleistocene has not been confirmed yet by palynological data obtained in the Pantanal and surrounding areas. Studies in neighboring Central Brazil have suggested a more humid paleoclimate during parts of the glacial period. Ledru et al. (1996), for example, envisaged a cold period of high moisture from 40,000 to 27,000 years B.P. Humid and probably cold conditions have also been interpreted to the period spanning from 27,000 to 20,000 years B.P. (Ferraz-Vicentini and Salgado-Labouriau, 1996). Evidence for high humidity levels associated with cooler climates has also been found at Lagoa de Serra Negra, State of Minas Gerais, in sediments attributed to the last glacial cycle (De Oliveira, 1992) thus permitting the expansion of Araucaria forests into northern latitudes of northeastern Brazil.

Fig. 3. The Pantanal seen in a composition of Landsat satellite images obtained during the dry season of 1991 (composition R3/G4/B7). See Fig. 2 for caption of numbers and letters. Landscape and subsidence are tectonically controlled, the Transbrasiliano Lineament being one of the most important recent tectonic features.

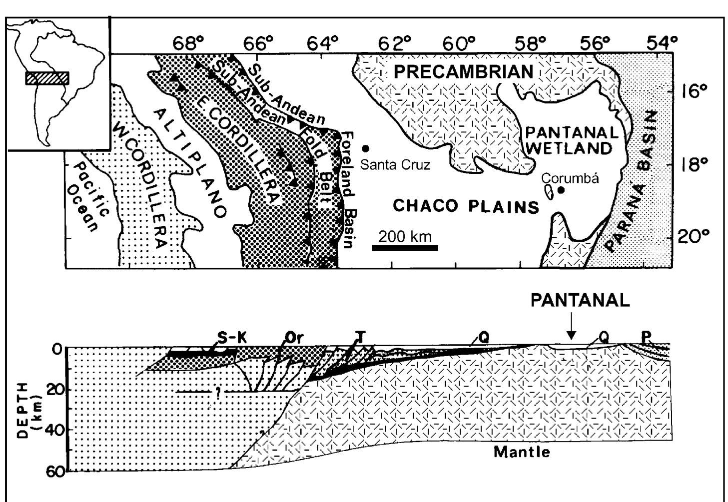

Fig. 4. Tectonic setting of the Pantanal wetland (modified from Ussami et al., 1999). The Pantanal is an extensional basin in the forebulge associated with the Chaco foreland basin.

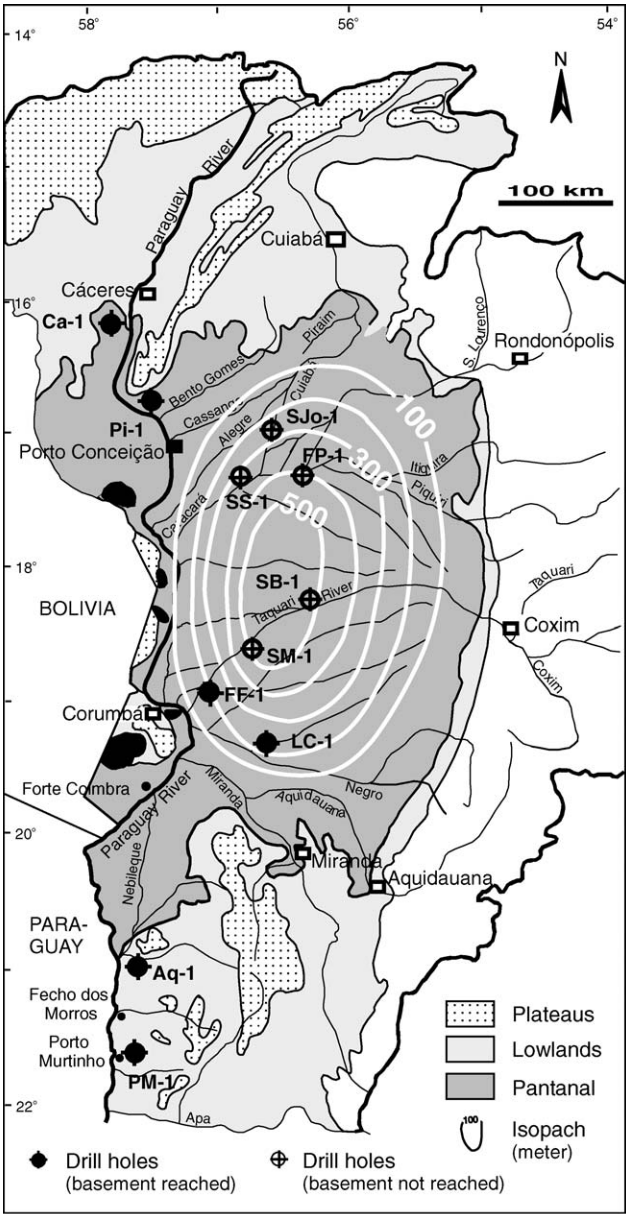

Fig. 5. Thickness of the Pantanal Formation and location of wells drilled in the Pantanal basin (Isopach curves based on Ussami et al., 1999).

Table 1
Wells drilled in Pantanal (after Weyler, 1962)

Well	Depth (m)	Basement
SJo-1	193.0	Not reached
SSs-1	302.4	Not reached
FP-1	340.7	Not reached
SB-1	412.5	Not reached
SM-1	217.0	Not reached
Ca-1	86.6	Reached
Pi-1	88.0	Reached
FF-1	182.0	Reached
LC-1	227.3	Reached
Aq-1	62.0	Reached
PM-1	37.0	Reached

On the other hand, eolian reworking was suggested by Almeida (1945) to explain the granulometric characteristics of sands in the Nhecolândia area, located at the southern portion of the Taquari fan. However, it is not possible to invoke an eolian origin based on granulometric analysis alone because the observed characteristics can be inherited from Mesozoic eolian sandstones present in the source area. In fact, the sands have good sorting, a bimodal fine to medium grain size distribution, a very low percentage of fines, but are poorly rounded and exhibit textural inversion due to mixture of populations.

Myriads of ponds in the area of Nhecolândia (Figs. 3 and 7) had remained unexplained until the beginning of the 1980s when eolian processes were invoked to explain them. Based on the study of satellite images, Tricart (1982) considered that the ponds were originally troughs or hollows produced by eolian deflation. Klammer (1982) considered them as salt pans generated through ponding in interdune areas. Klammer also recognized swarms of longitudinal fossil dunes and deduced constant winds from the NNE and NNW, based exclusively on interpretation of radar images.

In order to evaluate the assumptions made by Klammer (1982) and Tricart (1982), we carried out a research program based on analysis of satellite images, photogeologic interpretation, fieldwork and sedimentologic analysis in the south portion of the Taquari fan. The main conclusion was that there are many relict eolian landforms preserved in the Nhecolândia landscape. Many ponds are still closed depressions isolated from the superficial waters by marginal ridges of fine sands (called *cordilheiras*), which sometimes present crescent forms (Fig. 8). These features are typically forms produced by eolian processes and can be interpreted as salt pans bordered by lunette sand dunes, as pointed out by Goudie (1991) and Goudie and Wells (1995).

Otherwise, the results did not confirm the existence of NNE and NNW dunes interpreted by Klammer (1982). Longitudinal dunes were not observed in satellite images or in the field, so we consider that Klammer misinterpreted the geomorphic features, probably due to the low resolution of the radar images.

Eolian erosion probably was more effective at the glacial maximum as a result of rainfall reduction and lowering of the groundwater level. The drainage could be centripetal as suggested by Tricart (1982), and the wetland did not exist. In such a case, an intermittent playa lake could have existed where the Paraguay fluvial plain is located today.

Contemporaneously with eolian deflation in the Nhecolândia area, new fan lobes were active elsewhere. Avulsion, channel shifting and lobe switching occurred mainly in the north portion of the Taquari fan. Paleochannels can be recognized in that area (Fig. 3)

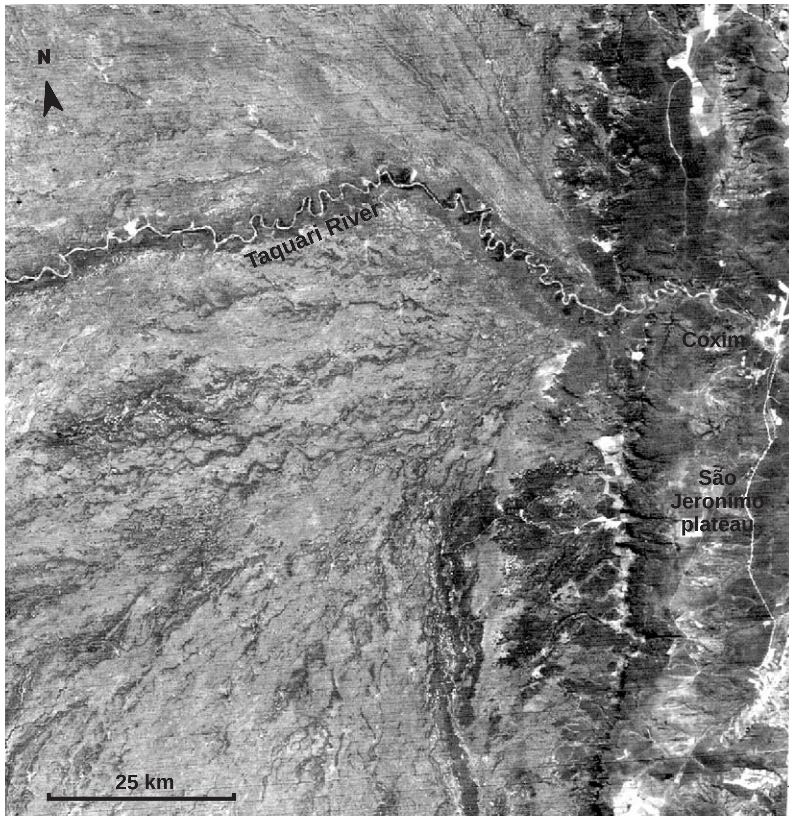

Fig. 6. Eastern border of the Taquari fan (Landsat satellite image, band 5, 06/21/1975). The catchment area is placed to the east in the São Jerônimo plateau, which is sculptured over Paleozoic and Mesozoic terrigenous rocks of the Paraná Basin. A steep escarpment is the natural limit between the catchment area and the Taquari megafan in the Pantanal wetland. Relict distributary paleochannels are visible in the entire upper fan surface, where the river is now confined within a meandering belt.

and are relicts of a different generation of lobes produced by stream-flood events.

According to global paleoclimatic reconstructions, deglaciation began around 16,000 years ago and promoted large changes in paleoclimatology, paleoecology and paleogeography around the world. As a result, different paleoclimatic interpretations for the terminal Pleistocene have been reported for several places in Brazil. Ferraz-Vicentini and Salgado-Labouriau (1996), for example, suggested a dry and cold phase at the end of Pleistocene, while De Oliveira (1992) and Ledru et al. (1996) suggest a gradual increase in humidity. The Pantanal certainly experienced strong paleoclimatic fluctuation during deglaciation, but the main events in that region have not been described yet.

4. Holocene

The landscape has been changing in the Pantanal area since the end of the Pleistocene in adaptation to a more humid and warmer macro environment prevailing during the Holocene. The modern Pantanal wetland was established, the drainage system was reorganized, and some temporary channels became permanent rivers.

Initiation of the wetland at the Pleistocene/Holocene transition is corroborated by data obtained from lake sediments. Based on radiocarbon dating and palynological data from sediment samples of the lakes Castelo, Negra, and Jacadigo (Fig. 2), Bezerra (1999) concluded that there was a change to a more humid climate with the individualization of lake systems from 10,200 years B.P. (Lake Negra) to 5190 years B.P. (Lake Castelo).

During the Early Holocene a progressively warmer and humid climate was detected in several other areas of South America. According to Ledru et al. (1996) and De Oliveira (1992), the early Holocene (9500–5000 years B.P.) was characterized by marked seasonal pattern and higher temperatures in southeastern Brazil. A wet event spanning from 8500 to 3500 years B. P. was recognized in northeastern Argentina (Iriondo and Garcia, 1993) and in the Upper Paraná River (Stevaux, 1994). High humidity levels and progressive warming from 10,540 to 6790 years B.P. were also deduced from evidence in the middle São Francisco river area (10° 24′ lat. S) in northeastern Brazil (De Oliveira et al., 1999), far to the north of the Pantanal.

Avulsion and fan lobe switching resulted in the deposition of thin layers of white sands that cover a considerable percentage of the Pantanal surface. Coal fragments recovered from sands of terraces in the Taquari drainage basin revealed a ^{14}C age of 8560 years B.P. (Soares et al., 2000).

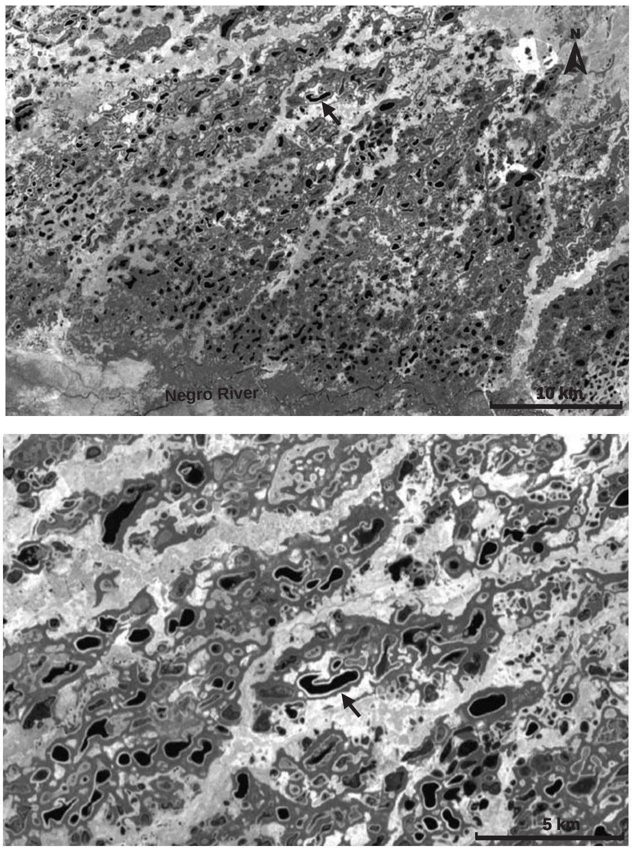

Fig. 7. The Nhecolândia area, located in the south portion of the Taquari alluvial fan, as seen in a Landsat satellite image (band 5, 1999). The upper image shows hundreds of different ponds. The lower image, which contains an enlarged view of the upper one, shows the conspicuous presence of isolated salt-water ponds (*salinas*) with white sand halos around them. A typical salina is shown by an arrow. Tributary shallow channels (*vazantes*) that flow southwards to the Negro River are fluvial features superimposed on a previous pond landscape.

Under a more humid climate, the water table rose and the hollows previously produced by deflation became ponds by groundwater influx. With increasing superficial runoff, many ponds have been progressively connected each to other and integrated to the alluvial drainage system.

Some ponds (called *salinas*) are still isolated from floodwaters by vegetated sand ridges (called *cordilheiras*) and their waters are salty (alkaline). They have calcium carbonate layers in their margins and/or bottoms, with preserved shells of molluscs. According to Boggiani and Coimbra (1995), limestone beds of the Pantanal are characterized by the presence of sub-rounded fine-grained quartz sand supported by fine calcite matrix.

Precipitation of carbonates suggests recurrence of temporary drier conditions. Based on the age of fresh-water mollusc shells recovered from limestone beds in the Miranda-Aquidauana wetland, which was dated at 3820 years B.P. by ^{14}C (Assine et al., 1997), these conditions have prevailed during some periods of the Late Holocene in Pantanal area.

This interpretation is corroborated by paleoclimatic record of speleothems from João Arruda Cave, located near the small town of Bonito, in the surrounding plateau to the south of Pantanal. Studying laminated sequences of growth in a Late Holocene stalagmite, Bertaux et al. (2002) interpreted a higher recurrence of dry events between 3800 and 2500 B.P. Drier conditions in the Pantanal area can be correlated to climate changes in the neighboring Chaco region, where Iriondo (1993) described a dry Late Holocene (3500–1400 years B.P.) after a humid hypsithermal.

Although climatic fluctuations have occurred throughout the Holocene, the alluvial fans have remained active depositional systems and several lobes were formed by progradation and abandonment. Abandoned lobes were subjected to pedogenesis and fluvial incision, so that superimposed drainage systems were established over ancient lobes. *Vazantes*, a special

Fig. 8. An isolated salt-water pond (*salina*) bordered by vegetated ridge of fine sands (ancient lunette dune), as seen in an oblique aerial photograph.

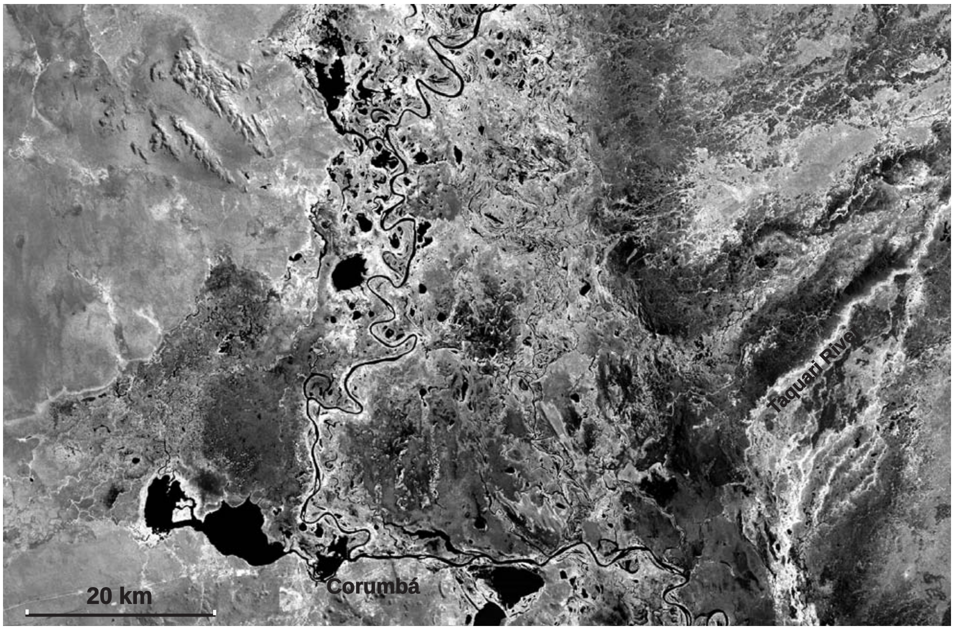

Fig. 9. Meandering fluvial plain of Paraguay River north from Corumbá (Pantanal of Paraguay–Paiaguás). The abrupt change to east is structurally controlled by an EW fault. The Taquari fan toe can be seen to the right (Landsat satellite image, band 4, 1999).

type of tributary intermittent streams that occur in the Pantanal wetland, are shallow channels that collect water from springs, river avulsions and flooding (Fig. 7).

5. Tectonics and alluvial sedimentation

Tectonics has been playing an important role in the development of the Pantanal landscape as a whole, changing base levels and topographic gradients. Evidence of tectonics is visible in the western side of the Pantanal basin where the Paraguay fluvial plain is structurally constrained by faults and the river course is sometimes adjusted to border fault traces.

Near the city of Corumbá, for example, the Paraguay River becomes structurally controlled by an E–W fault and its course changes abruptly to the east (Fig. 9). In the hanging-wall block to the north, subsidence and sedimentation are active and the river meanders in a large flood plain with extensive swamp surfaces. The fluvial plain is wider and lakes are more common than further downstream. This area (Pantanal of Paraguay–Paiaguás; Figs. 2 and 3) is almost entirely flooded during the rainy season when floodwaters invade the surrounding lacustrine systems.

On the other hand, erosion is active to the south in the footwall, where there are Pleistocene terraces up to 20 m high and metamorphic basement rocks crop out. Precambrian marbles, quartzites, iron and manganese formations (Urucum) occur in butte or mesa landforms, which are residual forms leveled at the same altitudes as plateaus that surround the Pantanal wetland to the south, north and east.

Fig. 10. The Paraguay River flowing towards south in the Pantanal of Paraguay–Nabileque. The present channel is less sinuous and cuts a previous network of abandoned meandering channels.

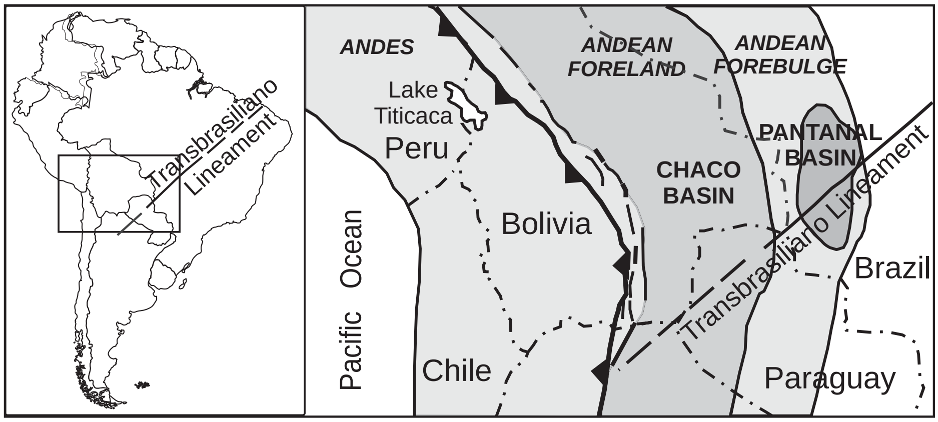

Fig. 11. Quaternary subsidence in the Pantanal area is a consequence of extensional tectonics, which has been associated with reactivation of the Andean forebulge. Recent tectonics are also indicated by the Transbrasiliano Lineament, a remarkable NE–SW trend of faults that can be traced from the equatorial Brazilian margin to the Paraguayan border, crossing obliquely across the Pantanal basin. See Fig. 3 for its more precise location in the Pantanal area.

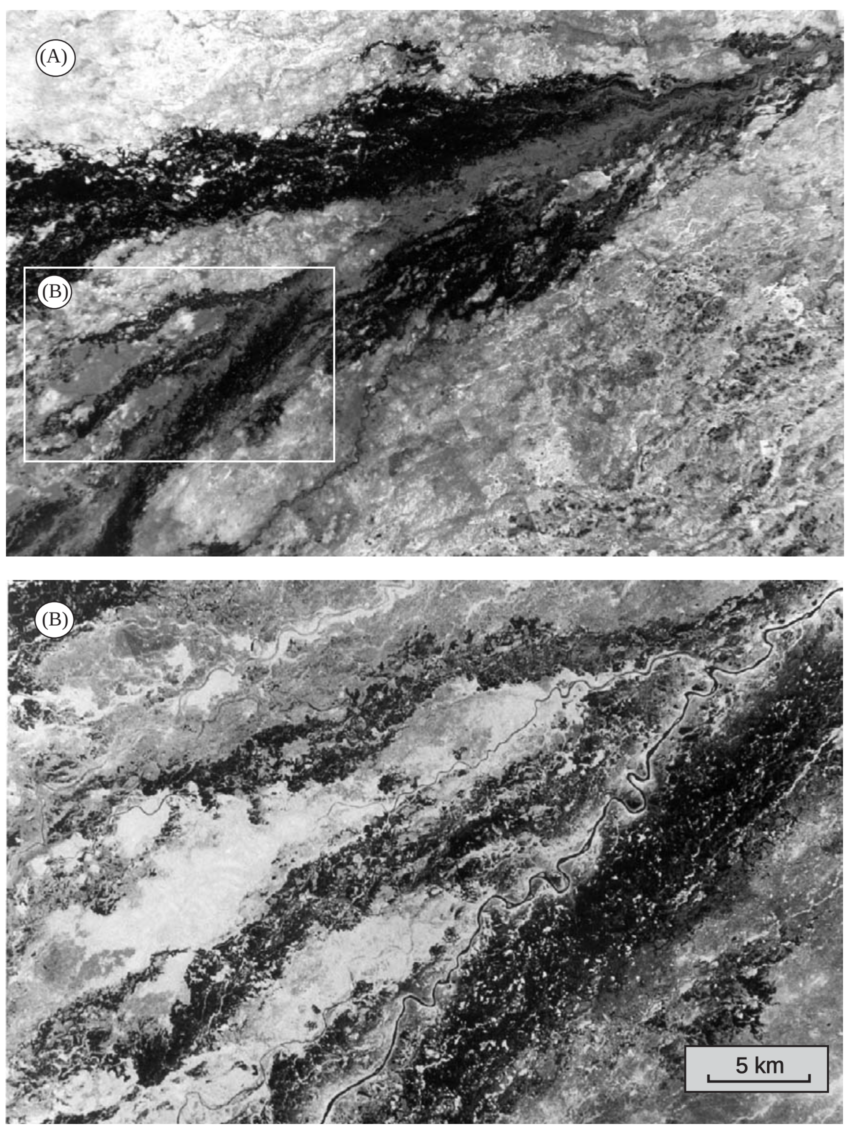

Fig. 12. The overall drainage pattern in the active Taquari lobe. Dark areas are humid floodplains. Sand lobules occur inside the flood plain, and are associated with ancient distributary channels (Satellite image TM, band 4, Oct/1990; B is a detail of A).

The sinuosity of the Paraguay River decreases downstream of the Taquari River mouth and the fluvial plain is narrow in the Pantanal of Paraguay–Nabileque, reflecting its entrance into a different tectonic block. There is superposition of different patterns of fluvial drainage in this area, showing recent hydraulic changes in the Upper Paraguay drainage basin. The decreasing channel sinuosity of the Paraguay River in the Pantanal of Paraguay–Nabileque reflects a tendency to braid (Fig. 10). This tendency has resulted from the increase of stream power, probably as a consequence of tectonics, although climatic changes can also be considered important.

The Transbrasiliano Lineament, the importance of which has been only recently recognized in the Pantanal area (Soares et al., 1998), is a remarkable NE–SW tectonic feature striking from the equatorial Atlantic margin to the Andes, crossing obliquely across the Pantanal wetland (Fig. 11) and constraining the basin geometry and the relative block movements. In the Paraguay–Nabileque compartment, for example, the course of the Paraguay River course is structurally controlled along 150 km by NE–SW fractures associated with the Transbrasiliano Lineament (see Fig. 3).

Morphological features observed in satellite images, aerial photos and in fieldwork permit the identification of faults associated with the Transbrasiliano Lineament, within the Pantanal wetland. Some faults are active, as evidenced by earthquake epicenters in the Pantanal area. A strike-slip fault was recognized by Ussami et al. (2000) in a seismic section registered north from Taquari river (51° 15′W), coincident with an earthquake with a focus indicative of E–W compression.

Nowadays, sedimentation occurs mainly in the active Taquari lobe (triangular dark area in Fig. 3), where the river exhibits a remarkable distributary pattern and experiences strong annual flooding. The Transbrasiliano Lineament defines the southeast limit of the lobe, suggesting that the lobe has been prograding onto a more subsiding area to north of the lineament. In this area, the river is characterized by the existence of many points of river avulsion and sand lobules inside the flood plain, testifying to the changing nature of the river channel (Fig. 12).

In the upper fan, the Taquari River is entrenched in ancient fan lobes and sedimentation takes place in a meandering belt confined by terraces up to five meters high (Fig. 13). Tectonics could explain the entrenchment, but the true cause is still to be discovered. This problem is common in the study of alluvial systems because at least four different causes produce channel incision, a good example of convergence (Schumm, 1991).

6. Conclusion

The Pantanal is complex and an unusual site of sedimentation. Knowledge of the Quaternary is still very poor, but clearly its geological history is much more complex than suspected before. Much more research is necessary to understand the origin and filling of this

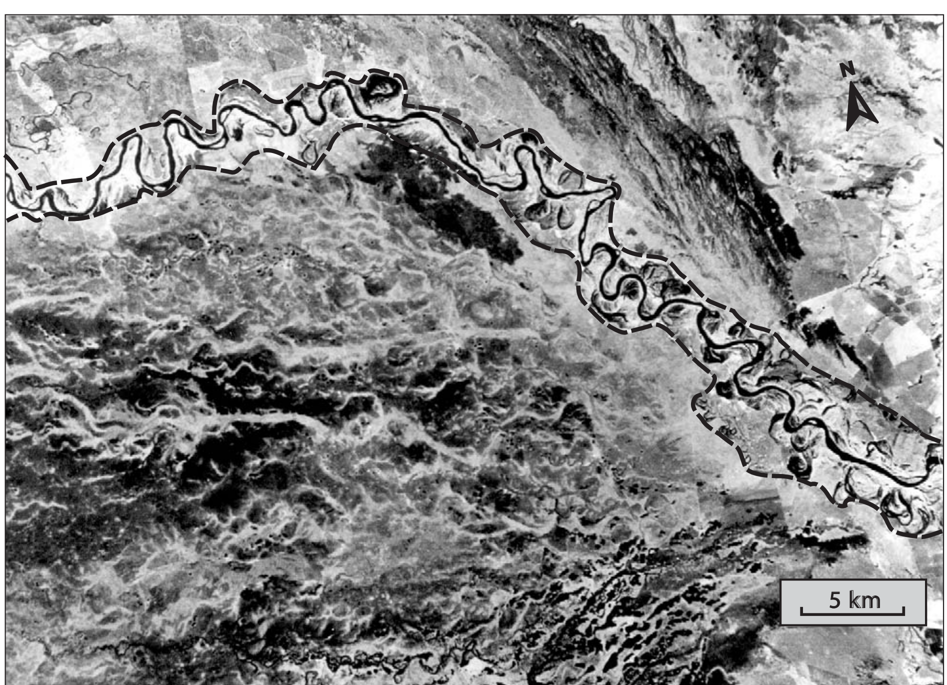

Fig. 13. Fanhead trench in the upper fan (Satellite image TM, band 4, Oct/1990). The Taquari River is confined in a meandering belt, where sinuosity is high and cutoffs are frequent.

active sedimentary basin. Sedimentation and flooding are not only conditioned by climatic changes and sedimentary dynamics, but are also constrained by tectonic activities, associated with plane stress transmission derived from the foreland Andean thrust front.

The depositional tract system, composed of several alluvial fans draining to a wide meandering fluvial plain, is a good sedimentary model to be applied to the study of old alluvial sequences.

The succession of the Taquari River fan lobes is still to be established and will greatly contribute to the reconstruction of the Pantanal paleogeography since the Late Pleistocene.

Avulsion and shifting are natural sedimentary processes in the evolution of the alluvial fans and have been occurring since the Pleistocene, but they are now accelerated by human occupation. Deforestation and agricultural activities in the surrounding plateaus have increased erosion and sediment input to the alluvial fans. As a consequence, the landscape is changing very rapidly, because sedimentary processes in the alluvial fans tend to occur at a faster pace than ever before. In the Taquari River, the rate of channel aggradation is increasing, causing shallows and triggering avulsion and floods in the lower fan.

Acknowledgements

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