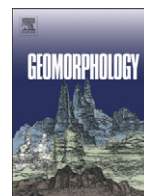




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Contrasting fluvial styles of the Paraguay River in the northwestern border of the Pantanal wetland, Brazil

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ABSTRACT

The Upper Paraguay drainage basin is situated mainly in west-central Brazil, near the Bolivian border. Flowing from north to south, the Paraguay is the trunk river of an alluvial depositional tract characterized by complex geomorphologic zonation that resulted from an intricate geologic evolution since the Late Pleistocene. This paper focuses on the geomorphology of the Paraguay River at the northwestern border of the Pantanal wetland, where two broad geomorphologic zones were distinguished. North from the Pantanal wetland, the Paraguay River flows in an aggradational fluvial plain, 5 km wide and incised into older alluvial deposits. The river exhibits a meandering style over most of its course, but sinuosity drops from 2.2 to 1.1 near the northwest border of the Pantanal wetland where the river has been forming the Paraguay fluvial megafan since the Late Pleistocene. The river deflects 90° eastward at the entrance into the Pantanal, changing its fluvial style because of a progressive loss of confinement downstream of the point where the river reaches lowland plains. The river becomes more sinuous, adopts a distributary pattern within the wetland and brings about the creation of the modern depositional lobe characterized by higher topographic gradient and active sedimentation likely linked to increased accommodation space allowing progradation. Fluvial discharge diminishes in the Pantanal wetland because of channel overbank flow during the rainy season and frequent levee crevassing. Avulsion belts and channel–levee complex are preserved on the floodplain as relict forms. South of the convergence of the two main channels that define the Taiaimã Island, a loss of gradient marks the base of the depositional lobe. Further downstream, the Paraguay River returns to a meandering fluvial style, but crossing a large fluvial plain populated by hundreds of small lakes and seasonally flooded that characterizes the Pantanal wetland.

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1. Introduction

The La Plata River basin is the fifth largest drainage system in the world and the second largest in South America, extending over 3.1 million km². It covers part of central and northern Argentina, a vast part of Uruguay, the whole Paraguay, a small area in southeast Bolivia and a large part of southern Brazil. The main tributaries are the Parana, Paraguay and Uruguay Rivers. The management of the drainage basin is crucial for economic development of those countries, especially because about 70% of the total GNP of the five countries is produced within the basin (Tucci, 2001).

The drainage basin of the Paraguay River has a total area of approximately 1,095,000 km² and encompasses areas of Brazil, Bolivia, Paraguay and Argentina. From its headwaters located at the Parecis

plateau in Mato Grosso State, Central-West Region of Brazil, to its confluence with the Parana River near the town of Corrientes in Argentina, the Paraguay River is about 2621 km long (Innocencio, 1988).

Based on its physical characteristics, Almeida (1945) recognized four main geomorphologic zones with distinct channel patterns and dominant sedimentary processes. Today, the two uppermost zones constitute the Upper Paraguay drainage basin (PCBAP, 1997) and encompass the area from the headwaters to the confluence of the Apa River (Brazil–Paraguay border).

Water management and conservation are matters of concern because the drainage basin has been undergoing a number of environmental impacts. These impacts, spurred by increased deforestation, cattle in pastures and intensive planting of annual crops after the 1970s, have enhanced the sediment load of the river by focusing erosion in the catchment.

Flowing from north to south near the Brazilian–Bolivian border, the Paraguay has a length of about 1693 km in the Upper Paraguay drainage basin, which is mostly located in Brazilian territory. Published research regarding its geomorphology are scarce; those studies that do exist focused on a broad-scale of investigation, such as

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that of RADAMBRASIL (Franco and Pinheiro, 1982; Ross and Santos, 1982), a Brazilian governmental mapping program based on synthetic aperture radar images.

Fluvial style varies significantly along the course of the Upper Paraguay River, especially within the Pantanal wetland and its surrounding areas, one of the most important wetlands in the world

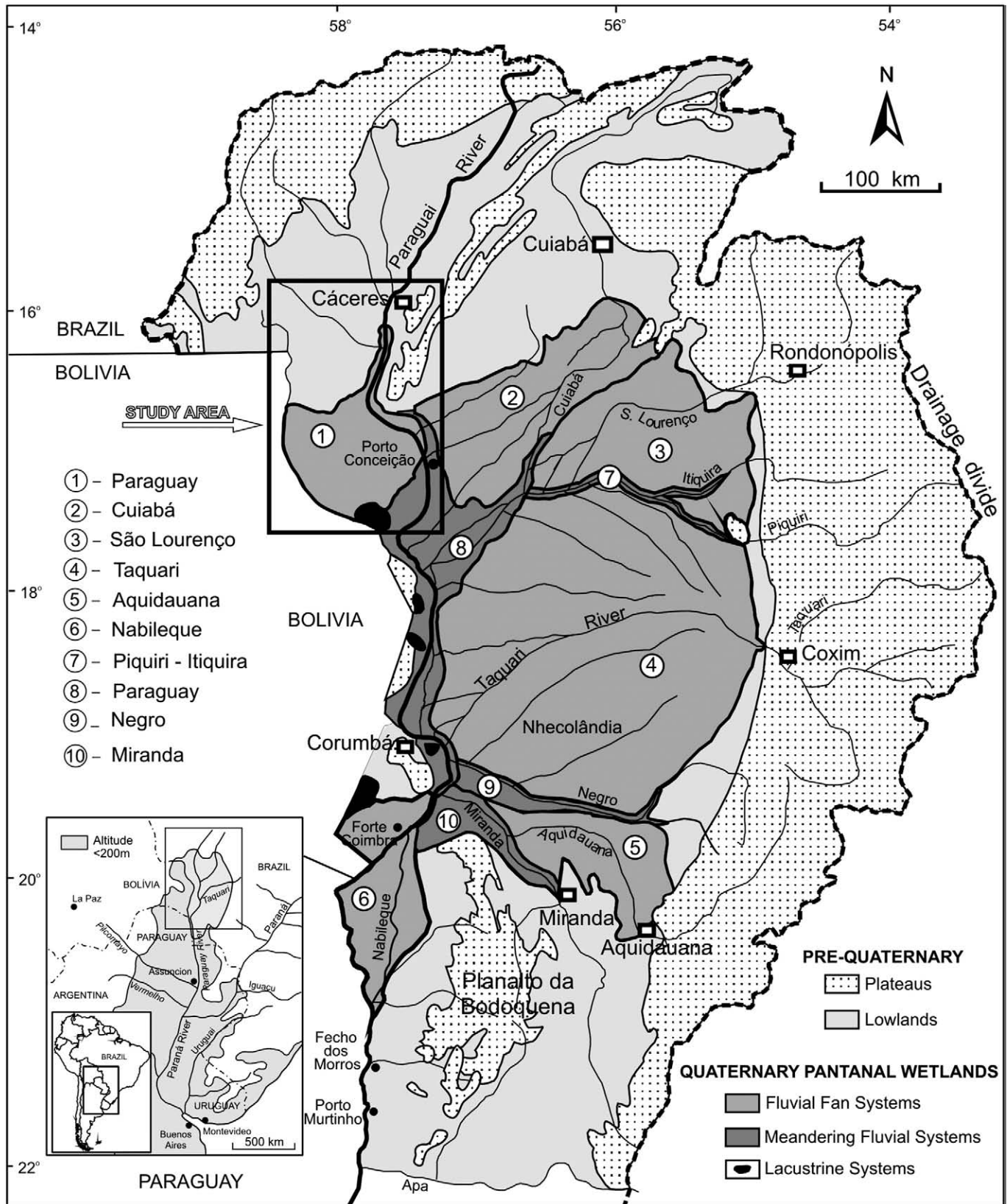


Fig. 1. Geomorphological map of the Upper Paraguay River drainage basin (modified from Assine and Soares, 2004). Eastern and northern plateaus are mostly sculpted on Paleozoic and Mesozoic rocks. Lowlands are peneplanation surfaces developed on Precambrian rocks. Pantanal wetlands are Quaternary plains made by river-dominated fans, fluvial plain systems and permanent lakes. The rectangle indicates the study area, located between latitude 15°45' to latitude 17°35' S and longitude 57°15' to longitude 58°30' W.

(Junk et al., 2006a). The wetland expanse is a fault-controlled Cenozoic sedimentary basin about 600 m deep whose origins have been associated with the Andean fore- and backbulge tectonic evolution (Horton and DeCelles, 1997; Ussami et al., 1999). The asymmetrical basin geometry constrains the course of the Paraguay River to the western faulted-border of the Pantanal basin; main tributaries are confined to the left margin of the river (Fig. 1).

Because of accommodation space generated by subsidence and increased humidity after the last glacial period, Pantanal has become an enormous seasonally flooded wetland dominated by alluvial sedimentation (Assine and Soares, 2004), and is referred to as the largest continuous wetland (Alho et al., 1988).

Contrasting fluvial styles are present throughout the Brazilian Pantanal, with especially marked variation at the borders of this wetland. The Paraguay becomes an erosive river at the Pantanal exit, and cuts Precambrian rocks downstream of the Nabileque confluence until the end of the zone at the border between Brazil and Paraguay.

This paper presents the main results obtained from the study of an area situated in the northwestern border of the Pantanal wetland, Municipality of Cáceres, where the Paraguay River enters the Pantanal wetland (Fig. 1). In this area, the river course undergoes many changes in its fluvial patterns, which are intimately associated with the evolution of a fluvial fan that has been taking place since the Late Pleistocene (Assine, 2003).

The importance of this work is threefold. First, the geomorphological zonation presented here can be utilized to significantly to improve conservation efforts in the region, such as those recently summarized in the “Conservation Plan for the Upper Paraguay Basin” (PCBAP, 1997). Second, we suggest that our results may also aid development planning efforts such as with the ongoing Paraguay–Paraná waterway project, known as “Hidrovia”, planned to develop the region by providing access to the Atlantic Ocean. Sound development of infrastructure in this region of Brazil is a key concern of environmentalists (e.g. Bucher and Huszar, 1995; Hamilton, 1999; Gottgens et al., 2001) and this contribution provides an expanded scientific perspective on key questions concerning the natural evolution of the landscape and its dynamic fluvial systems. Third, the Paraguay River in the northwestern portion of the Pantanal wetland is a good example of a large, tropical fluvial system forming a fluvial fan in a complex intracratonic tectonic setting. This configuration is not commonly encountered in nature, and, therefore, our study fills some of the knowledge gaps on the tropical river systems identified by Latrubesse et al. (2005).

2. Materials and methods

The geomorphological zonation of the fluvial plain presented here was developed from satellite image data through the: 1) recognition of morphologic elements and 2) mapping of homologous zones. Our approach to image analysis incorporated processing techniques designed to merge different panchromatic bands and colour composites into several band combinations. False-colour Landsat image composites 743 (RGB) and 742 (RGB) were especially useful for geomorphologic mapping (Fig. 2). Additionally, we used digital elevation models (DEM), generated from data collected by the 2000 Shuttle Radar Topography Mission from NASA, to differentiate boundaries between zones. Remote sensing products acquired during the 1960s and 1970s, such as synthetic aperture radar images and vertical black-and-white aerial photographs, were also analyzed to support the interpretations and to investigate the occurrence of recent changes.

The recognition of contrasting fluvial styles was based on the fluvial network patterns. North of the Pantanal wetland, the fluvial system is tributary and the flow of the Paraguay River is confined within a narrow incised valley. Panchromatic Landsat band 5 (mid-infrared) was very important to precise definition of marginal terraces and zone delimitation in this region. Zone discrimination and mapping within

the fluvial plain was performed based on the recognition of valley asymmetry, recognition of morphologic elements (active channels, point bars, levees, abandoned meanders and oxbow lakes, paleochannels, crevasses, etc) and the measure of morphometric parameters (valley and channel width, sinuosity channel index, etc).

The fluvial style changes downstream where the river enters the Pantanal wetland. The course of the river turns abruptly towards the east and the drainage pattern becomes distributary (Silva et al., 2007). The change is clearly visible on remote sensing images, but uncertainties in the mapping work emerged when, in certain instances, zones appeared with no clear boundaries on the terrain. In this case, SRTM 90m DEMs were used to solve the problem, allowing estimations of marginal terrace elevations and the variation downstream until the fluvial plain becomes unconfined. Data on fluvial discharge from three gauge stations were also analyzed to verify the consistency of zonation performed.

Groundtruthing of interpretations made from satellite data was accomplished by an overflight survey in 2006 and through a series of three field investigations. During these field investigations, relevant information on channel hydraulics and sedimentology have been collected (Silva, 2006).

An important scientific approach in the study of the fluvial geomorphology of the Paraguay River in the northwestern border of the Pantanal wetland is to take into account that the modern river plains integrate the Paraguay fluvial fan system. The modern landscape is the response of a combination of intrinsic and extrinsic factors (Heward, 1978) that control the evolution of the fluvial fan. Therefore, to understand the contrasting fluvial styles the river must be analyzed by taking into consideration other parts of the system, in particular depositional and erosive forms printed in the landscape of abandoned lobes. Because of this, efforts have been made in this study to recognize paleochannels, some of which record important past avulsion events.

3. Results

We identified four main geomorphologic zones on the modern fluvial plain of the Paraguay River. From upstream to downstream, these zones are: 1) entrenched meander belt plain, 2) entrenched low-sinuosity river plain, 3) modern depositional fan lobe, 4) fluvial meandering system (Fig. 3).

The zones 1 and 2 share valley entrenchment as a key characteristic, because they both incise into distal deposits of ancient alluvial deposits with sedimentary provenance from northwest (Fig. 4). Although these deposits have not yet been dated, they are often assigned a Pleistocene age (Braun, 1977; Tricart, 1982; Ab'Sáber, 1988; Clapperton, 1993). The main tributary rivers (Seputuba, Cabaçal, Padre Inácio and Juru) are also entrenched on the surface of ancient alluvial deposits, in which circular ponds and traces of paleochannels are still preserved.

The Paraguay incised valley location is closely related to the NNE fault trace that defines the western limit of the Serrana Province, a mountainous relief of Appalachian type developed on Precambrian metamorphic rocks. Because of this geological constraint, the watershed is asymmetrical in the northern portion of the studied area, with the main tributaries intersecting the Paraguay River on its right-hand margin.

The northernmost zone of the Paraguay River in the study area, located upstream of the confluence of Juru River, is an entrenched meander fluvial plain 71 km long, 6 km wide and laterally confined by terraces 5 to 10 m high. The river pattern is typically meandering with a sinuosity index of 2.2. The floodplain is characterized by the presence of numerous abandoned meanders, scroll bars and oxbow lakes. Flow in the rivers is strongly seasonal, and fluvial discharge can vary from 200 m³/s during the dry season (June to September) to 2000 m³/s during the humid season (January to April).

From the Juru River confluence to Baía das Éguas located 35 km downriver, the fluvial plain remains within an entrenched valley commonly narrow than 5 km, however, the fluvial style is completely

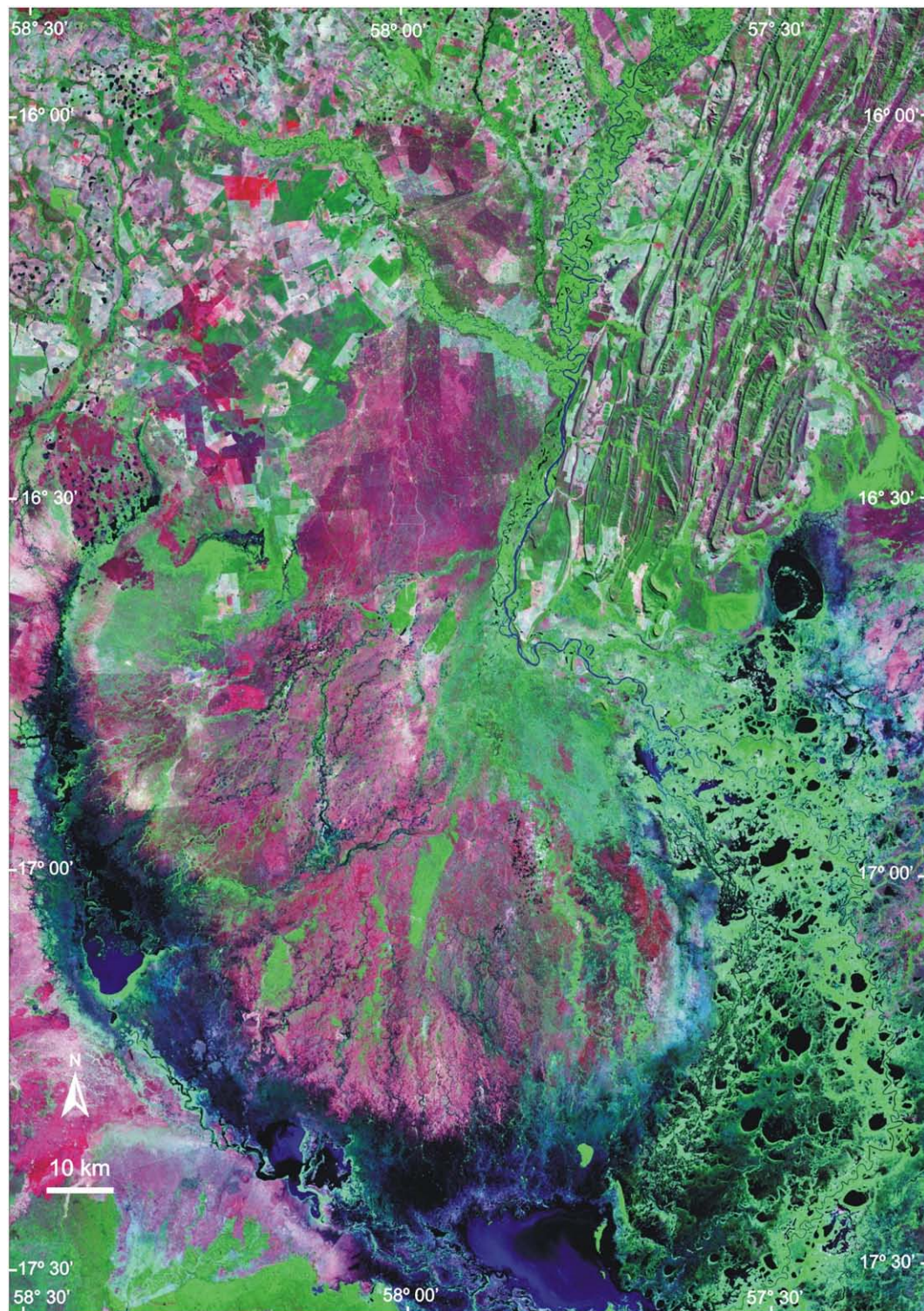


Fig. 2. Composite false-colour satellite image of bands 742 (RGB) combined with 15 m panchromatic band 8 (Landsat Thematic Mapper ETM+, Geocover Circa 2000, publicly available from NASA website <http://zulu.ssc.nasa.gov>).

diverse from the uppermost zone becoming of low-sinuosity (index of 1.1). The main channel is oriented NNE and up to 200 m wide, but the existence of alternate sand bars makes the thalweg slightly sinuous (Fig. 5). Abandoned channels present on the fluvial plain are more sinuous and narrower than the active channel, pointing out to the occurrence of an important hydrological change to the present situation.

Major changes in fluvial style are observed downstream of Baiazinha Hotel as a result of terraces lowering. An abrupt deflection

of the river towards the SE and fluvial plain unconfinement near Baía das Éguas (Fig. 4-B) marks the beginning of the modern depositional lobe of the Paraguay fluvial fan, coincident with the entrance to the Pantanal wetland. The river switches to a meandering style, crossing the first 50 km of the growing fan lobe, with a sinuosity of 1.6 and an average width of 250 m (Fig. 6-A).

The fluvial style becomes distributary on the fan as consequence of river splitting, but the sinuosity remains high for both channels. Besides

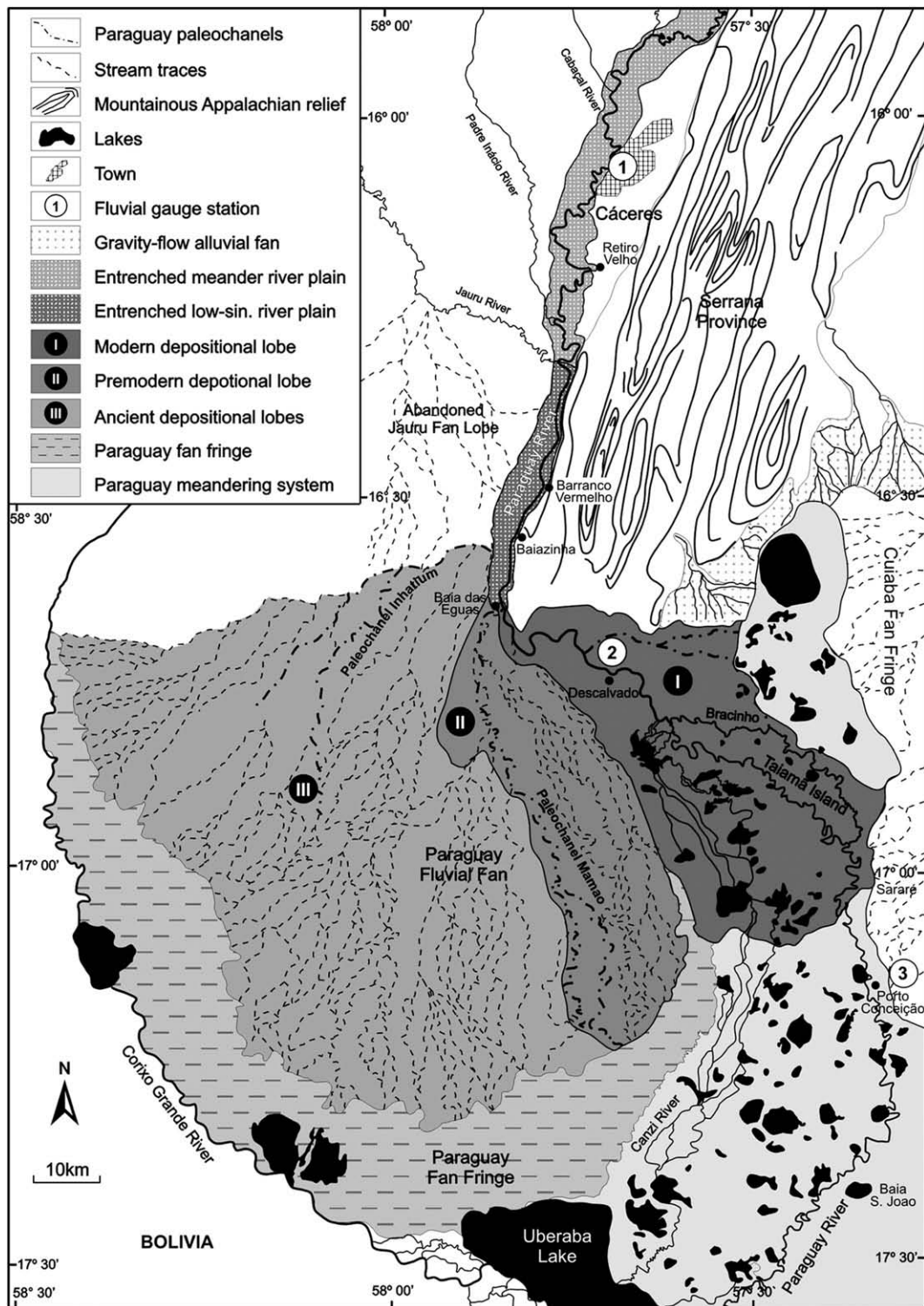


Fig. 3. Geomorphologic map. Gauge stations are indicated by 1) Cáceres, 2) Descaivaldo, and 3) Porto Conceição.

channel splitting, small crevasses, located 5 km upriver from the splitting point at Castelo de Areia, are draining water to the floodplain on the right margin of the river, and give rise to a seasonally flooded palustrine area, drained by an intricate network of small anastomosed channels that join downstream to form the Canzal River (Fig. 6-B).

The modern depositional lobe has been undergoing rapid sedimentation, because of channel infilling and also because of the large amount of sediment that is dispersed throughout the area by channel outflow during flooding. The resulting geomorphology is very

complex, and the environment is characterized by channel aggradation, crevassing, avulsion, river diversion and inundation.

Paleochannels reveal the changing nature of the river in the upper portion of the growing depositional lobe, which is characterized by a large and non-confined fluvial plain. Abandoned channel-levee complexes as well as swamps and lakes formed in between them are sedimentary morphologic features commonly found on the depositional lobe surface.

Among many abandoned channels visible on the floodplain, the Largo do Piteiro meandering paleochannel stands out because it has

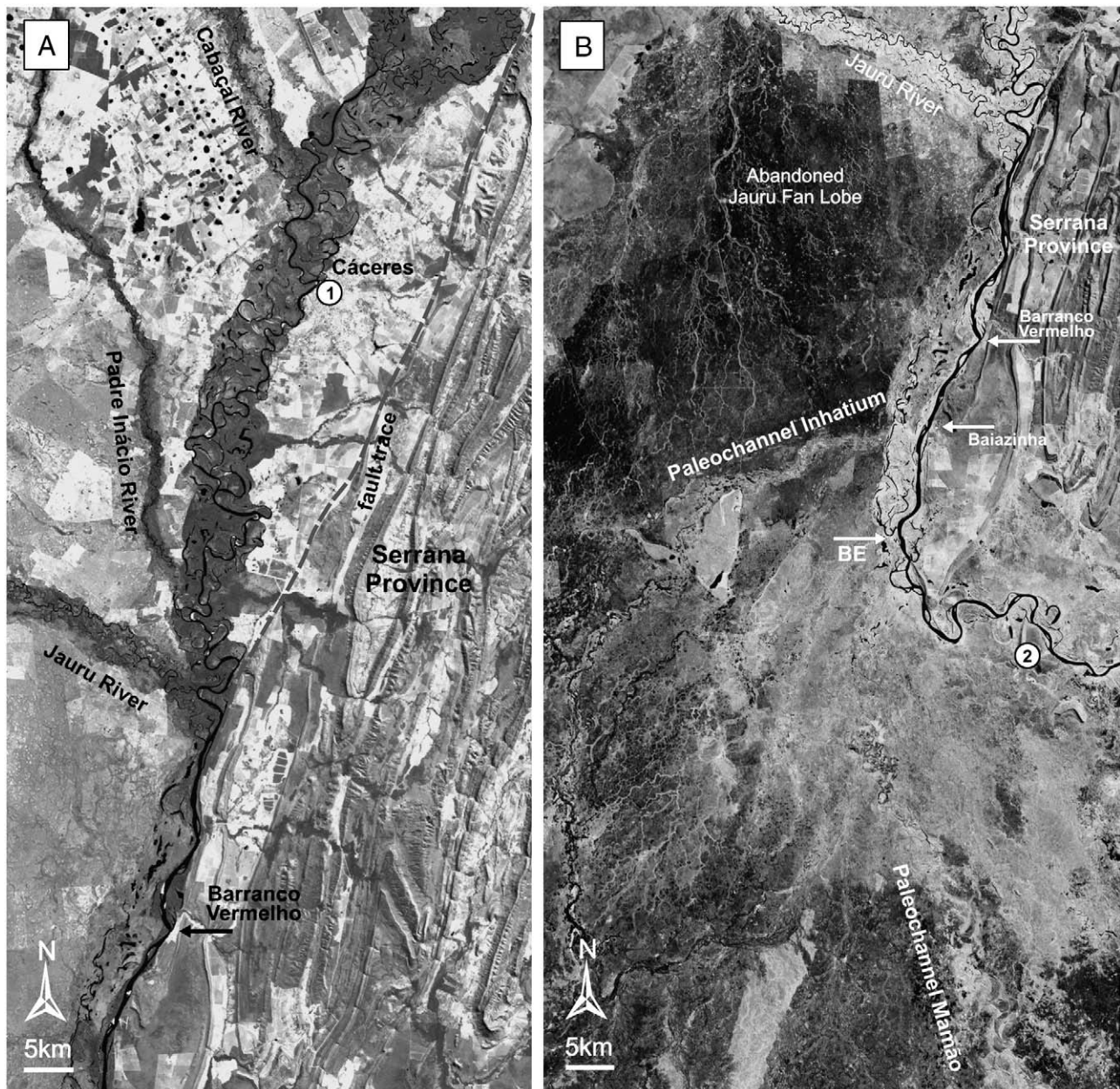


Fig. 4. Entrenched-valley fluvial plains: A) Meander river pattern (Landsat satellite image, band 5, from July 9, 2001), and B) Low-sinuosity river pattern (Landsat Thematic Mapper ETM+, Geocover Circa 2000, band 5). The end of entrenched uppermost zones is near the place named Baía das Éguas (BE).

dimension and geometry very similar to the modern channel river. The present interpretation is that this paleochannel is the relict Paraguay River channel before an avulsion event changed its course to its modern position (Fig. 6-A). This phenomenon is similar to what is going on near Castelo de Areia today, where river splitting has formed the Bracinho channel, which has progressively drained an increasing percentage of the river water during the last years, and may ultimately lead to the abandonment of the main channel.

The two channels rejoin at the lower fan lobe delineating the Taiamã Island. Downriver from the confluence, the river leaves the depositional lobe and penetrates into the meandering plain, a large grassland area punctuated by many lakes and fringing swamps. The river meanders freely across the floodplain for many kilometers south in this zone, and rises above the wetland surface because of the relative prominence of its levees.

The peak of fluvial discharge, almost synchronous at the Caceres and Descalvado gauge stations, demonstrates that the flood wave

moves quickly along the entrenched zones, reaching the upper portion of the depositional lobe in the matter of a few days. In contrast, the flood wave takes about a month to reach the Porto Conceição gauge station, travelling approximately the same distance and crossing the entire depositional lobe. Fig. 7 illustrates these points, as gauging data from the year 2000 provides the discharge chronology. Moreover, these data suggest a significant loss of water along the depositional lobe that exceeds 50% from the channel proper.

In addition to the four modern fluvial zones described above, ancient lobes of the Paraguay fluvial fan represent a vast expanse of seasonally flooded wetlands easily distinguished in remote sensing images and aerial photographs. Ancient lobes are characterized by a complex network of stream traces present on the surface.

Many of the stream traces, locally named vazantes, are presently active and they function as shallow and intermittent creeks that drain water during and following wet seasons. Some of these vazantes have reoccupied ancient Paraguay channels. This is the case

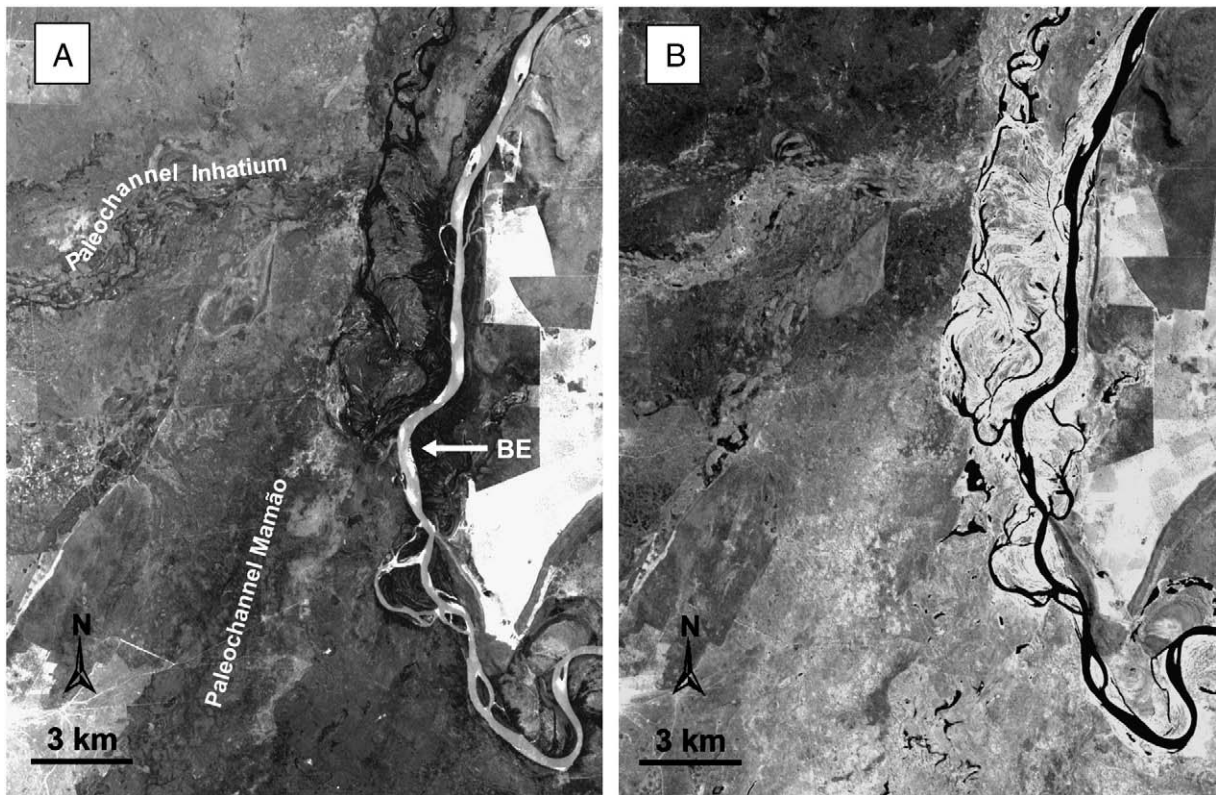


Fig. 5. Alternating river bars at the southern end of the entrenched fluvial plain. Meander paleochannels Chico Correia and Mamão record the former locations of the Paraguay River (ASTER image, bands 2 (A) and 3 (B), from August 14, 2007).

of Inhatium and Mamão abandoned meander belts, both of them beginning at the south border of the entrenched fluvial plains (Fig. 4). Vazantes spread water in radial patterns along the abandoned lobes and serve to drain water to the peripheral Corixo Grande River, which in turn flows into the Uberaba Lake, helping to form a prograding microdelta (Fig. 3). The total sum of water flowing through these systems eventually drains into the Paraguay River, south of the study area.

The complete recognition, mapping and chronology of different lobes are actively being investigated. The results of this analysis have already allowed the identification of a premodern depositional lobe (Fig. 3), wherein the Mamão paleochannel records a previous position of the Paraguay River channel, morphologically very similar to that one in the modern depositional lobe.

4. Discussion

Geomorphologic zonation using criteria, such as channel pattern, valley confinement and fluvial plain morphologic elements, is an effective method for reconstructing the sequence of events that led to the creation of the modern landscape, and to better understand processes of fluvial erosion and sedimentation.

Before its entrance into the Pantanal wetland, the Paraguay River flows in a Holocene fluvial plain confined in an incised valley. The river is strongly meandering (sinuosity = 2.2) within the northernmost zone and flows in an aggrading, low-gradient plain with a channel topographic gradient of about 0.048 m/km. The gradient remains almost the same where the river becomes of low-sinuosity, but the two zones are graded to different equilibrium profiles, so a discrete negative step in the long profile of river near Retiro Velho is considered a minor knickpoint. This morphological feature was likely generated by an upriver propagating adjustment front associated with

the smooth, concave, graded profile leveled by more resistant rocks that crop out at Barranco Vermelho (Fig. 8).

The location of the incised valley is tectonically controlled. Quaternary sediments were deposited over the western flank of a wide NNE asymmetrical syncline of Late Precambrian age (Alvarenga and Trompette, 1993), subsequently disrupted by a Cenozoic NNE normal fault that separates Precambrian metamorphic rocks of the mountainous Serrana Province from Quaternary deposits located at the western side of the fault. The surface of the Quaternary deposits dip southeastwards and as a result the drainage network is asymmetrical, because the Paraguay River is located on or near the fault trace and its main tributaries are placed on its right margin.

The height of confining terraces diminishes downstream, spurring unconfinement and the development of a huge fluvial distributary system that exhibits classical fan geometry. Besides the modern depositional lobe, a premodern and ancient lobes were also recognized (Fig. 3).

In considering a relative chronology based on our morphologic criteria, we suggest that the oldest Quaternary deposits are those alluvial sediments deposited by a former Jauru alluvial fan, because the stream traces are truncated by ancient lobes of the Paraguay fluvial fan. All of these sediments are highly compacted, sand-rich and characterized by the presence of very discontinuous pedogenic calcrete layers. These characteristics are very similar to ancient deposits found elsewhere in the Pantanal basin and considered of Late Pleistocene age (reference). Additionally, similar deposits sampled in the south portion of the Taquari megafan revealed ages between 15,000 and 40,000 years B.P. (Assine, 2003).

Several interesting questions have arisen as a result of this study, including: 1) what is the cause of entrenchment? and 2) what are the ages of incision and valley-fill fluvial deposits? With respect to the geochronology, it is hypothesized that these questions can be

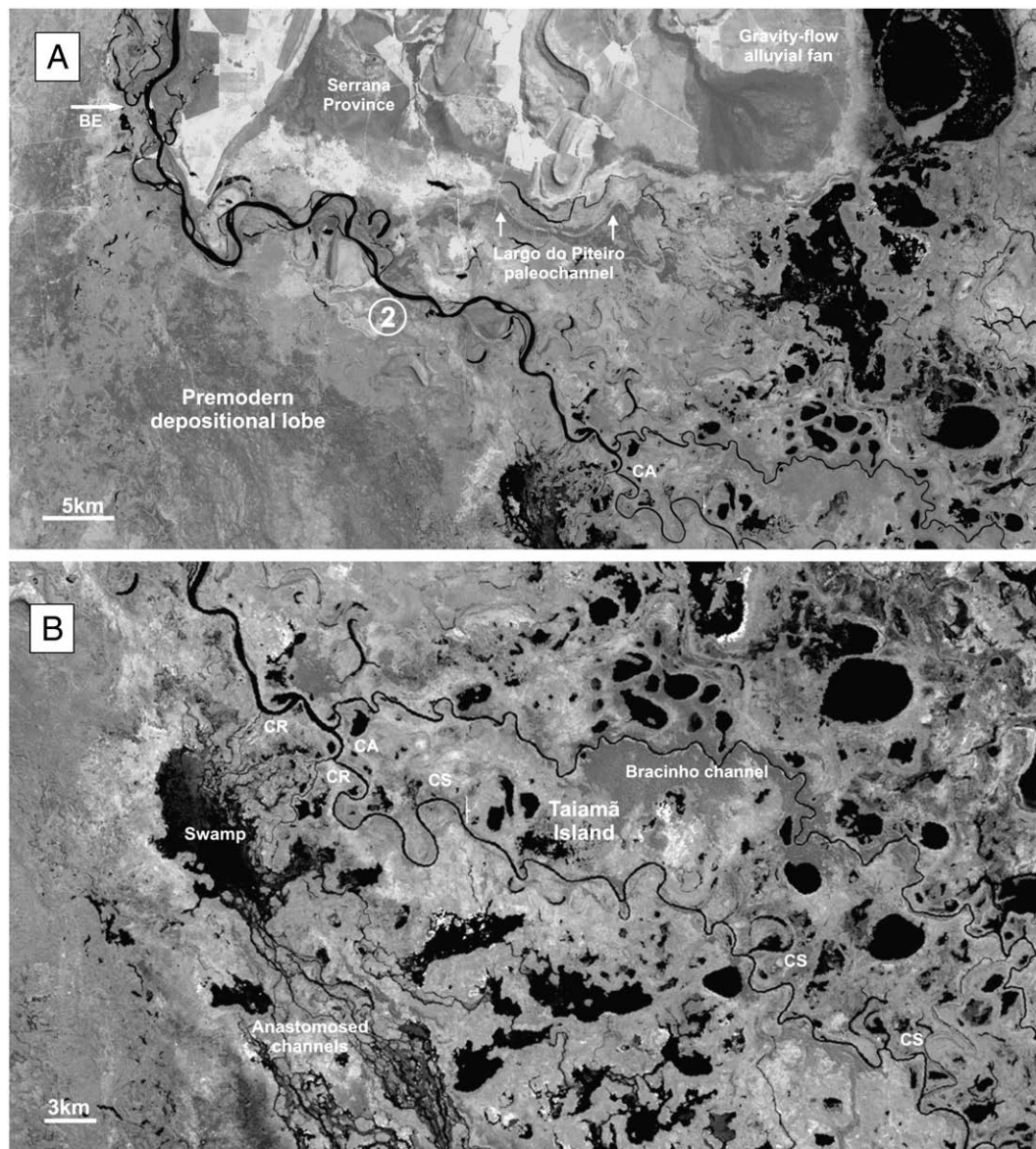


Fig. 6. Fluvial geomorphic features on the modern depositional lobe: A) The apex is placed at Baía das Eguas (BE), where the river abruptly deflects towards the SE and the channel changes its pattern and begins to meander. Many stream traces are present in the floodplain, including the prominent abandoned Largo do Piteiro meandering channel; B) The river becomes distributary near Castelo de Areia (CA), but remains highly sinuous. Crevasses (CR) and crevasse splays (CS) are common features along the river on the depositional lobe, particularly near the splitting point where a considerable amount of water is draining onto the right-hand margin of the floodplain, bringing about the origin of small anastomosed channels (Landsat satellite images, band 5, September 3, 2002).

addressed through the dating of samples from vibrocorer wells drilled within and outside of the entrenched zones. A single, discrete reason behind the cause of valley entrenchment is difficult to achieve because allogenic and autogenic processes causes channel incision (Schumm, 1991) and incision may result from a combination of two or more factors. Although the valley location is tectonically-controlled by the Precambrian folded belt framework and by Cenozoic NNE faulting, the incision seems to be result of climatic changes and/or autogenic processes related to the dynamics of lobe build-up and abandonment.

Avulsion to a lowland area modifies the base level and lowers the equilibrium profile, modifying hydraulic gradients and causing headward erosion. The process of headward propagation of knickpoints is a communication link between base level, the drainage network and the catchment area (Crosby and Whipple, 2006). Therefore, the phenomenon of lobe switching can be responsible for events of rejuvenated upstream erosion and incised-valley generation. Otherwise, subsequent sediment build-up on the floor of the new distributary lobe raises the base level, bringing about sedimentation in the upper fan

environment and trench backfilling, which are autogenic processes commonly associated in the evolution of alluvial fans (DeCelles et al., 1991).

Incised-valley backfilling and build-up on the premodern depositional lobe could have occurred at the same time. This pattern of events appears to be confirmed by the presence of older channels preserved within the incised valley that can be traced onto the surface of ancient lobes, particularly the paleochannels Mamão and Inhatium (Figs. 3 and 4).

The switch to the modern depositional lobe was a consequence of avulsion and abandonment of the premodern lobe. The apex of the new lobe is placed at the south exit of the of low-sinuosity river zone, where no marginal terraces occur and the river deflects to southeast into the Pantanal wetland. Avulsion has shifted the river to a lowland area placed in between the Paraguay and Cuiabá fluvial fans. The base level drop associated with this avulsion caused a lowering of the equilibrium profile and reactivation of headward erosion within the incised valley plain. This interpretation explains why no gradient

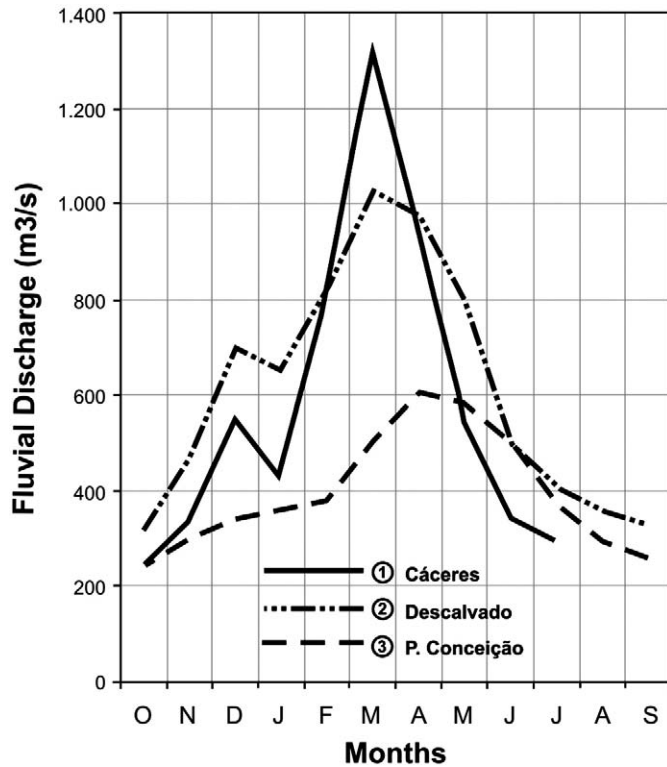


Fig. 7. Monthly average stream discharge measured in the Paraguay River during the year 2000 (location of gauge stations on Fig. 3).

break exists at the boundary between the entrenched plain and the depositional lobe; both morphological elements maintain the same lobe gradient of 0.071 m/km.

Retreating erosion generated a non-lithologic knickpoint in the middle of the of low-sinuosity river reach. The longitudinal profile shows discrete convex and concave steps at Baiazinha and Barranco Vermelho, respectively. The gradient on the longitudinal profile is typically quite low, except between these two steps where the gradient is enhanced to 0.12 m/km and the potential energy for fluvial erosion is high because the riverbed has not yet reached a state of equilibrium along its longitudinal profile.

The river course between the two retreating knickpoints is critical to navigation because rapids, riverbed and embankment erosion, and

fast-moving channel sand bars exist. Several points are currently being dredged to allow proper functioning and maintenance of fluvial transportation along the waterway Paraguay–Paraná. The need for dredging has been reinforced during the last three decades as a consequence of erosion in the catchment and an increased volume of sediment transported to the Paraguay River. The erosion and enhanced sediment supply, however, cannot be attributed solely to soya crops and cattle pasture on the surrounding plateaus. In addition, hydrological records show that rainfall and runoff have increased since 1970 (Collischonn et al., 2001).

Despite a length of ~100 km, the depositional lobe has typical lobate geometry and downstream reducing fluvial discharge (Fig. 7), which can be attributed to diverting channels, floodplain flow through crevasses, overflow during floods, infiltration and evaporation. All of these processes have been causing current deceleration and consequent aggradation within the channel and throughout the floodplain, making the depositional lobe the main site of modern sedimentation in the study area.

The active depositional lobe is characterized by the dynamics of a repetitive sequence of processes, including channel infilling, crevassing, avulsion, diversion, abandonment of the main channel and establishment of a new channel–levee complex. The abandoned channel–levee complex, represented by the paleochannel Largo do Piteiro, is a good example in the upper portion of the growing lobe. In this context, the main channel can be abandoned in the future and a new channel–levee complex can be established on the right-hand margin of the floodplain with increasing drainage of waters to the anastomosed channels that join downstream to form the Canzi River. This scenario is very similar to what is happening on the right margin of the Taquari River, one of the most important tributaries of Paraguay River in Brazil (Assine, 2005).

The base of the depositional lobe is marked by an abrupt reduction in the topographic gradient at the point where the river enters into the Paraguay meandering plain, an area of remarkably gentle gradient (0.015 m/km; Fig. 8). Although a reduction of 50% in fluvial discharge occurs (Fig. 7), flow deceleration because of the reduced gradient and increasing accommodation space make this zone an important site of modern sedimentation.

The whole Paraguay distributary tract system in the northwestern border of the Pantanal wetland is characterized by down-river decrease in channel dimensions caused by crevasses, channel splitting, sediment aggradation and levee overflow during floods. Development of fan-shape geometry, repetition of avulsion and deposition of channel–levee and lobate sandbodies make the

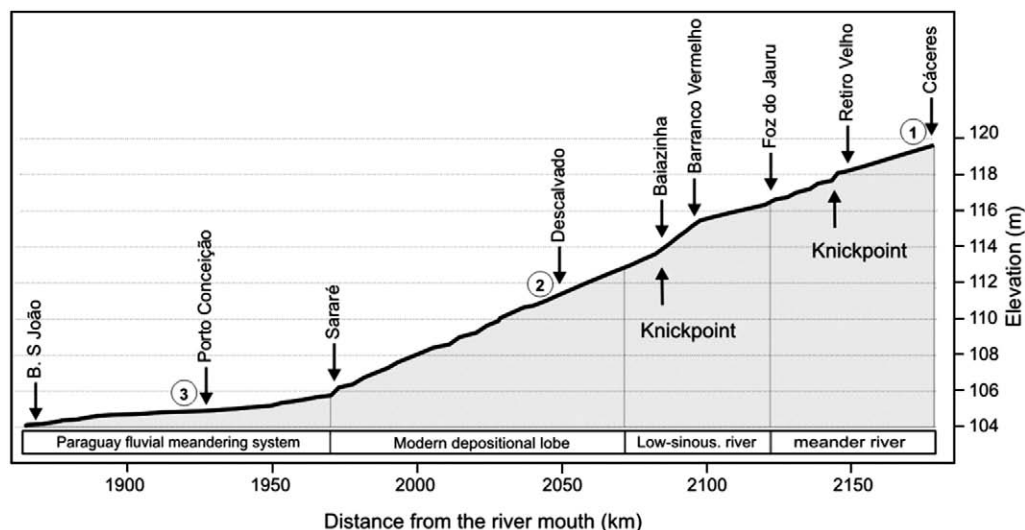


Fig. 8. Longitudinal profile of the Paraguay River (from the town of Cáceres to the Baía de São João). Numbers refer to gauge stations displayed on Fig. 7.

geomorphology and sedimentology of the system very similar to the fluvial distributary model described by Nichols and Fisher (2007). Important distinctions between the Paraguay system and the proposed model exist, however, including: 1) sub-humid climate; 2) exorheic drainage; 3) downstream channel confluences and 4) the almost total absence of terminal splays.

Considering its size of about 100 km in length and width, the Paraguay distributary system can be considered an fluvial megafan comparable to the large-sized and very low-relief fan-like systems of the Indo-Gangetic Plain, such as the megafans of Kosi, Gandak and Ganga rivers (Mohindra et al., 1992; Singh et al., 1993; Shukla et al., 2001). The Paraguay is not a megafan built by a braided river, however, like those placed in the northern parts of the Indo-Gangetic Plain along the Himalayan foothills.

The system is closer to the Okavango megafan (Stanistreet and McCarthy, 1993) because the feeding river meanders in an aggradational incised-valley before the drainage changes to a distributary fluvial pattern. Despite these similarities and both are sand-rich systems, two important differences are noteworthy. First, the role of vegetation stabilizing the channel and controlling avulsion is secondary in Pantanal compared with Okavango (McCarthy et al., 1992; Stanistreet et al., 1993). Second, in the Paraguay River the higher suspended load makes the build up of channel-levee complexes possible, which remain preserved as relict forms in the floodplain when the channel is abandoned by avulsion.

The Paraguay fan represents an important example of a river-dominated alluvial fan unconstrained by the presence of adjacent high relief, commonly associated with major basin-bounding border faults. No scarp line separates the lowland from upstream highlands, representing an interesting case of a modern sandy distributary fluvial system in intracratonic settings.

5. Conclusion

The Paraguay and other rivers of the Pantanal basin are not easily classified using current fluvial models, principally because the drainage pattern becomes frequently distributary at the entrance to the wetland (Fig. 1; Assine and Soares, 2004), giving rise to fluvial megafan systems similar in size to those found in other megafans around the world (Latrubesse et al., 2005; Leier et al., 2005).

The Upper Paraguay River follows a roughly southward course, crossing the entire western border of the Pantanal wetland, close to the Brazil–Bolivia border for a short distance, and collecting water from many distributary fluvial systems that integrate an enormous alluvial depositional tract. Contrasting fluvial styles characterize the whole Upper Paraguay River basin, particularly where the rivers enter and exit the Pantanal.

The Paraguay River runs for as much as 2621 km through the Brazilian and Paraguayan territory before joining the Paraná River in Argentina. The river is the primary waterway of the Pantanal, subject of a channelization project planned to make the Paraguay–Paraná river system navigable for 3440 km from the sea as far as Cáceres. Regarding navigation, the *Waterway Transport Agreement*, approved by the member countries in 1992 and entered into force in 1995, was one of the most important achievements of the CIH – Intergovernmental Committee for the Paraguay–Paraná Waterway (WWAP, 2007).

It has been argued that the Paraguay River channelization would cause lowering of the river level and would have a devastating impact on the Pantanal. It is common sense among bioscientists that the dependence on the flood pulse makes the Pantanal very vulnerable to hydrologic changes (Junk et al., 2006b). According to Collischonn et al. (2001), two main questions require attention: 1) Will channelization reduce the water volume dispersed over the Paraguay floodplain? and 2) What would be the likely effect of the advent of drought years on the floodplain?

In any case, the Waterway Programme is ongoing and the response of the river to human induced changes has to be considered for successful economic and environmental management of the Upper Paraguay River basin. The uppermost segment between Corumbá and Cáceres is critical and construction providing at least 1.5–1.8 m of depth is necessary for navigation (Tucci and Clarke, 1998).

An important issue arising from this study regards river management. For a successful channelization project, the Paraguay River cannot be treated in a simplistic way and be classified solely using traditional terminology of channel patterns. The Paraguay fluvial system has been affected by tectonics, differential subsidence and generation of accommodation space, and experience fluvial pattern changes along its course since the Pleistocene.

The Paraguay River has been forming a fluvial megafan on the northwestern border of the Pantanal, where distinct fluvial reaches can be distinguished on the basis of physiography. The zonation performed is the first step to interpret the Quaternary succession of events that have led to the present landscape and the key to understand the present processes and to forecast future river changes.

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