Volume 83 (2025) 01-40

boletim paranaense de Geociências
ISSN: 0067-964X

# PANTANAL BASIN: ORIGIN, EVOLUTION AND ENVIRONMENTAL CHANGES

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***Abstract:*** *Pantanal basin is a singular environmental and geotectonic entity in central South America. It differs from the extensive tract of depositional systems in the foreland of the Sub-Andean overthrust belt, characterized by the presence of alluvial mega-fans, the most visible feature of these landscapes. The Pantanal basin occupies an entrenched zone in the continental interior and is surrounded by highlands up to 800 m above sea level. Alluvial fans are sourced from the interior. Intraplate tectonic movements and climate changes are active drivers of landscape evolution and human occupation. The fracture basin hypothesis for Andean-related forebulge is reevaluated, together with the role of a transcontinental lineament. Tectonic events and climate changes during the Neogene and Quaternary constituted the driving factors for the source-to-sink movement of sediments, the development of alluvial fans and fluvial mega fan processes. An active regime of tectonic activity submits the Pantanal basin to deformations that significantly modify its landscape at a perceptible speed. Uplift and subsidence, tilting and wrench tectonics, and climatic changes drive landscape evolution. Current tectonic changes impose differential subsidence with drowned landscapes and local uplift zones, where older sediments are eroded. These changes have geometric and kinematic relationships with two active tectonic regional elements: (1) the foreland bulge of the Andes at the back of the Bolivian orocline, moved by reactivation of the Arequipa Massif collision over the South American continental plate border; and (2) the SW–NE continental lineament zone. This lineament represents a right lateral fracture zone, which has implications for the neotectonic model and is therefore meaningful for understanding the evolution of the Pantanal environment.*

*Keywords – Pantanal basin, South American neotectonic, Interior fracture basin, Neogene*

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ISSN: 0067-964X

# 1. INTRODUCTION

The Pantanal is a large plain, approximately 140,000 km2 wide, located in central South America in the Alto Paraguay hydrographic basin (Fig. 1). It is part of a wide belt of Cenozoic sedimentary deposits covered by herbaceous vegetation, "cerrados" (savannah formations), meadows, and, in some areas, eolian sand sheets. This belt is located among the Andes and the Brazilian Plateau and extends northward to Venezuela, Colombia (Llanos), and western Amazonia (Acre); toward the west and south, it extends to Bolivia and Paraguay (Chaco); and to Argentina (Chaco and Pampas). These belts are occupied by ponds and anastomosed or braided river plains, giant alluvial fans and even dune fields. In the Pantanal, many seismic events occur, including the strongest event in Brazil. The basin origin has been associated with Andean evolution, either as a broken forebulge (Almeida, 1945) or a backward flexure (Horton; Decelles, 1997). The crossing lineament has been interpreted as a modifying factor driven by differences in the southern and central Andes (Soares et al. 1998). Most of these areas occupy a belt of Cenozoic foreland basins, but the Pantanal basin is offside this belt, toward the interior of the plate, and surrounded by older rocks (Fig. 2).

In the last four years, many contributions have been presented to better understand the dynamic evolution of the region during the Quaternary. Many advances have been associated with research on structure and tectonics (Soares et al. 1998; Ussami et al., 1999; Paranhos Filho et al. 2013; 2017), erosion (Fiori et al. 2011), deposition (Fernandes et al. 1999; Soares et al, 2003; Assine, 2003; Assine e Soares, 2004; Assine et al. 2005; 2013), paleohydrology (Machado et al. 2014) and climate (Soares et al. 2003; Guerreiro 2016). Ussami et al. (op. cit.) presented a dense analysis of old and new data at the time, with consistent discussion about the tectonic origin and evolution, dynamic model and conclusion, accepting the influence of the Andean forebulge migrating over the Paraguay fold and thrust belt. Soares et al. (1998) highlighted the influence of longitudinal and oblique faults associated with a SW–NE megalineament zone that modifies the basin geometry. The hypothetic relations with Andean tectonic are presented by Rocha et al. 2022).

At least three concepts are attributed to the Pantanal designation: (1) the wetland, a plain approximately 100-200 m in altitude; (2) the basin, an elliptical sedimentary basin 200 km wide, 400 km long and 400 m deep; and (3) The ecosystem, or biome, a semi-humid, seasonally flooded plain that supports a wide variety of wildlife and is severely threatened by plantations and cattle ranching. The Pantanal may be viewed as a geosystem: a natural entity constructed across crustal segments in the last two or three million years; sustained and modified by geodynamic factors; and in dynamic equilibrium with the environment, geomorphic as climatic, but threatened by intense human occupation. The main processes that act within the system to self-organize and sustain itself are (1) subsidence, (2) uplift of the source area, (3) weathering, (4) erosion, (5) sediment transport, (6) storage, (7) deposition and bypassing, (8) deposition, and (9) deposit rework. All these processes are space- and time dependent.

## 1.1. Subjects, data and methods

The main purpose of this paper was to assemble multisource data acquired by different researchers at different times and to analyze pertinent geophysical, geologic and geomorphic information to consolidate an interpretation of the dynamics of Pantanal system evolution as geotectonic and geoenvironmental entities. The most independent components and variables are those of the macroenvironment of the system: the geologic substratum, the structural framework, the regional active tectonic kinematics and the climate. The most important responses are the structural, geomorphic, depositional and hydrological features and stratigraphic records.

The main sources of data and information used here are air photography (USAF/1964), remote

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ISSN: 0067-964X

sensing data (Landsat V), digital terrane elevation data (SRTM/USGS, and 1:100,000 charts of IBGE and SGE-Brazil), gravimetric data (USGS, Green et al. 1993; Shiraiwa & Ussami, 2001), and geological and geomorphologic maps (Alvarenga et al. 1984; Lacerda Filho. et al. 2006), water well logs, oil well data (Weyler, 1962), seismic section data (both from Petrobras) and field observation data (Soares et al. 1999; Assine & Soares, 2004), including panoramic flight view. Field observations and sampling were carried out on several field trips from 1977 to 2000. Geomorphic environment, relief and anomalies, drainage patterns and depositional records were collected from many sources and local observations; field work has searched for unleveled surfaces and terraces, deposits and fractures. Independent geologic and geophysical evidence was obtained to advance interpretation.

Thus, several sections include data and facts (new and old), analysis, assumptions and partial interpretations to construct the final conception of the driving forces responsible for basin evolution. This approach characterizes a phenomenological approach in which each part of the object is investigated and reported as an object itself. Some distinctive subjects are as follows:

The research reported here differs from Cartesian methods in geological research, especially experimental work. In the present research, the approach was mainly phenomenological and hermeneutical. For this approach, an important point is to understand that the phenomenon is part of a significant whole and is more difficult to analyses it without the understanding of other associated meanings. The previous results are reinterpreted to be consistent with results derived from other sources. The property of a part of the object determines the attribute of the entire object. In this analytical sense, for the various subjects and parts of the work's development, the method was analytical and Cartesian, given that, according to the concept, we have such conclusions. Partial conclusions or interpretations are assumed for the subjects; later, they must be selected to be consistent with different sources or perspectives. In these procedures, each discipline has its own methods and techniques for contributing to understanding the subjects listed above: sedimentology, stratigraphy, tectonics, geomorphology, the composition, processing and interpretation of photos and images, cartographic composition, and the analysis of seismic, gravimetric and magnetic data. Nevertheless, the presence of the heuristic method cannot be relegated to the long duration of immersion in the question “Why is a sedimentary basin active in many senses placed in an intraplate environment?”.

The article preferred this construction by parts—noteworthy complex—because of the high diversity of subjects, data, facts and previous assumptions from different disciplines and authors. The preferred meanings of different subjects, viewed from different techniques and perspectives or disciplines, change when they are used to integrate one perception of the completely natural entity, the system, for the team's experience.

This work presents and evaluates new and old results from various disciplinary methods and techniques, published or new contributions. Four main challenges were identified: the tectonic origin and evolution of the basin, the effect of a transcontinental lineament, the tilting of the basin, and the environmental meaning of those dynamic changes. Several results were previously published (Soares et al. 1999; Assine & Soares 2004; Assine 2005). Understanding the tectonic movements and their indicators as drivers of ongoing Pantanal changes is the final goal of this paper.

The report follows the sections bellow:

1. Geological and geomophological setting and tectonic environment
- Regional setting
- Data sources and methods

2. Data acquisition, retrieval, analysis and interpretation

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- Image alignments and lineaments and fractures
- Changes in drainage, plain boundaries, alignments and faults
- Deep gravimetric alignments and depocenter
- Eastern margin escarpment and basin longitudinal fault
- Erosion and deposition areas: basin tilting
- Surface and Cover sediments and depositional dynamic
- Seismic section and deep well: basin structure and sedimentary filll
- Correlations, ages, timing and basin history
- Ongoing erosion, deposition and uplift rates

3. Discussion and Conclusions

- Pantanal basement high  and the Sub-Andean belt
- Crossing faults and lineaments: relations with Andean belt and with  the continental interior
- Ongoing faults
- Basin origin and evolution

### 1.2. Tectonic, geomorphic and sedimentary setting: an overview

A particular aspect of the Pantanal is its location in the continental and plate  interior and its development in front of the Bolivian Orocline. The orocline is an anomalous curved feature made up of a fold and thrust belt around the Arequipa crustal block and represented by the strongly elevated Altiplano (Isaak, 1988; Ramos 2000). The basin and bulge are located approximately 400 km from the edge, which seems to be an excessive distance for a flexural forebulge.

The basin lies over the Precambrian basement, the Paraguay collision belt, which is crossed by continental lineaments and surrounded by the Paleozoic Parana and Parecis intracratonic and later Beni and Chaco foreland basins. Its relationship with the Andes is not simple because of the Bolivian orocline (Isacks, 1988) and frontal overthrust, with signals of rotational blocks and bending folds in the north (NW–SE left strike slip) and in the south arm (NE–SW right strike slip). Quaternary sediments cover Late Cretaceous to Pliocene deposits in the two foreland basins separated by an upwarping nose interposed between the frontal overthrust and Pantanal basin. A sinuous belt of exposed Precambrian rocks follows the Andes front, interposed between foreland basins and cratonic basins (Parecis, North, and Paraná, Southeast). Lineaments cross the foreland, extending from the Andean thrust belt to the cratonic area, crossing the Pantanal basin (Soares & Rabelo, 1998; Soares, 2016).

In geographic and geologic terms, the Pantanal constitutes a special situation: it is located in the transition of the sub-Andean zone to the Brazilian western plateau and is supplied by this plateau and escarpments (Amambaí, Maracaju, São Lourenço, Araras, plateau of Guimarães and Parecis) (Fig. 2). Surprisingly, the Pantanal wetland, in its largest extension, is a sandy plain within 350,000 km2 of the Alto Paraguay basin bellow 150 m in altitude.

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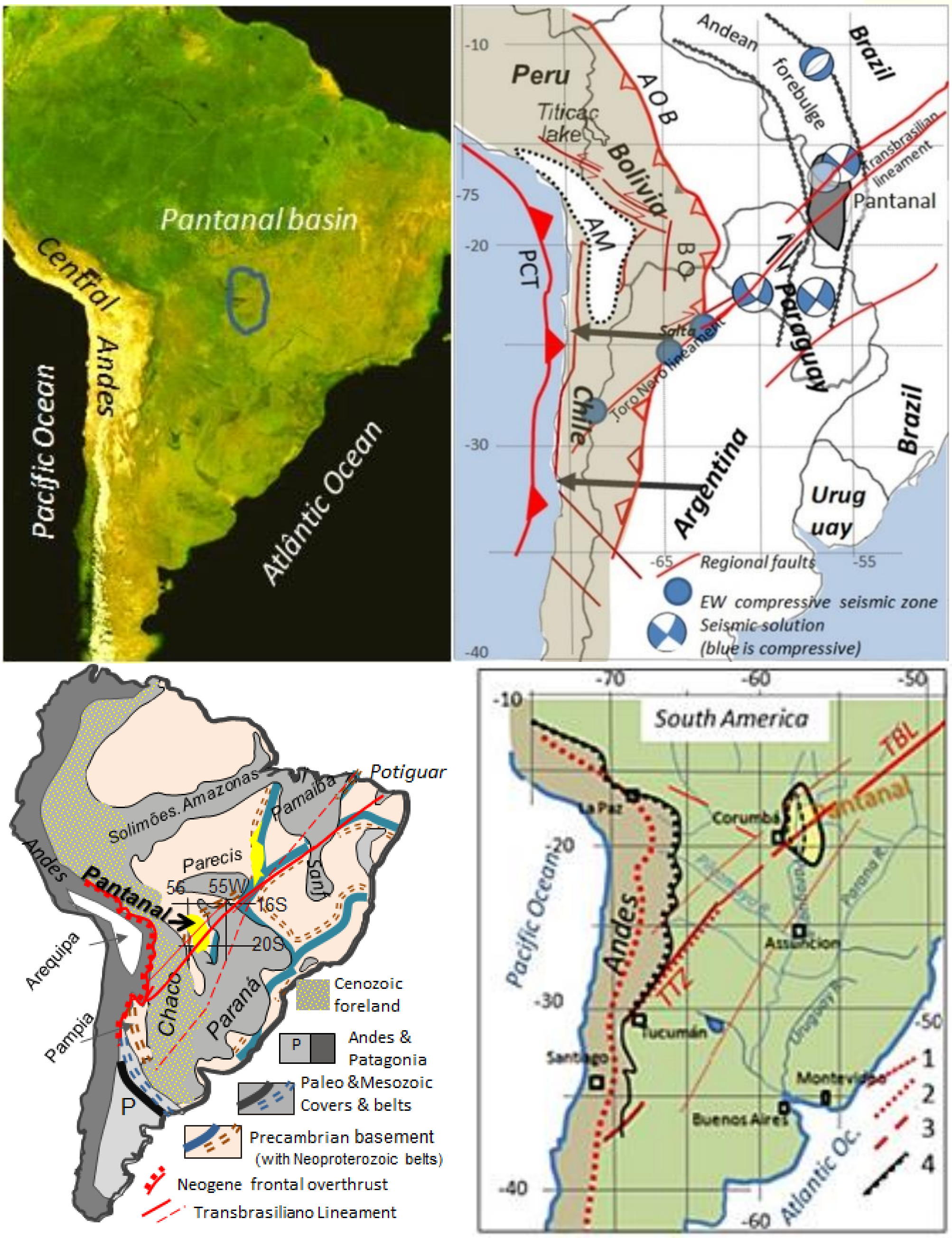


Figure 1 - Location of Pantanal within South America and some previously recognized regional features: Left, top - satellite view (NASA image) showing high relief of Central Andes Orocline and Pantanal basin in its front, far away. Left, bottom – Andean frontal overthrust and its deflection at the Tucumán Transfer zone, projected toward Pantanal. Center - the Pantanal basin and the main geotectonic elements in South America, including the hypothetical position of continent crossing Transbrasiliano Lineaments (red lines) (P is for Patagonia terrain). Right – The Andean belt between the subduction of Nazca Plate at the Peru-Chile trench (PCT) and overthrust belt (AOB), the main faults red) with their kinematic, some major earthquakes with estimated stress (blue is compression), the bulge and the EW convergence vector different, north and south of mains fault zone. TTZ Tucuman Transfer Zone and TBL Transbrasiliano lineaments. Right – Proposing relationship between Pantanal basin and the tectonic elements in Andes: PCT – Subduction line of Nazca Plate. (Modif. from Soares et al. 1998; Soares et al. 1999).

The basin is a subsiding depression in the continental interior bounded by inferred, sediment-covered, north–south faults, at the eastern and western borders. The basement depth was not mapped but may reach up to 400 m. Only the structural trend of the fourth-order surface of the minimum basement depth below sea level was estimated, indicating an elongated north–south basin. The giant Taquari fluvial fan fills the basin, where signals of active faults were identified (Fig. 2), which were later related to the Transbrasiliano lineament. Spectral, geomorphic and gravimetric features; alignments with outside faults; outcrop fractures; thickness data changes; seismic horizon discontinuities; and earthquakes are considered indicators of active

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ISSN: 0067-964X

faults during basin evolution and during the present. The gravimetric anomaly indicates longitudinal N–S faults, as noted by Ussami et al. (1999), on the western side. Fault-line escarpments and pediments are noteworthy on the eastern border (Fig. 2), and drowned inselbergs occur on the western side. Transversal faults are less noteworthy and loosely recognized in surface images of Quaternary sediments (Soares et al. 1998) and are associated with transverse continental lineaments.

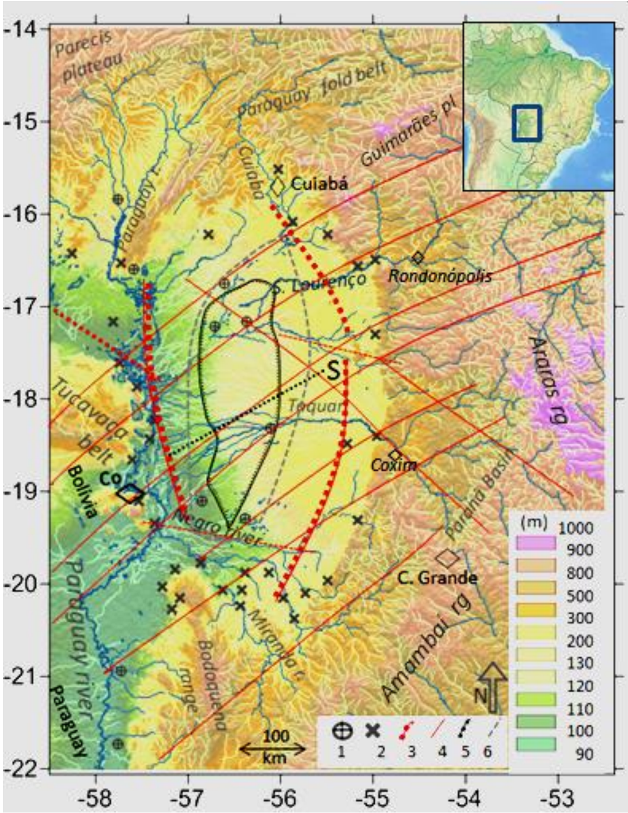


Figure 2 - Regional relief view of Alto Paraguay hydrographic basin: relief (DEM, using SRTM data, INPE;), some geotectonic entities and selected lineaments (red lines): exploration wells (1, from Weyler, 1962), control points (2), main supposed faults (3), lineaments (4), simplified basement contour at -100 m (5) and at sea level (6), inferred by 6th degree polynomial fitting. Note marginal escarpments and plateaus over 800 m (pink) above sea level. Co= Corumbá town; S= Seismic location of seismic survey.

The basement of the Pantanal basin is composed of metamorphic rocks from the late Neoproterozoic Alto Paraguay fold belt (Fig. 3A).

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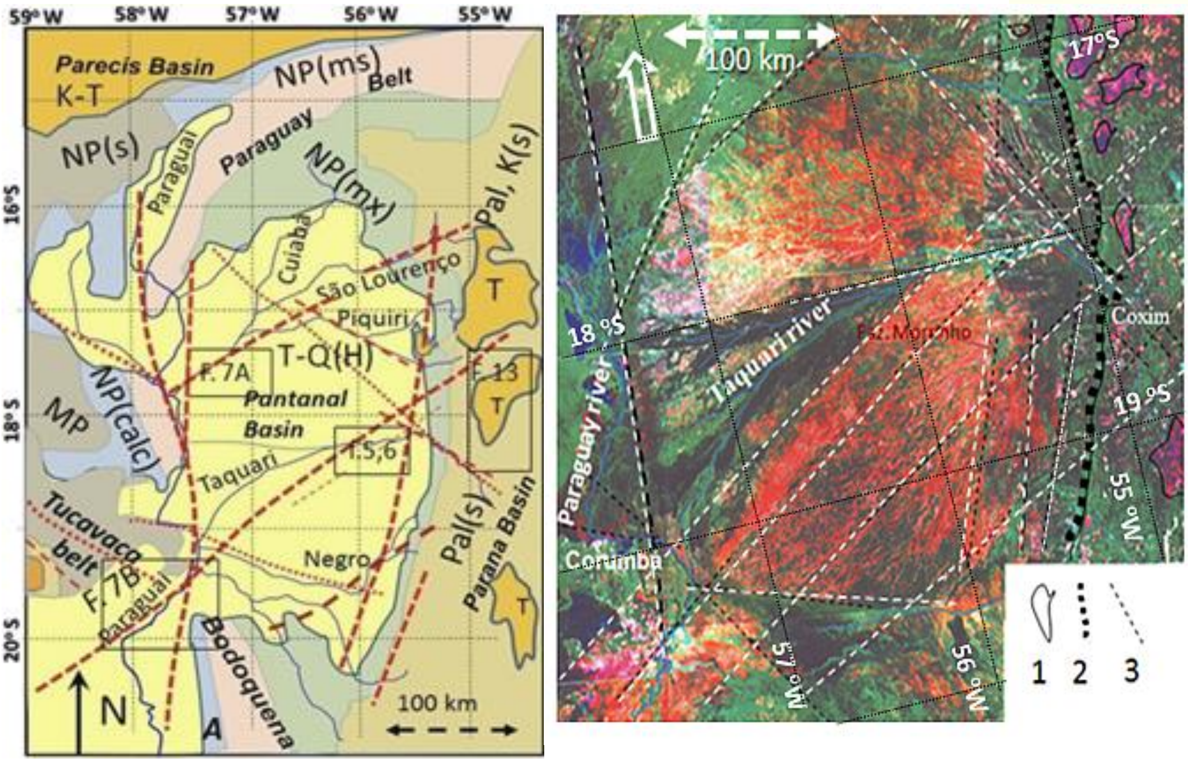


Figure 3 - (A, Left) Simplified geology of Pantanal wetland, neighborhood formations and some proposed active fault zones: A - Archean migmatites; NPx – Neoproterozoic schist; NP(ms) - Neoproterozoic phillites and metalimestones; NPs - Late Proterozoic sandstone, limestone and iron formations; Pal(s) - Early to Late Paleozoic of Paraná Basin; K(s) – Cretaceous Bauru Group; K-T - Cretaceous Parecis Group and T - Paleogene cover; Q – Quaternary Pantanal Formation. Main structural lineaments are interpreted as fault zones: SW–NE as branches of Transbrasiliano lineament, following the Taquari River, as proposed by Soares et al. (1998) and the north São Lourenço branch; NS west and eastern marginal fault zones; others interpreted buried faults (rectangles are the location of figures referred ahead).

B (Right) – Old composed scene of Landsat V (1992 images, dry season, before intense anthropic changes) showing many alignments and some aspects of the Taquari fan, in central part of Pantanal Basin, with 180 km diameter and 180 m of elevation difference between the canyon at Coxin and the Paraguay river at Corumbá (1 – in the eastern side and SW corner, pink color remnants of Eocene peneplane at 700-1060 m a.s.l; 2 – fault line escarpment, in Paleozoic sediments, retreat approximately 15 km from fault line; 3 – main lineaments (Soares et al. 1996). (At that time, 1992, the vegetation was little modified by human occupation, compared to recent images, presented ahead, and natural alignments are more visible). Many linears trends correspond to fan distributary features

Many indicators of recent tectonic processes are present in the region, including stronger earthquakes in the continental interior of Brazil (Assumpção, 1992; Soares et al. 1998; Paranhos Filho et al. 2012).

Two striking features are very interesting:

- the giant alluvial fan system tract, made of many fans and multiple lobes constructed of fine-medium clean white sands, terraced relative to the present-day meandering plain and the Taquari Novo crevasses lobe (Assine & Soares, 2003; Fig. 2);
- the morphostructural elements indicative of ongoing intraplate tectonics.

It is estimated that the residual remnants of Paleogene paleosurfaces reach elevations of approximately 500 to 1,000 meters in the surrounding area. On the plain, alluvial deposits of the Tertiary and Quaternary periods, comprising up to 400 meters of material, have been identified. The alluvial basin extends away from the tectonic basin as a result of regressive erosion of marginal escarpments, as evidenced by the presence of inselbergs along the basin margin. A distinctive inselberg of ancient sedimentary rock from the Paraná Basin has been identified within the Pantanal basin (Morrinho Farm), situated at the convergence of two principal lineaments (NE, Taquari, and NS, East Margin). In the eastern margin pediment, the paleosurfaces are overlain by a thin layer of alluvial sediments. The presence of a high escarpment away from the basin margin fault is associated with backward erosion.

All the fan lobes displayed evidence of slight erosion in their upper regions. The Taquari fan exhibited a height differential of 70 meters from the head to the base level at a distance of 180

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ISSN: 0067-964X

kilometers, indicating a very low gradient of 0.39 meters per kilometer. The primary mechanism of erosion is through the sub parallel tributary drainage network, known as "vazantes," which results from shallow incision valleys that are periodically active during the flooding of the plain. In contrast, on the west side, accumulation is the dominant process, accompanied by avulsion and the formation of new lobes, anastomosed plains, and lakes.Fans accumulate sediments at a rate greater than subsidence and are abandoned by their feeder rivers. The main lines of the new drainage network, the so-called "vazantes" and "corixos", occupied most of these paleochannels. The drainage of these vazantes results in dynamic erosion during floods.

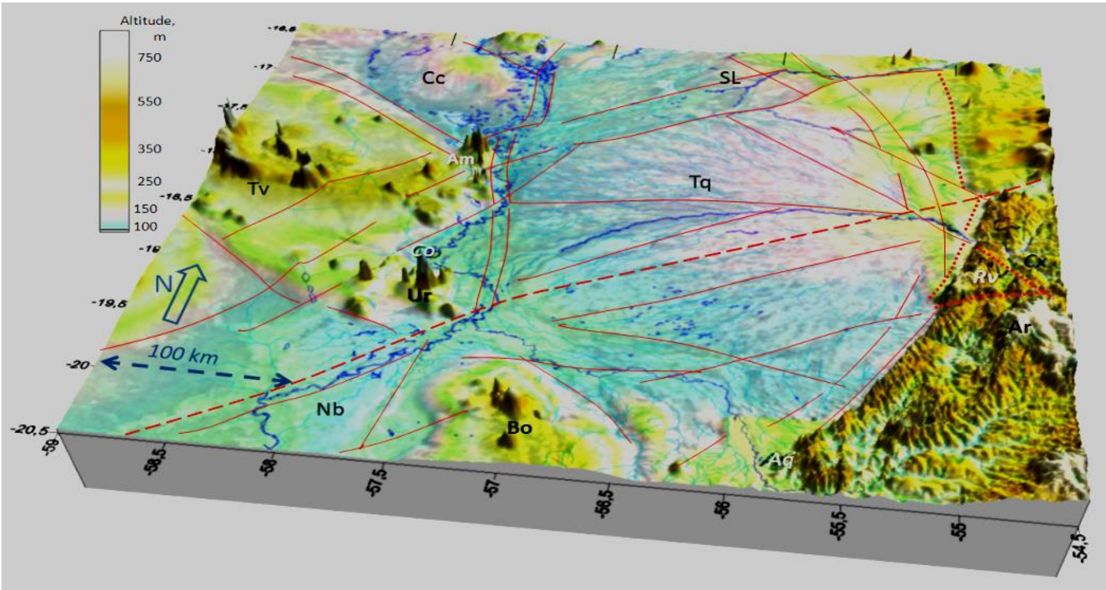


**Figura 4** - Oblique 3D view of Pantanal, with highly exaggerated relief, showing the relationship of the larger alluvial fans (Tq, Taquari; Cc, Caceres, Aq, aquidauana; Nb, Nabileque; SL, São Lourenço), with the main alignments proposed as faults and the surrounding escarpments and ranges (Ur, Urucum; Am, Amolar; Bo, Bodoquena; Tv, Tucavaca; Ar, Araras) and towns (Co, Corumbá; Aq, Aquidauana; Cx, Coxim).

Metasedimentary rock sequences, including the Araras limestone, Urucum iron and manganese formations, and Serra do Amolar quartzite, are present on the western and southwestern margins of the Bolivian crustal block. The same age association of metamorphic schist and phillite (Cuiabá Group) agglutinated to the Paraná crustal block occurs in the east, south, and north, thereby constituting the primary source area of sediments for the Paraguay, Cuiabá, and Miranda rivers. On the west side of the Pantanal, the northwestern-striking metamorphic Sunsas Mesoproterozoic belt is present. Remnants of the Paleozoic strata (mainly Silurian and Devonian beds) occur sparsely as NW–SE elongated and faulted monoclines. Additionally, local Cretaceous sediments are present. A wide folded belt of meta-limestones, from the Bodoquena Range northward to the Araras Range, composes a large part of the Pantanal substratum, composing a large buried karst bellow Cenozoic sediments, as indicated by sampled breccia in the 412 m deep well.

To the east of the Pantanal, there are eastward-dipping subhorizontal cratonic terrigenous deposits of the Paraná Basin, which constitute the primary source area of the São Lourenço, Itiquira, Taquari, Negro, and Aquidauana alluvial fan sediments. These formations comprise the Ordovician Alto Garças sandstones of the Rio Ivai Group, the Devonian Furnas sandstone and Ponta Grossa shale of the Paraná Group, and the Carboniferous-Permian diamictites and conglomerates. The stratigraphic sequence also comprises sandstones and mudstones from the Aquidauana Formation; (4) Jurassic Botucatu sandstone; (5) Early Cretaceous Serra Geral Formation basalts; and (6) Late Cretaceous Bauru Group conglomerates and sandstones. Remnants of the sub-Andean basins (Ordovician-Silurian Coimbra sandstones) are present in the southern

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ISSN: 0067-964X

and western regions of the Pantanal, exhibiting a westward dip. Large thrust faults and folds of Neoproterozoic age are present, mainly parallel to the belt. Oblique to the belt, mainly northeast striking, there is a fracture zone of regional extension previously referred to as the Transbrasiliano lineament (Shobbenhouse et al. 1984; Rabelo and Soares, 1999).

## 2. DATA ANALYSIS AND INFORMATION ACQUIRED

### 2.1 – Image features: alignments and lineaments

The primary sources of information searched and utilized in this research were alignments derived from a diverse array of sources. The linear features from each source were combined to ensure continuity across narrow belts. The consistency of this continuity of discrete elements is considered an alignment (Soares and Fiori, 1976). For lineaments, it is employed the conventional concept of a mappable association of natural surface elements that occur aligned following a line or a band, rectilinear or slightly curved, and, presumably, represent unexposed and exposed structures. Lineaments are alignments of features that are explained only by subsurface structures. The association of surface features with possible subsurface or geological features provides an alignment of the concept of lineaments. Using this reasoning, many lineaments were identified, traced and compared to previously mapped lineaments and faults. Many alignments may involve only erosive or depositional features forced by gradient flow or artifacts during data processing. Some of these faults are very consistent, representing early or active fault traces. Many loose alignments of elliptical pans have been interpreted as tectonically driven (Paranhos Filho et al. 2012), although in deflation plains, alignments of depressions, side by side with dune alignments, are common surface features.

The region is distinguished by the prevalence of linear features and boundaries, which represent the most prominent anomalous features. The linear arrangement of the eastern NS escarpment represents a noteworthy regional element. In the west, the north-south elongated drowned plain of the Paraguay River represents another regionally significant feature. In different satellite images, the presence of rectilinear boundaries between lobes and plains is indicative of fault control during sedimentation and, in some cases, of flood extension during rainy seasons or early deposit erosion. This interpretation is supported by the findings of Soares et al. (1998), Assine et al. (2009), and Paranhos Filho et al. (2012) (Fig. 5) and more recent analysis of better quality images (Oliveira et al. 2018). The considerable number of lineaments that can be delineated using these arguments is noteworthy for sediment plain. Some of these lineaments may be indicative of active tectonics. However, caution is required when inferring tectonic significance.

The different forms of potential structural control result in a irregular hexagonal pattern (nearly NS, EW, NE) within the Pantanal basin and extend from the basin margins. NW alignments are subsidiary. The many alignments obtained were combined with previous traces of different authors (Fig. 6). Some are prominent, and others have weak signals and may be illusions or casual combinations of features. However, the pattern is strong evidence of the tectonic cause of the alignments, especially in view of the associations with some mapped faults and the known occurrence of earthquakes in the basin (Assumpção 1989, 1992; Soares e Rabelo, 1998) and gravimetric and magnetic lineaments.

The other variables are dependent on image quality, time and spectral band composition, as shown in Figure 5. Some features are good linears, as expected, when fractures generated by earthquakes reach the surface. In the next figures, some examples of linears used as indicators of faults are presented. The difference in arguments, criteria and results for different authors could be an indicator of author preferences or feelings about drawing and interpreting lineaments. Nevertheless, some other anomalies are too prominent to constitute only a depositional arrangement.

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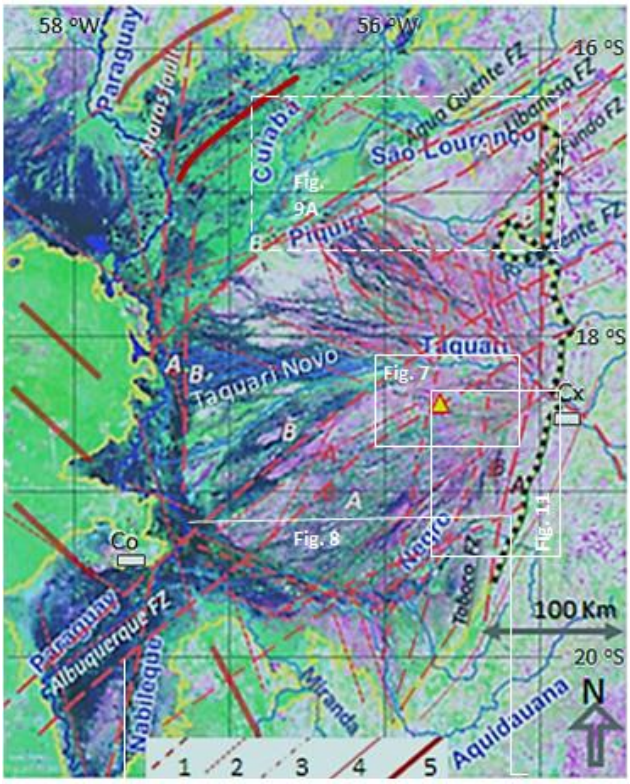


**Figure 5** – Lineament traces from different authors superposed to Landsat image (Google 2013): whitish – soil; rose whitish – sandy dry sediments; blue–gray – flooding areas; green vegetation. Linears previously used: 1 & 4 – Soares et al, 1998 & later; 2 – Assine et al. 2011; 3 – Paranhos et al. 2012; 4 – Mapped faults; 5 - Old structures in the three folded belts; Triangle marks the anomalous presence of Morrinho inselberg top of Ordovician (?) or later rocks, silicified and fractured. A and B means up and down warp sides of faults. Towns: Co, Corumbá; Cx, Coxim. Pantanal alluvial plain delineated by yellow line (Modif. from Assine, 2003), and alignments based in rectilinear spectral contrast; FZ are named fault zones, previously mapped, outside the Pantanal basin margin, by Alvarenga et al. (1982) and Lacerda Filho et al. (2006); inserts show locations of some detailed images presented ahead.

Single linear alignments not explained by surface rework of sediments and bearing associated relief are interpreted as typical signals of fracture or fault expression (Figure 6, A); in this case, structures are located in the vazante zone, approximately 90 m high (a.s.l.) and surrounded by paleodunes (94 m, white ground and green trees).

Hundreds of linear depressions are covered by grass, with channel remnants, linear bars and low-relief sandy crests (cordilheiras) covered by savannahs, such as those of the "cerrado" and arboreal biomes ("cerradão"). Discontinuity and oblique boundaries are the dominant criteria for separating several lobes. However, when discontinuities are characterized by many interruptions of paleochannels (scars form) along a linear boundary, which are made up of multiple segments (as shown in Figure 6A and B), they are considered geomorphic expressions of active faulting.

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ISSN: 0067-964X

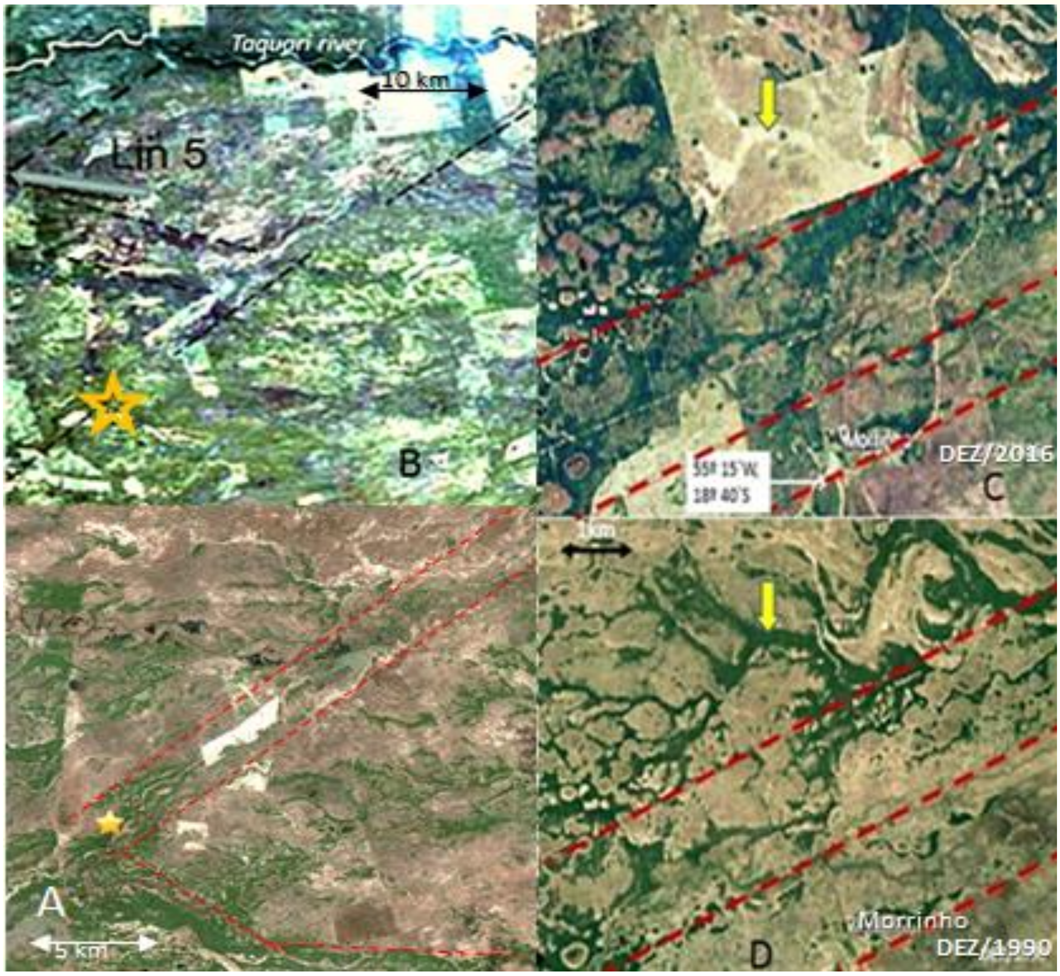


**Figure 6** – Typical examples of active fault surface features: (A, top) Stereoscopic pair composed with two different views in Google Earth (2013) images, allowing detail 3D view (with stereoscope), which highlights the rectilinear humid depression, first, interpreted (Soares et al 1998) as a strong signal of recent fault (red lines aside); (B1) Image of well-defined lineament traces (Taquari lineament) crossing the sinuous eolian paleoforms, with the location of the last earthquake (18.513°S 55.797°W in 2009: uhttps://earthquake.usgs.gov/earthquakes; Dias et al. 2016) and abrupt interruption and superimposition of landforms, bounded by 1 km wide rectilinear zone (detail B2) of intense meandering channels; (C), as example of a band of NE linears (red lines) crossing a paleodune field indicated by yellow arrow in cleared polygon (image, Google Earth, 2016); (D) The same curved lunettes forested in 1990 (yellow arrow),

Many thousand ponds, lagoons or pans of different origins are noteworthy features of old alluvial fan surfaces and meandering and anastomosing plains, in the southwestern Pantanal, the Nhecolandia zone, as shown in Figures 6 and 7. Many of these features are elliptical and aligned, but they may not be associated with active tectonics. The alignment of deflation depressions and sand dunes is a characteristic feature of regions around deserts. When the phreatic level rises, deflation stops, and ponds form, as exemplified by semidesert zones around the lake of Chad.

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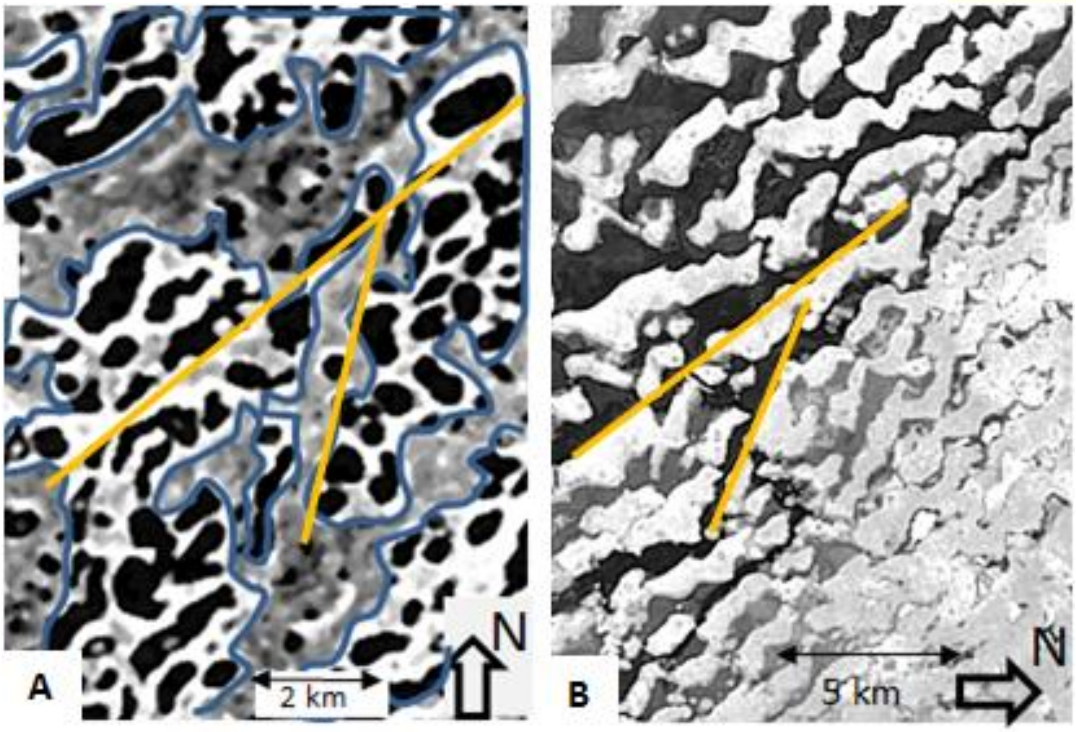


**Figure 7** - Pans and lunettes in Pantanal: (A) Nhecolandia preserved deflaction landscape (19.4 oS x 56.2 oW ) formed by thousands of pans (black) surrounded by eolian white sands called "cordilheiras"covered by cerrado (white),isolated (blue line), by present wide channels flooding and draining the old fan lobe. (B) Similar landscape in sub-Saharan zone, near Chad Lake, with pans (black) an paleodunes (white) covered by forest and zones of recent erosion by "vazantes" (gray).

The erosive boundary of a previous lobe of the alluvial fan, in rectilinear form, may represent structural control, as indicated by the noteworthy Itiquira River eroding the northwest lobe of the Taquari megafan (Fig. 8) or the Paraguay River deviation and erosion of early deposits of the Rio Negro and Nabileque fan. The acute deviation of channel locations is typical of fault crossings (Fig. 8 B).

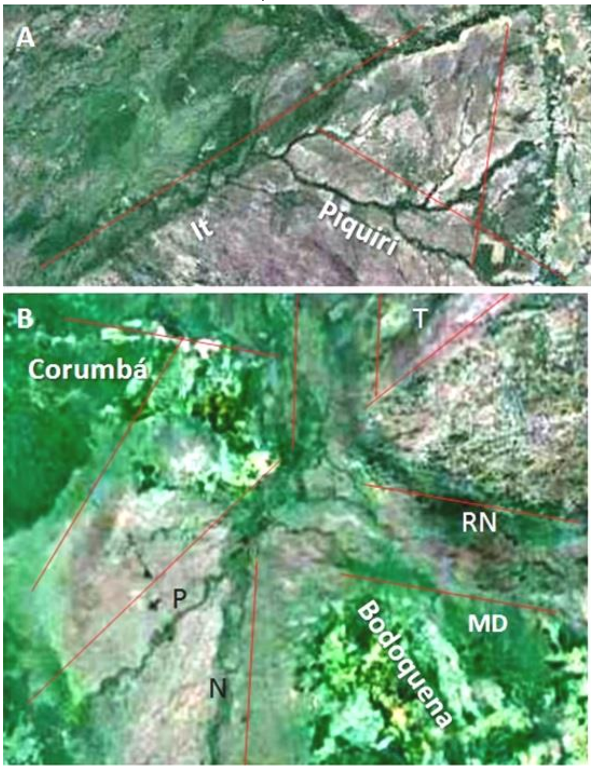


**Figure 8. A** – The straight and narrow limit between the Piquiri lobe (south) and the Itiquira São Lourenço fan provides compelling evidence of an active fault (Itiquira ft.) at the extension of lineament Aguas Quentes.B - Intersection of NE Albuquerque fault (P, Paraguay

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river deviation; Fort Coimbra, F7B in fig. 4), crossing NS Nabileque (N) fan and abandoned Paraguay channel and Taquari lineaments; and West Paraguay alignment, WNW Rio Negro (EWRN) and Miranda (MD) alignments.

## 2.2. Changes in drainage, plain boundaries and feature alignments

The drainage network (Fig. 9) of the highland source areas is quite different from that of the lowland areas, as shown in the detailed descriptive analysis of Paranhos Filho et al. (2017); drainage in source rock areas is controlled by lithology and old structures. The detailed drainage of the alluvial plain in the central quadrangle follows a diverse pattern consisting of linear bifurcate and branching subparallel segments, reflecting the distributary pattern of the alluvial fan. In the upper alluvial fans, drainage lines are intermittent and use older distributary paleochannels during floods.

Anomalies are found in many places, some of which are indicative of faulting, tilting and uplifting, as interpreted by many authors and recently by Paranhos Filho et al. (2017). Several lobes in the main Taquari fan are revealed by the formation of a superposed drainage network. The relative ages of the fans and lobes were inferred from superposition, preservation of surface features and erosion patterns. Older fans are at the margins of the basin (Fig. 5, letters). The oldest is locally preserved in the Nhecolandia region (Fig. 5B, g) and has the surface reworked by wind, preserving elongated deflation depressions (locally called "corixos"), pans ("Salinas" and "baias") and paleodunes ("cordilleras"). The latter two are located on the west side, close to the Paraguay River, the Taquari Novo lobe (Fig. 5 B, m) (Assine e Soares, 2004; Assine e Silva, 2009).

The straight edges of the lobes are clearly fault-bounded controls of sedimentation, as observed at the northern boundary of the Taquari fan (Fig. 5B, j and i), Piquiri River, southern Negro River (h and d), western Paraguay River (m), and eastern Pediment boundary (Fig. 9).

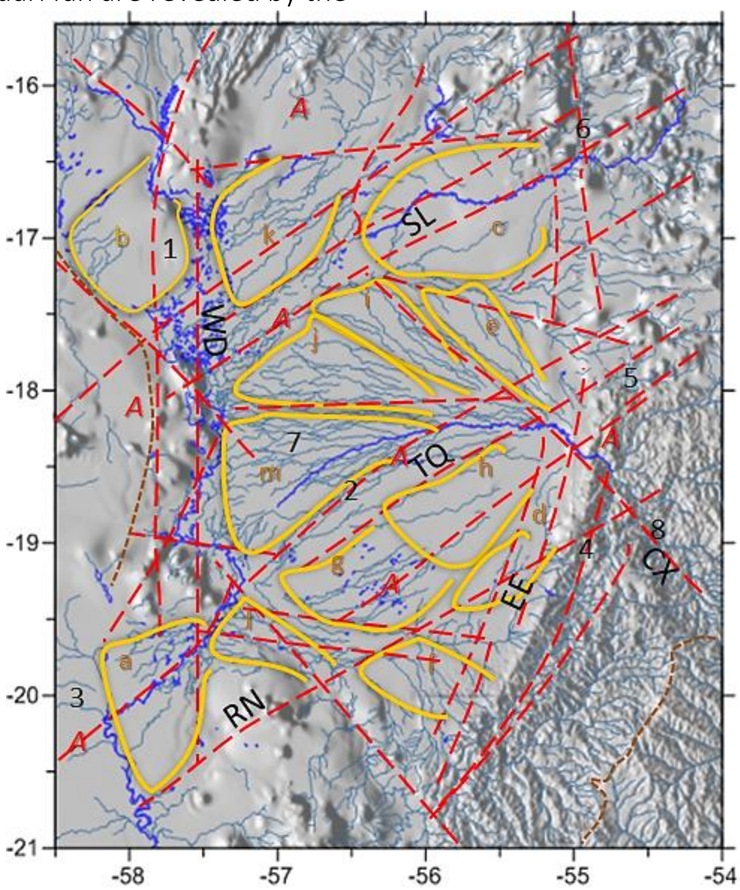


Figure 9 - Drainage network anomalies as lineaments and fans lobes boundaries based: (1) Anastomosed channel network, associated with inselbergs and lakes, as drowned landscape, (2) distributary to tributary network in upper fans indicating depositional to erosional change and subsequent fracture associated drainage, in Paraguay; (3) southwest Albuquerque fault zone, in the Paraguay channel deviation; (4) eastern side Taboco fracture zone; (5) mapped NE faults, like Correntes and Vale Rico and Água Quente (6); (7) Taquari

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Novo lobe: active avulsion changes dominates the distributary drainage, confined within E–W and SW–NE linear boundaries; (8) NW anomalous linear controls in different segments of drainage indicating active fault. Aluvial fans and lobes classed by ages: older [a (Nabileque);b (Caceres); c (São Lourenço)]; intermediate [g (Baixa Nhecolandia), d, e, f (Aquidauana)]; later [ h (Alta Nhecolandia), i, j], latest [k (Cuiabá),l (Miranda), m (Taquari Novo)]. Main Lineaments or fault zones: RN, Rio Negro; TQ, Taquari; WD, Western drown zone; EE, Eastern Escarpment; SL, São Lourenço fan.

The ocidental shoulder of the basin exhibits a relief comprising elevated pediments and inselbergs, which contrasts with the drowned zone (WD) and the oriental shoulder, which is intensively dissected. A high number of drainage anomalies are present, with rectilinear trends simulating structural lineaments. Many of them have natural surface trends along steeper depositional slopes. Other zones have subsurface control. Some features of noteworthy subsurface controlled drainage anomalies are highlighted and numbered (Fig. 9):

- The alignment of plain edges, ponds and anastomosed channel networks on the western side of the basin indicates the continuity and activity of the Araras fault, with subsidence prevailing over sedimentation on the eastern lower side (1).
- Subparallel confluence, a tributary pattern developed in a zone of older branching distributary network in older fan lobes; this change from depositional channel network to erosive form indicates local uplift and increase in hydraulic energy and uplift above base level (2).
- The local channel drift is similar to that in the Paraguay River in the Nabileque fan and is associated with the Albuquerque fault zone (3).
- The active channels of distributary drainage in the Taquari Novo lobe migrated northward (7).
- The NW controls different drainage segments, from erosive to depositional areas, indicating active faulting (8).
- The drainage segments from different drainage basins, such as the NE fracture zones outside the basin, were similarly and anomalously aligned; examples include the Correntes (5), Vale Rico, and Água Quente (6) gorges.
- A deviation from the NW toward the SW of the Aquidauana River inside the Aquidauana fan (Facincani 2007; Facincani et al. 2011) occurred as a continuation of the Rio Verde NE fault zone (4) toward the SW.
- The local channel set deviation and catchment feature a nearly orthogonal, subsequent channel (candelabrum form) associated with the fracture, as on the eastern side (Taboco NS Eastern fracture zone, 4).
- NS deviation of the Negro River and its dead channel toward the south along the NS alignment zone parallel to the pediment fringe and NS escarpment

## 2.3 - Gravimetric anomaly and alignments

An independent set of features indicative of lineaments was obtained from the contour map of gravimetric Bouguer anomaly data presented by Shiraiwa (1994) and Ussami et al. (1999). The main positive anomaly, which is nearly N–S on the western side, reflects the basement source. The anomalous alignment of forms such as gradients, deflections and peaks identified in the map presented by Shiraiwa & Ussami (2001) was used to trace gravimetric anomalies; a new contour of the data with declustering was fitted (Fig. 10 A). The obtained alignments are compared to geomorphic and spectral derived lineaments (Fig. 10 B). The fitting of some lineaments at the two longitudinal margins (NNE) may be noted. Two others cross diagonally the basin center (the São Lourenço and Taquari lineaments) and correspond to mapped faults (the Libaneza and Correntes FZs) and to the Poxoréu and Sonora magnetic lineaments toward the east from the basin; a third and fourth NE lineaments are weakly defined. Some NW lineaments are coincident. These findings support the definition of active tectonic structures as deep sources and Holocene surface effects. Other surface lineaments are not identified as gravimetric anomalies, which may indicate weak near-surface tectonic structures or insufficient resolution of gravimetric data. The conjunction of sources is marked by a 50 km wide

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anomalous zone due to the imprecision of location.

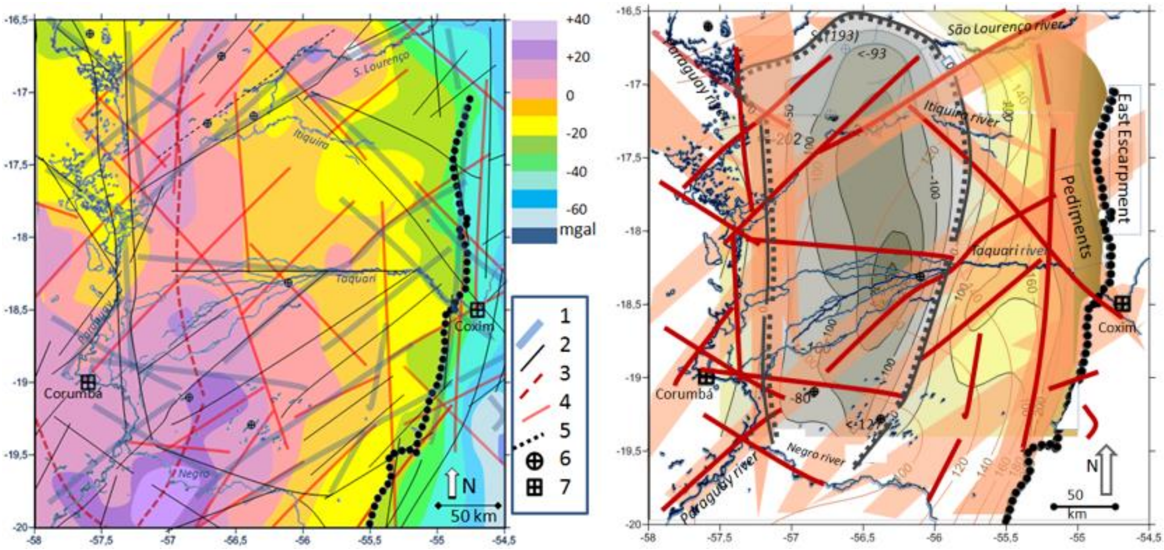


Figure 10 – Superposition of deep source and surface feature alignments from different authors and sources: (A) Left – Bouguer anomaly map (Minimum curvature contour of residuals from fifth degree polynomial adjusted to gravimetric data from Shiraiwa, 1994; Ussami et al. 1999 and Shiraiwa & Ussami, 2001): 1 – lineaments from drainage; 2 – lineaments from satellite images; 3 – main axial Bouguer anomaly;4 – positive, negative and deviation anomalies in Bouguer values ; 5 – Eastern fault escarpment; 6 - wells; 7- towns. (B) Right – Belts (rose) of spatially related anomalies, and main lineaments over the basement contour map: gray for below and brown for above sea level.

## 2.4. Eastern basin margin faults

On the east side of the basin, a fringe of pediments represents the geomorphic transition from source areas to flatlands of the Pantanal. The eastern escarpment, which includes the São Jerônimo, Maracaju and Amambai ranges, constitutes a fault line escarpment that was retracted by erosion approximately 4 km (Soares et al. 1998) but may reach 20 km (Fig. 11), forming pediment surfaces. These pediments are terraced relative to the sedimentary plain, 1 to 5 metermetres higher (Fig. 10), and dissected. Some dissection valleys are filled with colluvial white and gray sand. The lower boundaries of these zones are marked by linear drainage arrangements (e.g., Vazante Feitosa and Santa Clara), which records pediment drainage; these linear features have been interpreted as structural lineaments across the hidden eastern border fault, whose high side on the east is terraced approximately 3 m relative to the fan surface. In the southern part, around the Bodoquena range, terraced pediments gently sloping toward the Miranda Valley are common features. These pediments may be as old as the first sediments of the Pantanal basin, possibly Miocene, as indicated by the occurrence of conglomerate cemented by laterite at the base, a typical formation of a long-lasting warm climate. An example of this formation is described by Assine (2003, p.52, with photo).

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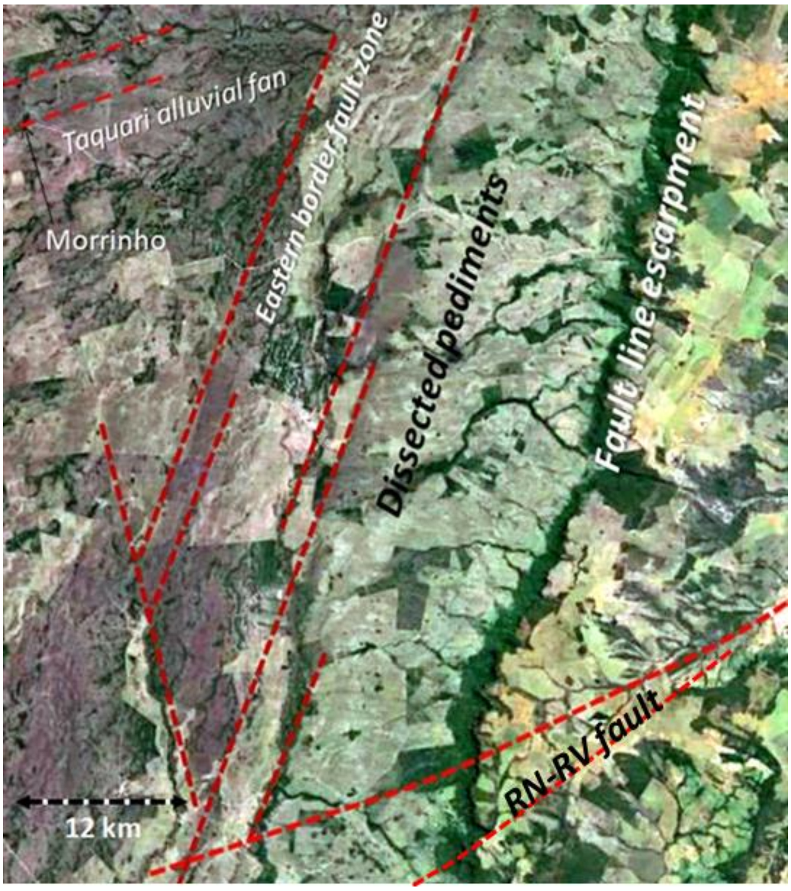


Figure 11 - Images of lineaments: Spot image (Google 2013) of the Plateau, escarpment, pediment fringe and southeastern part of Taquari fan, south of Coxin town, showing some geomorphic elements associated with faulting, mainly alignments: NNE escarpment, as result of fault line back strip, with formation of pediments, now under dissection; NS linear boundaries of pediment fringe, with small terrace form, up to 3 m from flood surface; a silicified sandstone inselberg (Morrinho da Pimenteira) from a buried pediplane, isolated by alluvial cover; RN-RV fault refers to continuation toward southwest to Rio Negro lineament (Fig.. 7) and toward NW to mapped Rio Verde fault.

At least two main faults are present on the eastern side: one at the edge of the pediment fringe with an escarpment regression of 20 km striking N15E; this fault is indicated by an alignment of gravimetric anomalies. The second is inside the fan, striking N60E, and is marked by the Morrinho da Pimenteira (Morrinho farm, Fig. 11) sandstone inselberg. The sandstone is densely fractured and silicified and seems to be Ordovician (Alto Garças) or Jurassic (Botucatu Formation), which indicates a vertical fault throw from half to one thousand meters.

Fracture measurements (Fig. 12) indicate right lateral displacement along the NE fault zone, which is consistent with the main fracture indicators.

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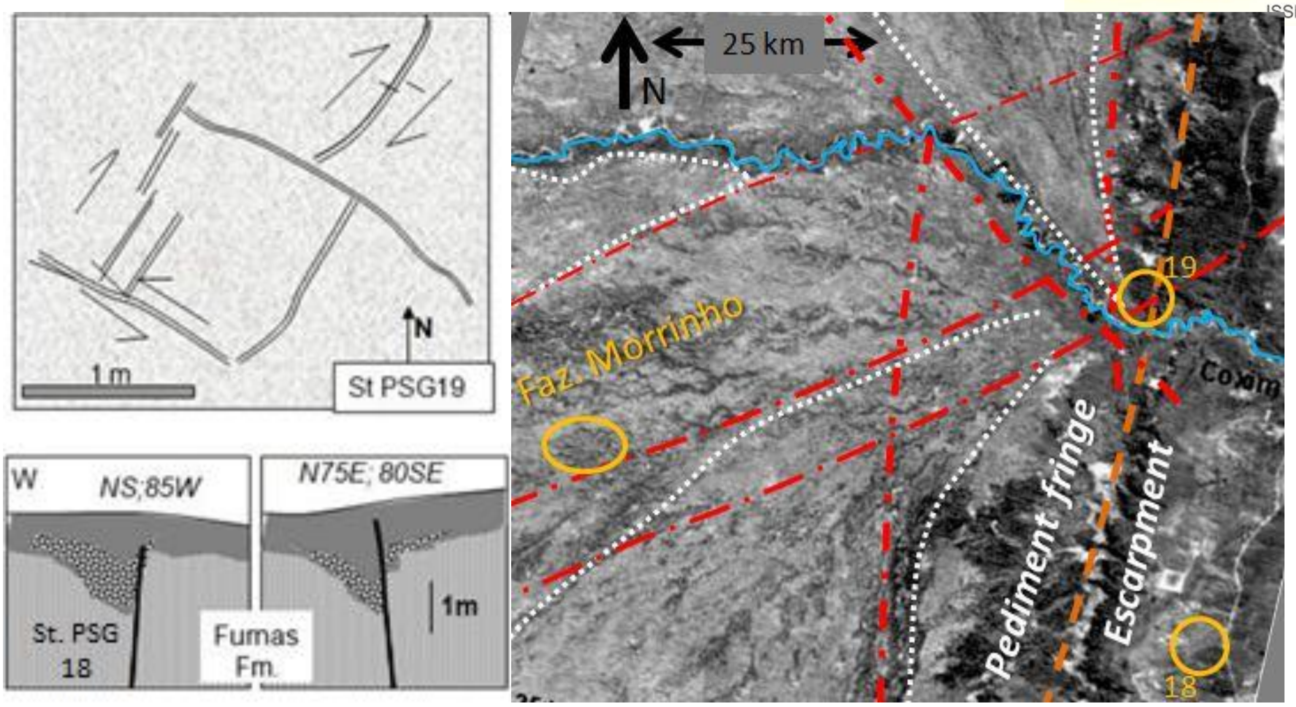


**Figure 12 -** Left - Two sketched outcrop examples of recent shear fractures: the upper, plant view, at the Coxin canyon (point 19, in the right figure , 54.87 W x 18.42 S), fractures N25E e N60 W, with Mn, Fe and salt exudation, and weak kinematic indicators. Bottom: road side outcrop near Coxim (point 18, 54.83 °W x 18.76°S)), showing faulted Neogene sandy pediment surface formation, with a faulted gravel lag deposit, over Devonian Furnas formation. Right – Location of outcrop points 19 and 18 and of th intrabasin inserberg of basement sedimentary rocks, represented by silicified and fractured sandstone topographic hill (Morrinho Farm).

The main eastern fault, recorded in the geomorphic elements, is an old fault, as indicated by the backward escarp line. Nevertheless, the main forming and older fault lies fifty kilometers west, around the 56°W meridian, as indicated by the seismic section (ahead), although this forming fault is covered.

An interesting seismic event was recorded in 2009 near the NE–SW fault zone (55,75°W, 18,5oS) and was investigated by Dias et al. (2016). The epicenter was in the eastern part of the basin, near Morrinho Farm (Fig. 12) and the Taquari-Correntes fault zone. The tectonic meaning of this important event will be discussed later.

## 2.5. Basin tilting and west side drowning areas

Some EW transverse rivers, such as the Itiquira, Negro and Taquari Rivers, have meandering entrenched plains and cut older fan sediments, which leave terrace features 3 to 5 meters high on the east side of the basin. Toward the west, these plains change to anastomosed plains, as in the case of Itiquira and São Lourenço, which approach the Cuiabá River plain, and Negro, which approaches the Paraguay River. The Taquari meandering plain is entrenched (approximately 5 m) down to Santa Luzia Farm (Fig. 13); there is a change to the distributary plain and then to the anastomosed plain close to the Paraguay River at the same level or even above previous sediments. The unlevelled step or height difference between the present-day flood plain and the terraced margin in the topographic profile of the Taquari River (Figure 13) is a good indicator of basin tilting. The river erodes earlier deposits on the eastern side of the fan and overlies sediments on the western side, creating unstable avulsions and floodplains in the Taquari Novo lobe (Assine & Soares 2003; Assine 2005).

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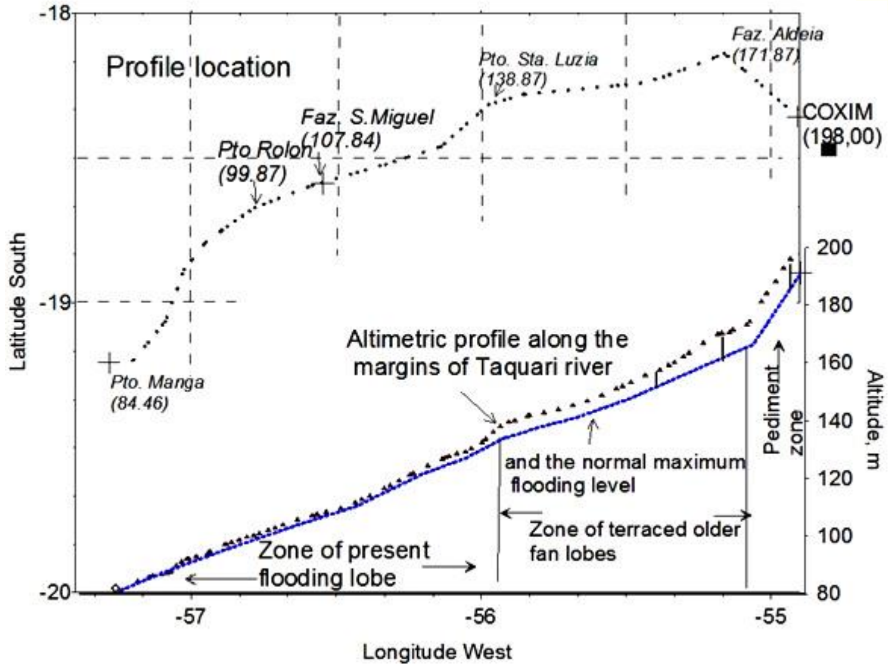


Figure 13 - Taquari river in plant (top) and profile (bottom) along the present day fan lobe , showing segments with progressive height difference between the margins (terrace) and flooding zone. Note two main breaks in the profile: at Porto Sta. Luzia (-56) and Faz. Aldeia, near Coxin, the locations of two-fault zones crossing the Taquari river. (Above, location of points in the Taquari river (geographic coordinates).

On the west part of the Pantanal basin, four anastomosing areas are noteworthy: near the mouth of the Cuiabá, Itiquira, and Taquari Novo and Negro Rivers (Fig. 9). Lakes and anastomosed fluvial plains side by side with mountains show a typical drowned landscape within a NS corridor (Figs. 9 and 10), between the continuity of the Araras fault, known outside the basin, and the Paraguay River; in the NS segment, the river channel is pushed toward the marginal Serra do Amolar mountain zone down to Corumbá town (Fig. 14). These geomorphic elements are considered typical of fault movement, with downside subsidence in the east occurring in the drowned landscape. Gravimetric alignments support these interpretations.

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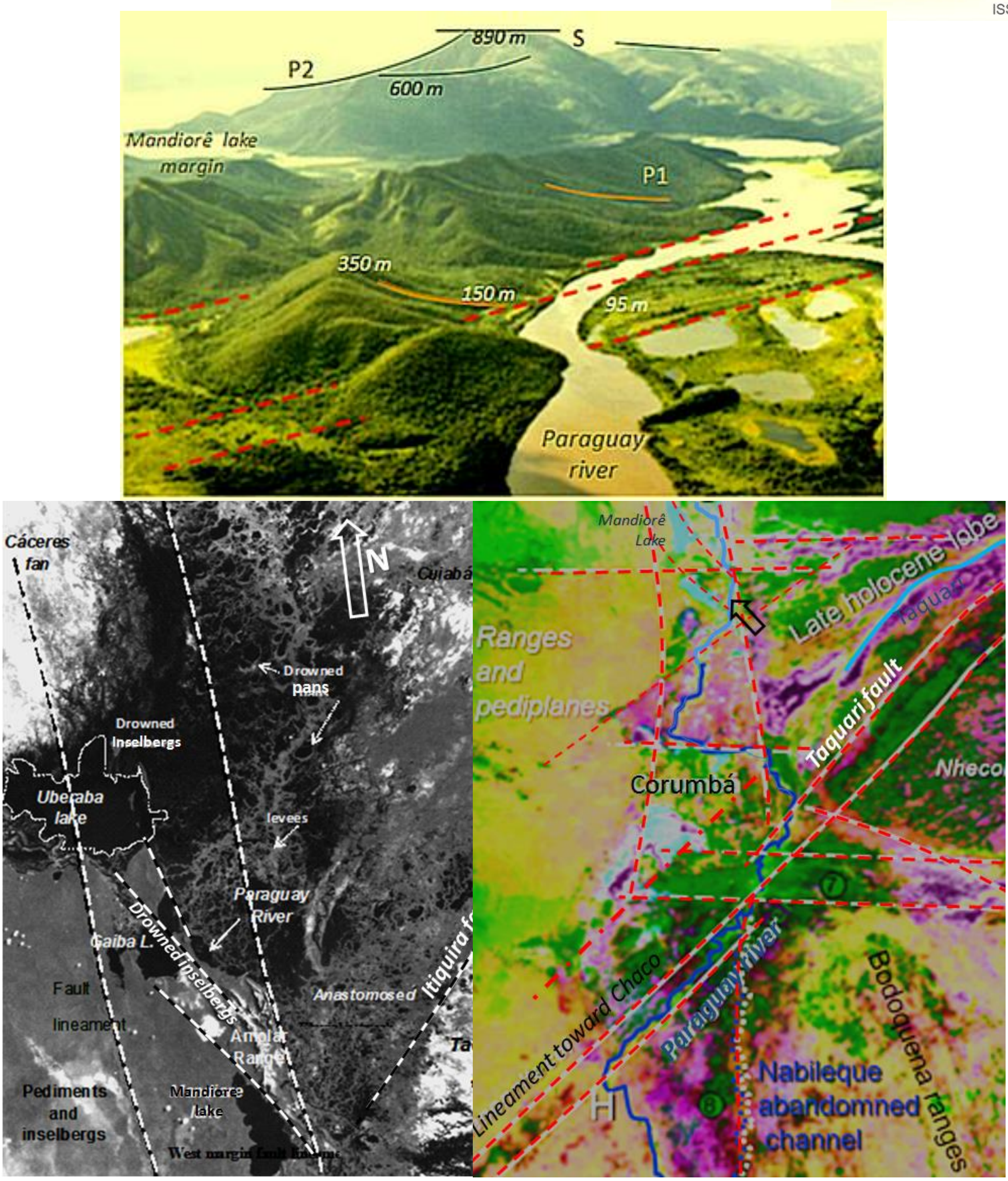


**Figure 14** – (A, Top) - Panoramic aerial view of drowned landscape at the west side of basin (Serra do Amolar, mountains around southern border of Mandiorê lake, Amolar range and Paraguay river; –noteworthy photo from Haroldo Palo Jr.; in Martins, 2018) showing summit paleosusface (S), two generations of pediments (P2 and P1), NS lineaments (red) (view located by the white arrow in the figure C bellow). (B) - Landsat view (dry season, 1993) of the lacustrine (black) and alluvial anastomosed plain (dark gray) at the northwest side of Pantanal basin. The Paraguay channel is pushed toward the marginal drowned mountain zone.

(C)- NOAA-GOES image view of contrasting dry soil and savannah (yellow and green) and wet (pink) or water (blue) zones in the southwest Pantanal: lineaments around Corumbá and the extension of main NE–SW toward Chaco Plain; Basin tilting and block subsidence along faults, associated with low supply in the area, produce permanent marshland associated with anastomosed fluvial and lacustrine landscape. Northwest ridges (Amolar Range) are exposures of folded Neoproterozoic rocks. (Location as F13, in Fig. 3). Note the drift of Paraguay river (H), leaving the dead channel of Nabileque (locations as 7B, in Fig. 3);

The existence of these disorganized nets and anastomosed plains outside the fans in front of

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the fans in the western part of the basin is an interesting aspect of the Pantanal: the under filling blocks. These plains are composed of a high density of small irregularly sinuous channels that join or cross one another and with bays. During floods, the plain is completely drowned (Fig. 14b), including some rounded pans similar to those preserved in deflation paleosurfaces. Close to these plains, there are large lakes, such as Uberaba and Mandiore Lakes, juxtaposed to a series of hills and mountain ranges typical of drowned landscapes. The buried or drowned plains and lakes in the west, opposed to terraced fan sediments in the east, correspond to a higher rate of subsidence/supply. This drowned landscape has been interpreted as a fault block downwarping by Paranhos Filho et al. (2012) and Assine et al. (2011), but it seems more appropriate to associate this fault block with basin tilting on the lower side of the western fault zone. The west side of the fault zone displays evidence of elevated older planation and erosive steps, which have been formed by the remnants of a peneplane (labeled S) and of two pediplanes (Pd2 and Pd1).

## 2.6. Cover sediments

Sedimentary deposits in alluvial fans are highly sensitive to tectonic movements both in source areas and in its accommodation zones. Thus, the late important depositional system tract of the Pantanal basin, deposited mainly by the giant multilobate Taquari alluvial fan, which is nearly 60,000 km2, is a good source of contemporaneous tectonic information. Five other small fans surround it: the Caceres fan, in the Aguapeí and upper Paraguay rivers; the Cuiabá and São Lourenço fans, in the north; and the Aquidauana and Miranda fans, in the south. These fan sediments extend behind the basin boundaries (Fig. 15). Some of these deposits represent fossil depositional systems, such as Cáceres (or Aguapeí), São Lourenço, Aquidauana and the Taquari fan. These areas are under erosion and develop contributory drainage. In the Taquari fan, an active lobe (Taquari Novo) is under active construction.

Three zones of anastomosed drowned alluvial plains were identified: the Cuiabá River mouth, the Taquari Novo mouth, and the Negro mouth. Many successive lobes were mapped in the Taquari fluvial megafan using surface features and discordant boundaries between homolog zones, similar to the findings of other researchers (Assine e Soares, 2004; Paranhos Filho et al 2011). The sediment compositions are very similar and consist of fine to coarse white sands with some light reddish exposition. Santa Maria, Capivari and Mangabal present remnants of lunettes, which are typical of deflation landscapes and sand accumulations. Nhecolandia is a special old lobe characterized by thousands of small lakes, wide channeled depressions (vazantes and corixos), and lunette-type sand crests.

Many boundaries of the lobe are coincident with alignment traces, some of which are correlated with faults. Most of the lowlands around fluvial sediments are pediments covered by colluvial and alluvial reddish sediment or soil and, locally, white sands.

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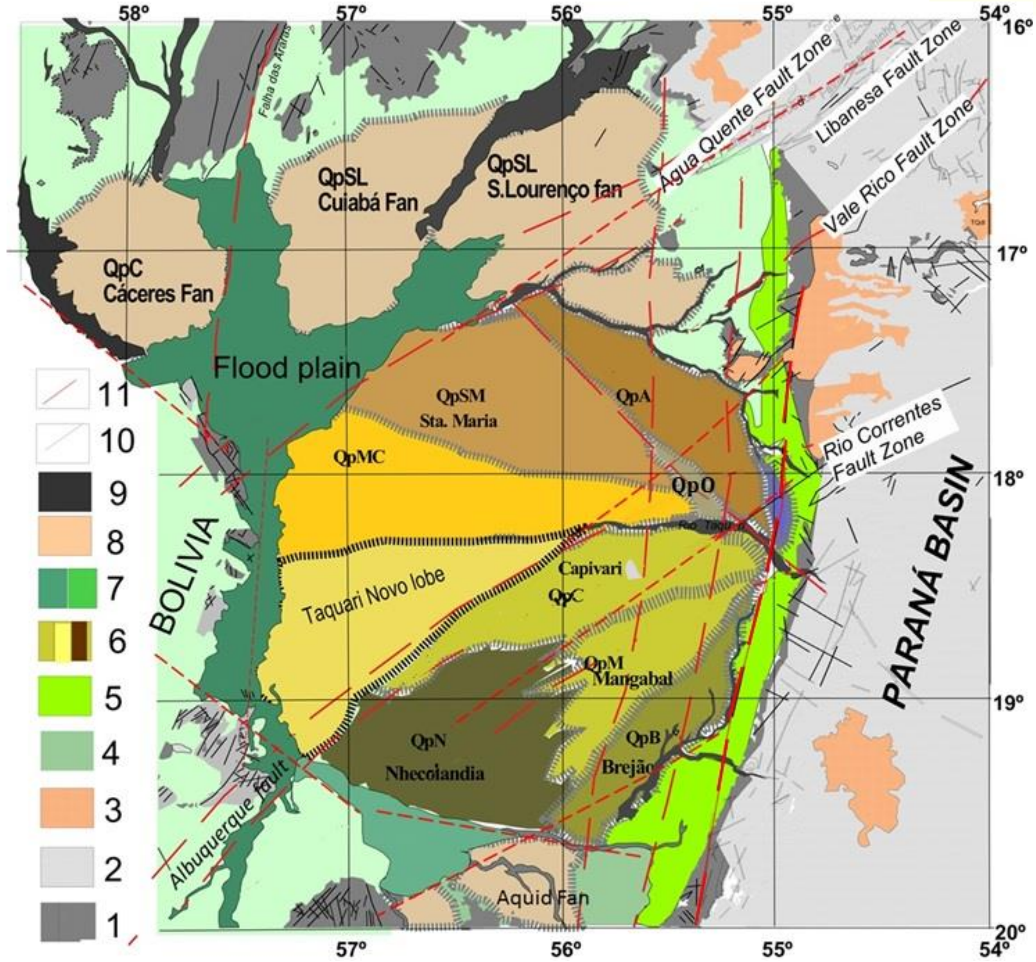


Figure 15 – Geologic map of Holocene and earlier sedimentary covers and their geomorphic classifications in the Alto Paraguay region; 1 – Rocky basement covered by sediments (a), or exposed (b); 2 – Phanerozoic sedimentary rocks; 3 – Tertiary (Eocene?) cover, detrital or residual laterite; 4 – Pediplanes around basin margins; 5 - Eastern side terraced pediments fringe; 6–old lobes and Taquari Novo lobe of the Taquari mega fan, with renewal deposition/erosion (different names have been used; see Assine & Soares, 2004 and Paranhos et al. 2012) ; 7 – anastomosed (a) and meandering (b) alluvial plains flooding zones of active lobes; 8 – old lobes with reworked surfaces; 9 – terraced alluvial plains; 10 – previous mapped and named faults; 11 – Lineament and interpreted fault zones

The fossil geomorphic surfaces of the fans show remnants of wide, slightly sinuous and braided distributary channel patterns in many lobes. In Nhecolandia, Capivari and Santa Maria, alluvial sediments were reworked by wind through deflation and dune accumulation (Soares et al. 2003). In Nhecolandia (low Nhecolandia), the deflation depressions were drowned by elevating the phreatic level (Fig. 7C). In the other older lobes, crescent sand crests are remnants of dunes (covered by Fig. 6D). The Taquari Novo, the active lobe, is characterized by a distributary pattern that is highly changeable and dominated by avulsion processes and crevasse splays (Assine 2003; 2005; Assine & Soares 2004; Assine et al. 2015). Recent sediments in the paleochannel are sand, fine to coarse, and rounded to subrounded grains with low matrix contents and are well to poorly selected. In some remnants, in the upper fan plain, there is very coarse to fine sand, with poor selection and ferruginous cement beneath the soil in paleochannels or "vazantes" (Ex. : Aldeia farm, 51.16°W × 18.21°S).

Many surfaces preserve evidence of multiple historical landscapes. In the Nhecolandia zone, there is a remnant of deflation surface (Soares et al. 2003), with thousands of small, rounded lakes or pans, many of which are supplied periodically by rain and runoff and others by the water table (Fernandes et al. 1999; Paranhos Filho et al. 2015). These pans are isolated pans floored by silt and clay sediments and surrounded by sand paleodunes. Later, erosional surfaces are reworked by channel and sheet flooding. In the Mangabal lobe, recent channels spread through the distributary network within remnants of the previous deflation surface down to the low Nhecolandia lobe. These deflation surfaces are

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recorded in georadar sections surveyed locally (Taioli et al. 2021).

Conglomerates are absent, and muddy fine sands are rare, thin and grayish. In some places, limonite cement may be found in the sandstone at the bed of channel deposits (e.g., Santa Monica Farm, lobe 3, upper plain) or in deflation pans (Bahia das Pedras, Nhecolandia; already reported by Cunha, 1956). The homogeneity of the sediment characteristics is a striking feature of the Taquari fan. The scarcity of conglomerates and mud deposits is surprising in view of the dimensions of the fan.

The brownish sand undercover and sediments have less selected sand. These near-surface, light brown sands, which are weakly lateritic, have ages estimated by thermoluminescent data of more than 30 Ky (Assine, 2003). These sands, in some places cemented by goethite and used as row material, may represent the exposed deflaction surface in semi humid and warm climates. Thin silt and clay beds within the sands above this surface are grayish green (Guerreiro, 2016), indicating a cold climate during sedimentation (Curtis, 1996).

A thin sediment cover made of white sands that preceded present flooding plains made of medium to fine white sands extends across all the fans and to the Quaternary fringe pediments. This cover is made mainly of dune white sands and has age indicators of approximately 9-11 Ky (Soares et al., 2003; Assine, 2003) based on 14C and thermoluminescence ages obtained from correlated deposits. It is covered locally by gray silt and fine sands, with higher contents of organic matter. It was deposited at a later Holocene age and filled depressions in pediment planes, floodplains and fan lobes.

The old fans and lobes are now being reworked and involved in meandering alluvial belts, where high-sinuosity rivers (Cáceres, Cuiabá, Itiquira, Negro) drain the large alluvial plain. On the western side, in the Paraguay Plain, fluvial anastomosed and lacustrine plains developed near the mouths of these rivers. These diverse regime and age of lobe formations and later reworking give origin to diverse types of landscape or sub-regions as the one surveyed by Mioto et al. 2012).

### 2.7. Subsurface structure and sedimentary fill

An elongated north–south body (Fig. 16) of approximately 300 m thick sandy sediments provides the general structure of the basin. The contour of the basement was inferred by a fourth-degree trend surface, using the basement altitude in some wells and in outcrops around the basin as control points. Longitudinal N–S faults are secondary structures, as are NE–SW and NW–SE faults.

The basement depocenter lies approximately 200 m below sea level. The sedimentary fill is poorly documented with gutter samples from wells drilled by Petrobras for oil prospecting (located in Figs. 2 and 15; Weyler, 1962). The loose sands and soft mud sediments associated with high drilling velocities have restricted lithology identification. Several water wells were more effective at identifying different types of muddy intercalations.

In the deepest well, at 410 m (Weyler, 1962), the last 70 m may be misinterpreted; the presence of limestone fragments with sand indicates Precambrian limestone mixed with collapsed sand. Seismic velocity anomaly is suggested in the N–S profile, as estimated by Silveira et al. (2021), may fault-associated. Small anomalies were estimated in the Rio Negro and São Lourenço fault zones. Possibly the anomales are associated with mineralization of sedimentary rocks in the basement as in the Morrinho hill anomaly nearby the main fault zone.

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ISSN: 0067-964X

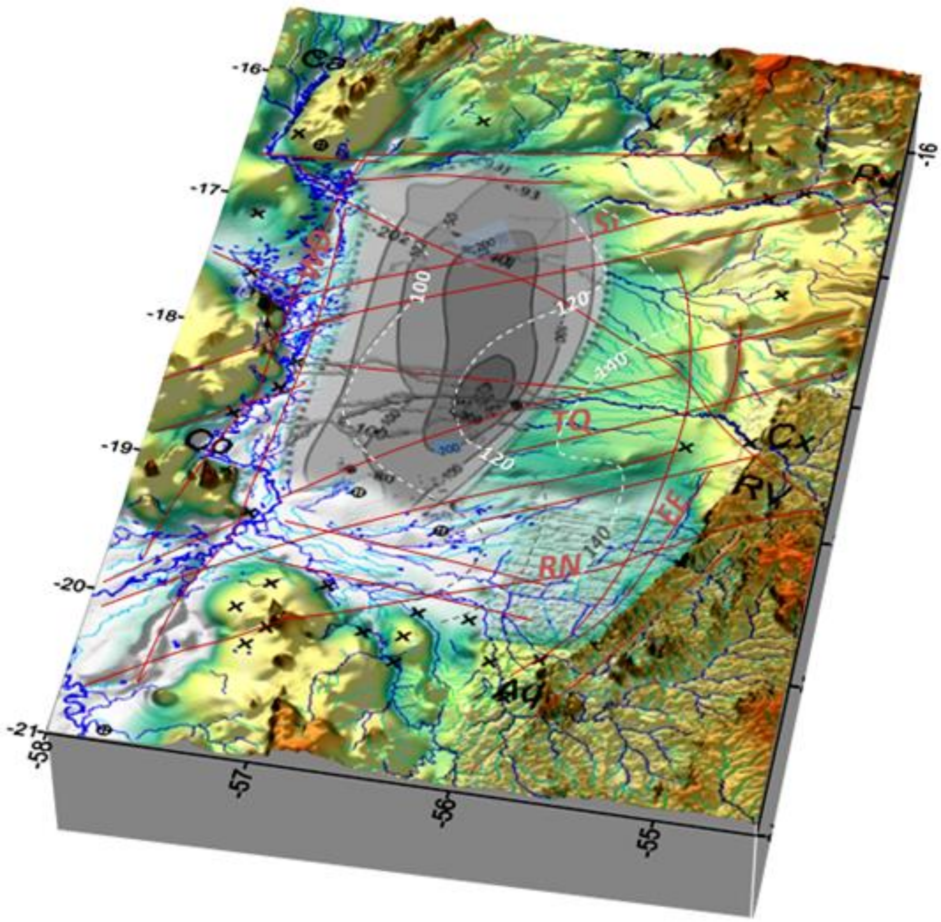


Figure 16 – 3D view of Pantanal basin (blue) with the basement contour below sea level (gray area), surrounded by plains (whitish blue), pediments (green to yellow), escarpments and mountains (brown); feeder drainage from the eastern side. (1) lineaments in red; (2) white dashed lines contouring the surface of Taquari fan; (3) black contour lines for basement (may not reach -300 m) (Modified from Soares et al. 1999). (4) S1-S2 shows the position of seismic section; (5) A-B section shows the strong negative anomaly of velocity, as estimated for the propagation of seismic waves generated by a seismic event starting in A, from station (SALV St) located in B (redrawn from Silveira et al. 2021, Fig. 12), coherent with deep basement and Taquari fault zone. (Geographic coordinates).

The SW–NE seismic section obtained by Petrobrás (Catto, 1975) across the central part of the basin is very elucidative (Fig. 17) and has been used for geometric interpretation by Ussami et al. (1999). Seismic activity, although poor in resolution, features a basin with a tabular geometry thinning toward the borders, as schematically shown in Figure 18A. The internal faults are visible as discontinuities, mainly longitudinal faults, as steps at the altitude of the basement. The sedimentary cover may be divided into two parts: the first is delimited by faults against the basement, and the latter overlaps the former and extends over the basement. This geometry indicates space accommodation caused by fracture-controlled subsidence, superposed by tilting controlled by different downwarping and uplift fault blocks (Figure 18A). The seismic horizon in the middle is interpreted as the top of Unit 3, representing a stratigraphic marker.

The nearest well to the seismic section (SM-1-MT) was described by Weyler (1962) as 40 m of fine- and medium-grained sand, quartzose and well-sorted, followed by 50 m of coarse to conglomeratic sand, the upper unit. The next section, the middle unit, is made of reddish to brownish very fine to fine-grained sandstone that is hard and brittle, with recuperated fragments of laterite. This change was the main lithological change, and the upper contact seemed to be a marker of basin filling; this change meant that the climate changed from warm and semihumid to cold and dry. Approximately 70 meters of fine to coarse sandstone follow down (the lower unit). At the base of the drilled section, from 210 to 217 m, there is a layer of gray to brownish mudstone.

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In the deepest well (SB-1-MT; Fig 16), at the base of the sedimentary column, a conglomerate with a sandy and muddy matrix was drilled (lower Unit, 1). This unit is followed by sand, fine to coarse, pale gray, greenish and yellowish with quartz pebbles up to 120 m thick (lower Unit 2); this unit is overlain by sandstone, red–brownish, laterite cemented, and compact reddish mudstone, reaching more than 30 m (middle Unit, 3); this unit may be equivalent to the weak seismic reflector near the middle of the section (Fig. 17). This laterite-cemented material is followed by yellowish sands and greenish muds that are medium to coarse (upper Unit, 4) and (Unit 5) light brown sands, which crop out in some places. Overall, fine to medium clean white sands (Unit 6) spread, grading to very fine sands and gray mud to the western and southwestern parts of the basin.

The tilting of the Pantanal basin, as interpreted from eastern erosion and western drowning, suggested that the bulge was migrating eastward. The original axis was located around the western ranges, where the elevation of the Paleocene summit surpassed one thousand meters, and the summit was long exposed (Vasconcellos et al. 2018) but strongly dissected in recent times, where it formed a drowning lanscape.

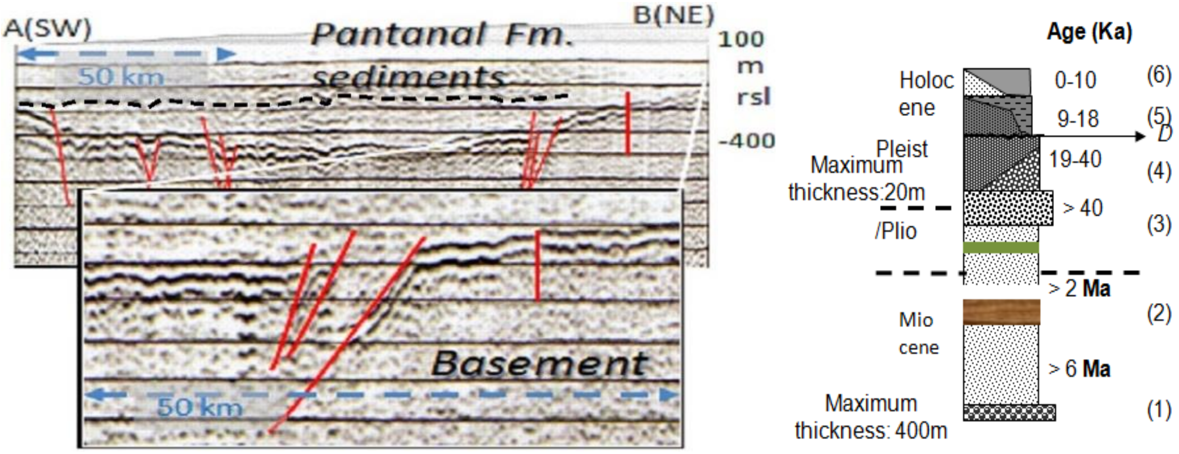


**Figure 17** - (A, left) Composed seismic section within Pantanal basin (see Fig. 16 for location), with 170 km of extension, SW – NE direction (modif. From Catto 1975, Milani 2003; Assine 2003); the basement is well defined by a strong seismic reflection surface; a weak reflector ion horizon is detected near the mid of the section. Interpreted fault zones are shown, with a noteworthy normal fault, which is shown in detail (Note the high vertical exaggeration, approximately 100X and altitude in meters relative to sea level, mrsl). (B, right) – Simplified composed columnar section of Pantanal sediments: (1) Conglomerate, red–brownish, quartz pebble, mud matrix, laterite cement; (2) Sandstone & mudstone, compact, red–brownish, laterite; (3) Sandstone & mudstone, greenish cement; (4) Sand, light brown, medium to coarse; ; (5) Sands, white, fine to very fine, mud, greenish; (6) Fine sands and muds, gray.

Correlation with wells and seismic sections allows the construction of a schematic distribution of the units (Fig. 18): some breccia (limestone and quartz clasts?) found at the base of the deepest well (340 or 400 m), may be interpreted as karstic relief filling developed in Ediacaran limestone and weathered Paleozoic sandstone and collapsed alluvial sands. The scarcity of muddy sediments in Unit 2 means that the overlying sediment was dominated by a fluvial braided or distributary fan depositional system. The red compact siltstone, mudstone and sandstone with lateritic cement and concretions (unit 3) may be correlated with Pliocene pediplanation surfaces and correlative deposits covered by latosoil in the source area. The age is inferred to be Miocene in view of the long time span of warm and semihumid climates needed for thick and broad lateritization. The main reference secion is the stratigraphy of Chaco Basin (Kuhn, adjacent to Pantanal

The sediments of Unit 4 are exposed in some erosive depressions, such as in the deflation surface (D) and “vazantes”. The lower Nhecolândia surface extensively exposes the 5/4 units boundary (D) as an uplifted block south of the Taquari fault zone. Unit 6 refers to present-day deposition in entrenched meandering plains and avulsion and splay zones in recent lobes, mainly on the west side. Ages are inferred based on data from Assine (2003) and Guerreiro (2016) and assumed by correlation.

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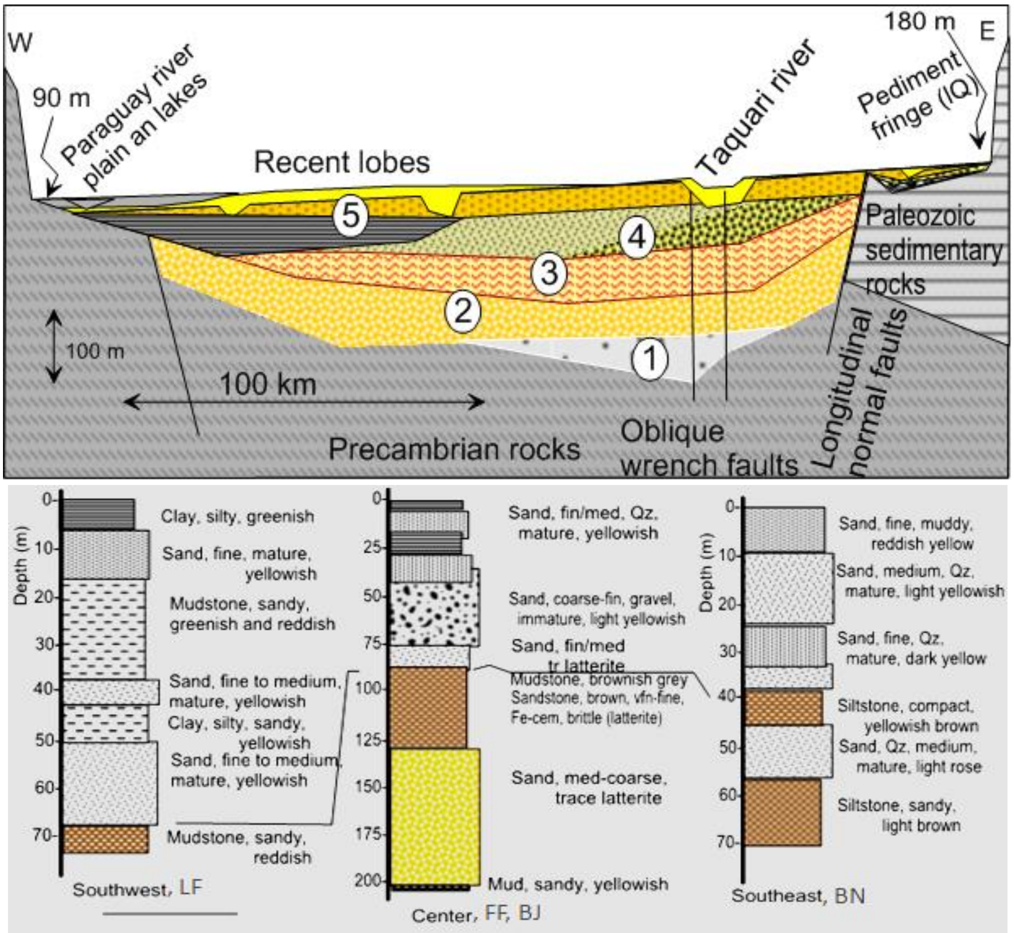


Figure 18 – (Atop) Diagrammatic representation of sedimentary fill of Pantanal basin, based on scarce data from drilled wells (oil and water) and on an east–west seismic section (Catto, 1975) crossing the basin depocenter (Well SB-1, Lat ~ 18,3 S). (1) Conglomerate, red–brownish, quartz, mud matrix; (2) Sand and sandstone, red–brownish, laterite cement; (3) Coarse and (4) fine to medium sand, light brown; (5) aeolian and alluvial sands, white, fine to very fine; (6), fine sands, gray mud of Holocene. Main longitudinal faults near the basin center.
(B, bottom) Lithologic log of three wells in the mid and southern part of Taquari fan: Left log (southwest, Water Well log (DNOS, 1977) Leque Farm, Corumbá, MS; (geol. V.G.Gonçales), represents unit 5 and mainly unit 4, stopping at top of red mudstone from unit 3. Center log (Composed lithologic column based on wells FF1-st (Petrobras) and Boom Jesus farm, B J-water (TJaner; 56o 12' W x 18o 22'S), representing units 2, 3 (lateritic), 4 (yellowish immature sands and mud and unit 5 (clay, silt, mature sands); right log.(water well log,1985, at Baia Negra Farm – BN well, Aquidauana, MS, from geol. G. Lastoria) - from 40 m downward represents lateritic lithology of unit 3and above unities.

Two logs of water wells located in the southern part of the Taquari mega fan in the more distal zone and in the central well (FF) record sediments from units 2, 3, 4 and 5 (Fig. 18-B). Muds make up one-third to half of the sedimentary pile; sands are fine and medium, texturally and mineralogically mature; unit 2 (west, left) has lighter and greenish colors; and unit 3 (bellow 40 m deep in Baia Negra, 90 m in the FF well and 70 m in the southwest) is compact, lateritic and brownish. The top of Unit 3 represents a marker correlatable with the seismic reflector near the middle of the section in Figure 18.

## 2.8. Ages and timing

The age of the Pantanal Basin was considered by Almeida (1945) to be Pleistocene, following the Paleogene uplift of the region between the Paraná Basin and Chaco-Beni Basin after the Bauru Formation (Late Cretaceous). The Pleistocene age was assumed by Ab Saber (2006). The exposed sediments of the Pantanal basin are considered to be of late Quaternary age (Assine, 2003; Assine & Soares, 2004; Assine, 2012), as previously mentioned, because the sedimentary covers preserve fossil depositional features at the surface. Near surface, light brown sands (unit 4) have ages estimated by thermoluminescence

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data within 30 to more than 45 Ky (Assine, 2003), which is similar to the previous to late glacial maximum. The latest sediment cover, made up of white sands, which precedes present-time flooding plains, extends over Quaternary fringe pediments and has age indicators of approximately 9-18 Ky (Assine, 2003; Soares et al. 2000), contemporaneous with semiarid aeolian sedimentation during maximum glacial times (Soares et al., 2003). Under the deflation, pang-gray greenish fine sands and silts aged older than 20 Ky (Guerreiro, 2016) and more than 70 Ky (Facincani, in press) were contemporaneous with the last glaciation. Among these older sediments, carbonate cemented sediments around saline pans in Nhecolandia bearing gastropod shells were dated to ages of 1.8 and 3.8 Ky (Assine et al. 1997; Assine, 2003), indicating a recent process of deposition in these lakes. Lake deposits near Corumbá (Bezerra et al. 2019) reveal a strong depositional break in the transition from the Plestocene to the Holocene, from sandy to more dry climae to muddy deposits; another break appears in the mid-Holocene, intercalating more dry intervals and back to semihumid.

The older age indicators are very poor: basin subsidence and fractures occurred after the South American planation developed in the Eocene (Carmo, 2005) but lasted until the end of the Miocene (Soares & Landim, 1976; Spier et al. 2006; Soares et al. 2011; Riffel et al. 2013). Along with Escarpments and inselbergs, in the source area pediment fringe, such as Serra Solteira, the northern and eastern plateaus and Amolar-Urucum ranges preserve paleosurface remnants of three main events (Fig. 19): summit lateritic plateaus (South American paleosurface remnants) and terrace pediments of two generations: one covered by siliceous surfaces (Oligocene) and the second covered by brown to reddish latosoil (Miocene age, Soares et al. 2011; Riffel et al. 2012). Vasconcellos et al. (2018) found ages as older as 70 Ma for lateritic paleosurface residual minerals in Urucum range inselbergs (western shoulder), which is a long-lived source area.

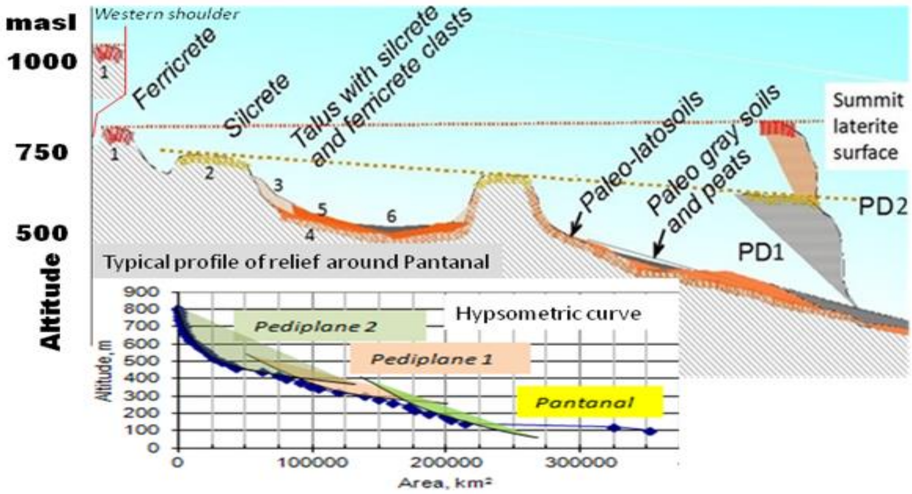


Figure 19 - Schematic typical relief profile of highlands around Pantanal basin, with the main geomorphic and surface formations, showing the three main paleosurfaces (Rabelo & Soares, 2000; SAP=Summit and pediplanes PD2 and PD1) and later valley fill sediments. Insert: hypsometric curve for Miranda, Aquidauana and upper Paraguay hydrographic basins modeled as denudation cycles (PL=Pantanal alluvial plain). Numbers: 1 – summit South America Planation (in Urucum, Maracaju, São Lourenço and other ranges); 2 – Pediment PD2, with silcrete (over Bodoquena range); 3 – talus at the head of Pediment PD1; 4 and 5 – reddish brown paleosoil, alluvial, colluvial and playa sediments; 6 – valley and pond fill with gray sediments and white sands (coal fragments 9.8Ky old). Insert: composed hypsometric curves for two cycles of erosion (PD1, PD2), Quaternary sedimentary surface (Pantanal, ) and the original peneplane (SAP- South America Planation surface)

Water well logs and the Porto Murtinho well record thick compact red mudstones bellow 40 to 70 m of sand, which are strongly correlated with the red sediments of the Chaco Formation, which includes locally Miocene marine sediments, as in the P. Lopes well (Kuhn, 1991).. These rocks seem to be correlated with red–brownish sandstones, laterite cements (unit 3) and reddish-brown PD1 paleosurfaces from the late Miocene compared with the relief evolution

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of the eastern flank of the Paraná Basin, Meridional Plateau (Soares et al., 2011; Riffel et al. 2012). This correlates with the Cuiabá pediplane (Ab Saber, 2006), the last warm phase in the region, which is warm enough to produce iron oxide-hydroxide concentrations controlled by semi humid and warm climates (Tardy and Nahon 1985; Curtis 1990) and is thicker than 3 meters. The explanation is that the bulge collapsed after that planation, forming the Pantanal basin, which coincided with the sandy Pliocene overfilling of the Chaco basin and the Quechua phase of the Andean orogeny (Ramos & Aleman, 2006).

Reddish lime sediments (as indicated by deposits referred to as the Xaraies Formation of Almeida, 1945) deposited in Bajada Lakes with Quaternary fossils north of the Bodoquena range seem to be correlated with the brownish sands in the interior of the Pantanal. By correlation, the corresponding late Quaternary occurred before the last glacial time. These sands were eroded during the dry and cold late Plestocene and early Holocene by winds, forming closed pan like depressions within a smooth relief covered with sand lunettes. Light gray, fine sand deposits are found filling small valleys and depressions.

2.9. Ongoing erosion and uplift rates

The ongoing vertical tectonic movements in the Pantanal may be accessed through the balance between the sediment supply from the source area and the space available for accommodation. The sediments supplied to the Pantanal basin, with 140000 km2, originate from an exposed area of 151x109 m2 and a total hydrographic area of 342x109 m2. Approximately 20x109 m2 are depositional sites outside the Pantanal sedimentary basin.

For the sum of erosive hydrographic basins, a suspended sediment discharge (SSD) of 17,4x106 tons/year was found, while when the depositional area of the Pantanal was included (363x109 m2), the SSD reached 7,4 x106 tons/year (Carvalho et al. 2005; ANA/ANEEL/DNAEE 2002). The number refers to the average for the period 1977-1999, although not continuously. These values indicate that 58% of the SSD is being retained in the basin, or approximately 10x106 tons/year. The total sedimentary load must be estimated by adding the bed and the dissolved load. The fraction for bed load was 17% (Carvalho, op cit.). Therefore, the total solid load retained must reach 11.8 x106 tons/year, or 17.7 x 106 m3/year. The dissolved load was not evaluated because it bypasses the basin, as there is no significant chemical deposition. Considering that approximately half of the basin (70x109 m2) on the west side is below the base level and composes the accommodation space, the total solid load retained represents a deposition and subsidence rate of 0.38 mm/y, which is a very high value.

Using the same ratio of denudation and sedimentation, for an average of 200 m of Pliocene sediment in the total volume of the basin, an age of 1.4 Ma is needed for filling. This age is compatible with several other previously reported age indicators.

A total sedimentary load of 30.1 m3/year in erosive areas (including the fraction of bedload, 18%) represents an erosive rate of 0.2 mm/year, which is a typical value for regions of active and intensive uplift. Using a half-time rate for erosion during basin evolution (for example, 0.1 mm/y for 900 m), we find approximately 9 My for the erosive process around the subsiding basin.

## 3. DISCUSSION AND CONCLUSIONS

- Erosion and sedimentation history

The three recognized paleosurfaces in the Bodoquena range, SAP, PD1 and PD2 (Rabelo e Soares, 2000; Fig. 18, insert), are strongly correlated with the relief evolution of other areas of central and southern Brazil (Soares e Landim, 1976; Ab Saber 2006; Soares et al. 2011). The lateritic surface of the summit in South America, which is found on several plateaus, is considered to be Eocene in age (Spier et al. 2006; Soares et al. 2011). Inside the basin, the Morrinhos buried and silicified inselbergs are similar to other inselbergs outside the basin from a pediplanation cycle that has succeeded South American planation destruction. Due to its paleoclimate correlation, absence of laterite, presence of feldspar and caolinite, and silcrete in

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paleosurface of inselbergs, this is considered cold Oligocene in age (Soares et al. 2011). The ages agree with the evolution of Chaco basin (Kuhn, 1991; Wiens, 1995).

The volume of sediments eroded between SAP and PD2, calculated by subtracting the logarithm of adjusted hypsometric curves from one another, is approximately 128.103 km³, which yields an erosion rate of 0.04 mm/a. This approach is suitable for estimating the age of the sediments, which are attributed to the Eocene-Oligocene period. The second step of erosion, with a volume of 87.103 km3 for an area of 250.103 km2 between PD2 and PD1, occurred during the Miocene period (before 12 Ma) and lasted approximately 10 Ma. This resulted in an erosion of 200 m, which equates to 0.02 mm/a. This estimation is considered to be a reliable estimate for a period of prolonged stability. The aforementioned sedimentary deposits could be accommodated within the confines of the Pantanal basin, reaching their stability during the and of Miocene period and comprising the red mudstone. The third phase of erosion, predominantly Pliocene and Early Quaternary in age, resulted in the erosion of 14,103 km³ of sediments within an area of 200,103 km³, with an average erosion of 70 m over a 10-million-year span, equivalent to a rate of 0.07 mm/a.

- Pantanal basement high and the Central Andean Arequipa block

The basement depth of the Pantanal basin is approximately 100 to 200 m below sea level, and highland adjoining source areas at altitudes of approximately 600 to 1000 m are less than 50 km from the center, indicating the strong uplift of basin shoulders and a collapsed central block. On the eastern side, old sedimentary strata and paleosurfaces, up to the Eocene or later, dip eastward (Paraná basin), while on the west, they dip westward (Chaco); on the north side, they dip northward (Parecis). This morphostructure is associated with basement uplift and extensive outcrops of older Precambrian rocks (Fig. 20) and positive relief after the late Cretaceous. The gravimetric Bouguer anomaly map shows a large residual positive anomaly associated with metamorphic basement uplift and exposition, reflecting the bulge flanked by sedimentary strata.

In the region where the central Andean block (Arequipa block) overthrusted the South American continental plate, the smoothed trend surface residuals of gravimetric Bouguer data showed two paired and curved anomalies. The western region is marked by a strong gravity low in the Bolivian Orocline due to Neogene crustal thickening and crustal or sedimentary piling in the Andean thrust belt (Isacks, 1988). After a frontal transition, which is occupied by a foreland anomaly toward the continent interior, a linear and curved positive Bouguer anomaly follows, representing the forebulge. The crest is approximately 300 km from the overthrust front. The bulge is curved following the Bolivian Orocline (Fig. 20A).

The basement bulge, although far east of what was expected according to physical models (for example, Watts, 2009), is documented by the exposition of Precambrian rocks in the axial zone, laterally covered by Ordovician to Cretaceous and Cenozoic sediments with divergent dips. The Pantanal basin is near the apical zone of this curved bulge, as indicated by relief, which is more than one thousand meters high at the western shoulder, although on the eastern side of the main regional gravimetric anomaly axis. This shift may be apparent due to the proper low gravimetric values in the Pantanal basin.

- Crossing faults and lineaments: relations with chaco Andean belt and with the continental interior

Lineaments and wrench faults striking NW–SE and NE–SW (Fig. 20A and B) are known to occur at the southern and northern edges of the Central Andes (Mon, 1976; Isaaks 1988; Urreiztieta et al. 1996). The wedge formed by the two bands of convergent lineaments constitutes a higher block (H) relative to the external lows (Beni and Chaco basins), where the older Precambrian and Paleozoic rocks (Tucavaca belt) are exposed.

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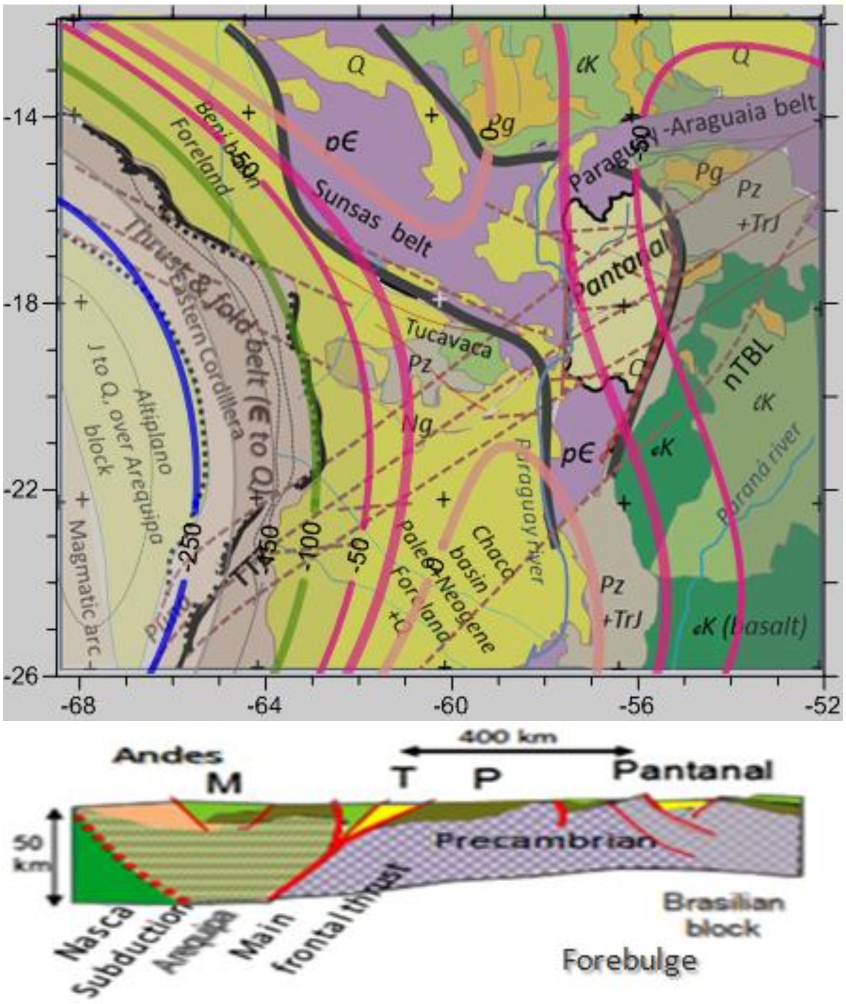


**Figure 20** – Forebulge and wedge indentation: A (above) Simplified regional geology and transverse lineaments superposed by six degree polynomial fit of Bouguer gravimetric anomaly, showing the gravity high in front of Bolivian orocline associated with exposition of old formations, reflecting the crustal uplift (Precambrian exposition belt, pe), and location of Pantanal basin (Gravity data from NGDC, USGS). B (bottom) Diagrammatic representation of the overthrust of Arequipa massif and Andean orogenic belt on the cratonic margin forming the continental bulge that broke down and hosts Pantanal basin (modified from a gravity and geological model of Ussami et al. 1999) (P – Paleozoic; M – Mesozoic (green); T – Tertiary and Quaternary (yellow).

The Andean orogeny was active in Bolivia and North Argentina since the early Paleocene. However, in the Central Andes, the modern cycle—the Incaic phase—had greater compression during the Oligocene, mainly folding obliquely to foreland Eocene sediments in the northern segment of Bolivia and Peru. This time is correlate with the Chaco Group and unities 1 and 2 of Pantanal. Subsequently, in the late Miocene and Pliocene (Quechua phase), in the southern segment of northern Argentina and southern Bolivia, folding and thrusting evolved into the Miocene (Parana Formation) and Pliocene (Chaco Group) beds, contemporaneous with unities 3. A new compressional pulse is recorded for the boundary between the Pliocene and Quaternary to Holocene (Sempere et al. 1990; Ramos and Alemán, 2000; Stern 2004). This late Miocene to Pliocene seems to be related to bulge uplift and collapse, creating accommodation space for Units 4 and 5 of the Pantanal basin.

The characteristics of an interior fracture basin, linked to uplift, seem clear in the Pantanal region: the gravimetric and uplifting bulge, the shoulders, the elongated form, and the fault-bounded buried sediments are all good indicators of this basin type. Its N–S strike agrees with the curve of the positive gravimetric anomaly that follows the Bolivian orocline associated with the Neogene collision of the Arequipa continental terrain with the continental South American plate. The sub-Andean fold and thrust belt, the frontal overthrust, bounds the collision zone. The Cenozoic foreland basins are

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the Chaco (southwest) and the Beni (northwest) basins. The distance from the overthrust to the Pantanal basin, approximately 400 km, seems large, supporting the doubt (Assine 2003) about the interpretation of a forebulge rupture-related basin (Almeida and Lima 1959; Shiraiwa 1994; Ussami et al. 1999). However, this phenomenon is not unexpected for old crust, high strain rates or flexure of the whole lithosphere (Cloething & Burov, 2011). The breaking down is interpreted as asymmetric because the main gravimetric anomaly and larger composite throw are on the west side, approximately one thousand meters.

The back bulge model (McQuarrie et al. 2005; Horton & De Celles 1987), considering a flexural basin subsequent to the bulge over the craton, seems not to be supported by the information gathered. This model would mean an interior flexural sag, but it is not sustainable because the basin geometry and the high topographic relief of the shoulders around the basin are not compatible with flexural sag but rather with uplift, fracture and collapse of the crest distension zone. This model accepts compressive (completely elastic thickness) and tractive brittle (shallow) deformation resulting from east–west shortening.

- Ongoing faults toward Andean belt and toward the continental interior

A second important tectonic element is the NE–SW fault, which may represent a branch or continuation of the Transbrasiliano Lineament, as previously described by Soares et al. (1998; Soares & Rabelo 1999; Soares e Assine, 2003; Paranhos Filho et al. 2012). Although the current use of the Transbrasiliano lineament (nTBL, in Fig. 20A) was reformed to include improperly a long Precambrian intercontinental colisional suture zone (Ramos, 2010; Cordani et al., 2013), the fracture structures crossing the Pantanal are well consolidated. The proposal for the continuity of the Transbrasiliano Lineament following the nearly NNE gravity anomaly (nTBL) at the western border of the Paraná Basin, instead of the lineaments in the Pantanal, follows the boundary between the Paraguay belt and the Paranapanema craton (Mantovani e Brito Neves 2005) or the magmatic arc at the border of the Paraná continental block (Soares 1988). This is the geophysical expression of a covered colisional belt and not a lineament made by a fracture zone.

However, as shown in the tectonic map of South America (Cordani et al. 2013), the TB lineament trace inflecting toward the SSW diverges from the SW–NE fault zone that crosses the Pantanal basin. The three main SW–NE faults that cross the Pantanal basin are part of another continental brittle structure that extends southwest toward the Andes, crossing the northern edge of the Chaco basin (Soares, 2016) and linked to the Tucuman Transfer Zone (Mon, 1976, Urreiztieta, 1996) and to lineaments at the southern edge of the Sub-Andean Trust and Fold Belt, crossing the Santa Barbara zone (Ramos, 2009), the Noroeste Basin and the Puna uplift (Salfity and Marquillas, 1981). The northeast arm of the indentation, NW–SE left strike-slip kinematic, is found on the faults of the Chiquitos graben and Titicaca Lake, among others, on the southern edge of the Beni Basin.

Additionally, the three main magnetic NE–SW lineaments defined in the eastern margin of the Pantanal basin (Fig. 21) are very well defined and have correlative geological features: mapped faults (the Rio Verde, Correntes and Sonora faults) and the absence of the Early Cretaceous Serra Geral Formation (basalts) in the wide fault zone north of the Rio Verde lineament, which indicates erosion of the structural high. These ENE–WSW magnetic anomalies recorded in regional maps (CPRM maps) and by Souza (2017) are well identified by Curto et al. (2016) and associated with the referred NE faults in the Pantanal. The faults were formed after the Cretaceous, deforming the Bauru Group and affecting the Paleogene paleosurface cover. These faults correspond to three main NE lineaments in the Pantanal Basin: São Lourenço (Poxoréu fault), Taquari (Sonora fault) and Negro (Rio Verde fault).

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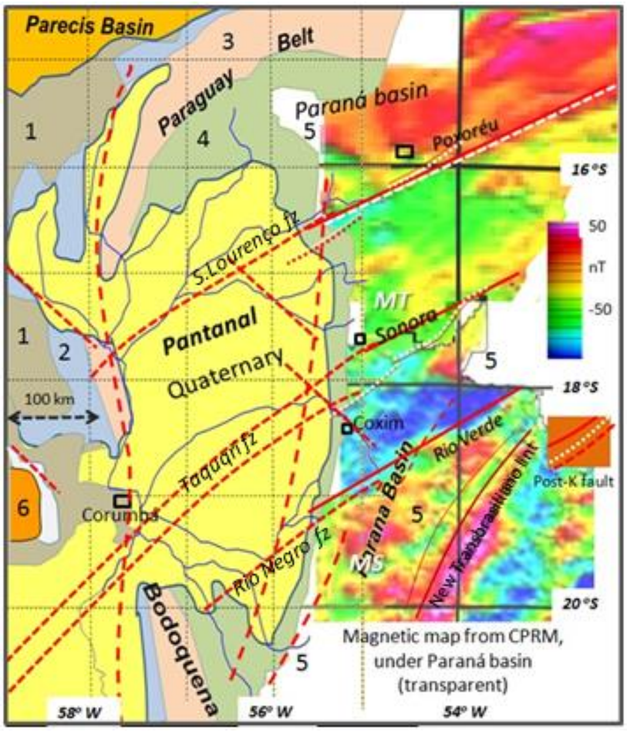


Figure 21 – Markings of Pantanal lineaments as fracture zones (Negro, south; Taquari, center and São Lourenço, north) with aeromagnetic anomalies in the eastern plateau (Paraná basin), showing the three main lineament zones and mapped faults in white/red (Rio Verde, Sonora and Poxoréu faults), some mapped structures associated (MT and MS, Mato Grosso and Mato Grosso do Sul states. "New"Transbrasiliano lineament is located from South America Tectonic Map (Cordani et al. 2011).

The stress tensor inversions obtained by Dias et al. (2016) for seismic events in the Pantanal (two) and Chaco (four) show consistent EW compression. However, for the Pantanal 2009 seismic event (Coxim), the nodal planes are estimated to be NW–SE or NNE–SSW, dipping approximately 45° with reverse oblique dislocation (Fig. 22). E–W compression seems, at first view, incompatible with the extensional origin of the basin, and the calculated nodal planes are not associated with the Transbrasiliano Lineament (Dias et al. op. cit., p. 1262). This apparent disagreement between the focal mechanism result and the extensive documentation from field observation may be reconciled if the magnitude order is assumed.

First, there is clear evidence of a first-order EW compression vector and nearly N–S flexure of the lithosphere in Central South America. Second, in the same order, the differences between the convergence vectors in the southern Andes (larger) and southern central Andes (Ramos, 2000) and the magnitude of the right slip fracture belt within the NE–SW fracture zone are shown.

The N–S fractures across the bulge and the basin formation are second-order-of-magnitude tectonic processes: the extensional N–S structures are due to the E–W crest extension of flexure, collapse and basin formation. The event is recorded in the lower part of the sedimentary pile in the seismic section. The contemporaneous process of right lateral movement in the NE–SW first-order dislocation band favored the opening of the oblique rift. As a consequence, on the north side of the transcurrent belt, flexure was greater, and the collapse of the crustal basement was more effective.

Although associated with the development of a new and young lineament zone, previously taken as the Transbrasiliano (Soares et al.1998), it is not a consequence of renewing old basement fractures by central Andean relax, as proposed by the interesting hypothesis of Rocha et al. (2022), nor explained by the flexural subsidence in back bulge model (Horton & Decelles, 1997) by a fundamental property of the basin: it was developed over a Paleogene eroded bulge, which removed Paleozoic and Mesozoic formations and exposed the Proterozoic metamorphic basement.

During the present time, deformation seems to have occurred along second-order structures of the transcurrent belt, which are represented by P (compression oblique), T (tension), S (synthetic) and A (antithetic) (Fig. 22). This may explain the shallow hypocenter and the low energy of seismic events. The transcurrent first-order movement would generate seismic events one order of greater magnitude.

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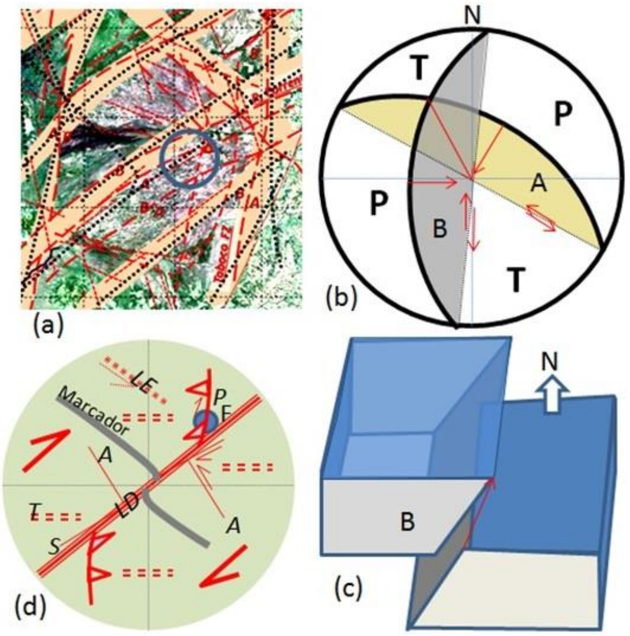


Figure 22 – The Coxim seismic event occurred in 2009 (Pantanal, MM 4.8): (a) – Above, left: location marked by blue circle, in the map reproduced from Fig. 10, near Morrinho point, and the extension of Corrientes (NE–SW) fault zone, closed to NS structures of the east margin and NW structures; (b) – above, right: focal mechanism estimated by Dias et al. (2016), with their alternative kinematic possibilities (A or B) for the nodal fault planes. (c) - bottom, right – Block diagram interpretation for the (B) nodal plane solution; (d) – bottom, left: diagram showing the conventional model of second order structures: LD – Right lateral first order fault; LE – left lateral subsidiary; S,T,A,P: synthetic, tension, antithetic and compression (reverse oblique) faults; F – interpreted position of the focal point (Note: the NS nodal plane in b was a little rotated clockwise, within the supporting data).

- Basin origin and evolution

The Pantanal basin is a fracture basin associated with the continental dynamics of South America. The N–S marginal faults are distension fractures that developed along the crest of the crustal forebulge related to the Neogene Central Andean orogeny. It cannot be considered a rift basin because it does not developed along a rifting zone, nor a flexural basin or sag because it is preceded by a uplifting and erosive bulge. NW–SE and NE–SW oblique faults are associated with lateral slip movements. The bulge begun in north and frontal region as response to Arequipa east-northeast convergence with continental plate, in the northern arm of Bolivian orocline, in front of Beni foreland basin. The second subandean inversion occurred in South Central Andes, after the Miocene Paranense Sea, during Quechua orogeny, beginning in the late Miocene extending to Pliocene (12-8 Ma), with eastward convergence (Giambiagi et al. 2016) succeeded by strike slip movement along northwest and northeast. These Northeast faults are associated with continental lineaments that crosses Argentina Northwest basin (Salfiti & Marquillas, 1981) , Chaco in Paraguay (Wiens, 1985) and Pantanal basin, extending to central Brazil. The Bolivian orocline is the result of east–west convergence between the Nazca and Arequipa massif pushed toward East against South American plates as an indentation on the edge of the Brazilian foreland.

The Arequipa Massif imposes a two-arm curved overthrust fault in the Subandean belt. The southern and northern arms of the frontal overthrust are rotated eastward in many tear fault slip. As the northern arm of the Peruvian Andes developed first during the Oligocene, the bulge subsequently uplifted the peneplanized South American surface (Fig. 23A and E). Subsequently, the bulge was deeply eroded and collapsed, being filled with unity 1 and 2 of Pantanal sediments. The southward drainage advanced over the distended and fractured swell, inverting the relief and forming the Paraguay hydrographic basin during a semiarid and cool climate, possibly ending the Oligocene.

The Pd2 Pediplane was formed (Fig. 23B and F), with a base level approximately 350-400 m above sea level. A new base level, approximately 150 m, was imposed, and erosion proceeded in a semiarid climate, forming a new pediplane (Pd1). This pediplane surface underwent semi humid and warm weathering, forming latosoils and lateritic crusts (Fig. 23 C and G), which are correlated with lateritic mudstone and sandstone in the middle of the Pantanal sedimentary pile (unity 3). This event was associated with the Miocene warming phase and Paranense Sea invasion in the Chaco Basin, which was contemporaneous with the lacustrine and alluvial redbeds in the Pantanal and with the Cuiabana pediplane surface (Ab Saber,2006) .

At the late Miocene and during the Pliocene, frontal overthrusting in the Andes became active, and the Bolivian block moved eastward, forcing the lithosphere to flex and the bulge to fracture and collapse (Fig. 23 D and H). Sandy terrigenous

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sediments nearly overfilled the tectonic basin under cold and semi humid fluvial fan regimes. Quaternary movements were dominant in the southern arm of the Bolivian Orocline, South Central Andes, compensated by the right strike slip along the SW–NE fracture zone that crosses the Pantanal. The preexisting fault zones along the Transbrasiliano SW branch are consistent with a terminal transition to the upthrust zone, the Tucuman Transfer zone (Urreiztieta et al. 1996), an anomaly of the Central Andes in the transition zone to the Southern Andes. The right lateral movement along the SW–NE fracture belt continued, elevating and collapsing the inner bulge to compensate for the eastward movement of the Bolivian block. Over the collapsed bulge, the Pantanal basin tilts to the west, causing erosion in the eastern part of the alluvial fans and drowning in the western part, including the plain and lakes surrounding the mountainous area of the shoulders.

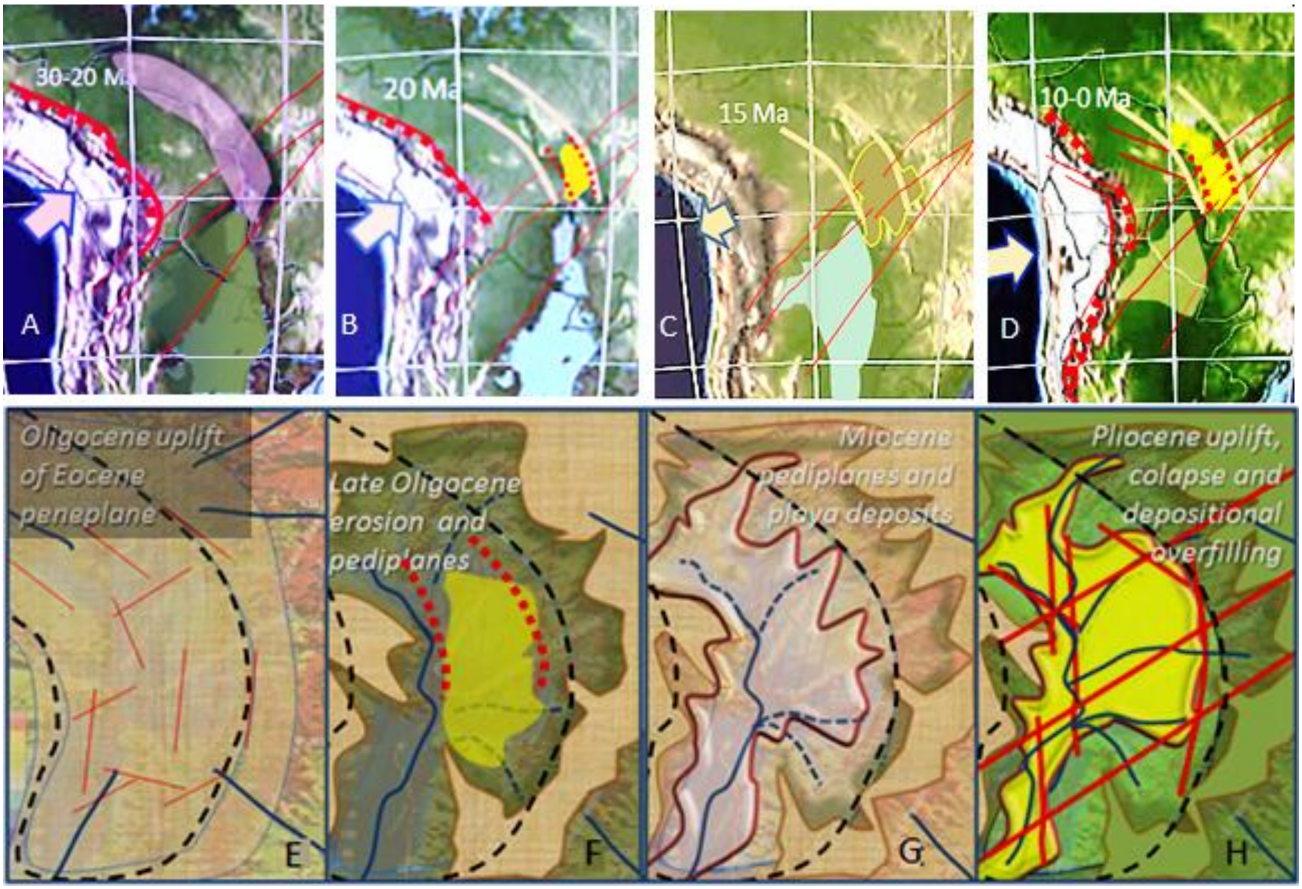


Figure 23 – How Andean movements controlled Pantanal evolution: Above: Paleotectonic of Andes from Late Oligocene to Present (modified from Scotese 2000). Below: Paleogeographic evolution of Pantanal basin for the same time span: (A, E) During Oligocene the region covered by lateritic residual sediments of South America Surface (Eocene, SAP) was uplifted due to ENE–WSW convergence and upthrust in northern Central Andes, approximately 500 m, forming a curved and fractured swell. B, F – with bulge uplift and collapse and northward advance of southward river drainage, the Paraguay subbasin excavated the fractured swell with the boutonnière form, as called by Ab Saber (2006), and where the Oligocene pediplanes (Pd2) evolved and left their fan deposits under semiarid and cold climate; the Paranense sea transgression begins over low plain of Meridional Chaco; C , G – Under Andes relax and semi humid warm climate, the basin is widen and stabilized with a new base level approximately 200 m below Pd1 and 500 m bellow SAP, submitted to lateritization (Pd1, Cuiabá pediplane); D, F – During Pliocene, under cold climate again, a strong orogenic phase, with EW convergence in Bolivian orocline and NE–SW wrench faults, produced upthrust and indentation and new bulge uplift, fracture and the collapse of central zone, with overfilling by clastic sediments in the alluvial fan environment up to the end of Pleistocene.

As these movements have been active during the present time, the stress differences associated with transcurrent faults, both south and north of the Bolivian Orocline, imposed continuous uplift of the bulge, similar to a pop-up, and space widening of the basin block tilted toward the axes of the bulge. The ENE-WSW-striking fractures are mostly oriented oblique to the main NE–SW lineament belt. This belt merges with the wrench Tucuman Transfer zone at the southern boundary of the sub-Andean overthrust belt. The lineament was active at least in the beginning of

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the Eocene but strongly after the Miocene (Urreiztieta et al. 1996). Recent right lateral movement in this fault zone is consistent with the convergence vectors and maximum horizontal stress deduced from earthquakes in the Central Andes and craton border (Ramos 2000).

The fractures are associated with forebulge arc extension in the upper crust, with longitudinal N–S secondary crest-normal faults (Fig. 24), oblique NW–SE and NE–SW wrenching fractures, and E–W extension faults. These E–W extension faults may be the result of indentation of the Arequipa Massif, which formed the Bolivian orocline, and extension derived from bulge curvature. The triangular uplift in Bolivia (H) worked as a pop-up structure pointing to the Pantanal, exposing older formations.

On the northern edge of the Bolivian orocline, the main NW–SE overthrust structures were active during the Oligocene and stabilized during the Pliocene (Sempere et al. 1990; Bump 2008), remaining active only as second-order structures. The frontal overthrust was active during the late Miocene and Pliocene. As a consequence, the movement of the indenter during the Pliocene and Quaternary was by almost simple shear stress (or the Tucuman Transfer Zone; Urreiztieta et al., 1996) along the SW–NE structures that extended to the Pantanal basin. These pushes of the Bolivia indentator (Arequipa block) against the Brazilian craton generated the inversion of the original extensional fault of the bulge.

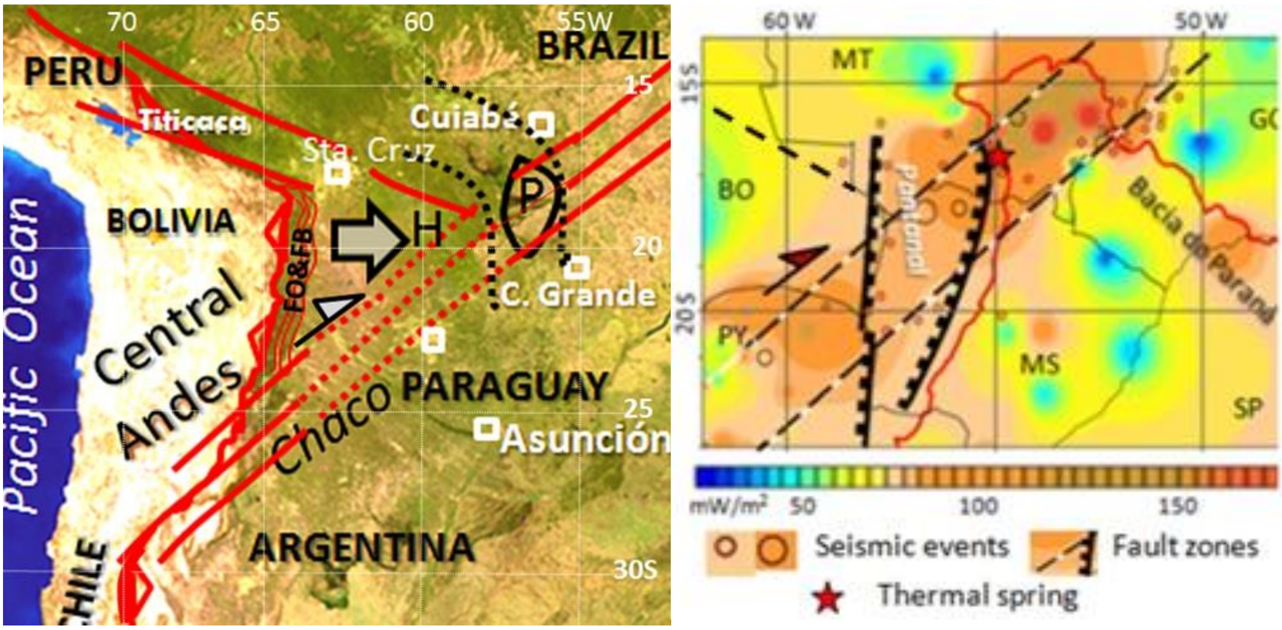


**Figure 24** – Left - Relation between Central Andes (Arequipa block and Bolivian Orocline), with its transcurrent north right lateral (Titicaca or Achacachi fault) and thrust and fold, the frontal overthrust and fold belt (FO&FB), the SW–NE right lateral faults (TTZ and TB lineament), the indenter uplift (H), the bulge and Pantanal collapse zone (P); Right - Heat flow anomalies (color) and seismic events (small circles) (map from Hamza et al., 2005), overlaid by the Pantanal NS border faults and the transversal SW–NE fracture zone, thermal spring, indicating active tectonics. The reverse movement along NS original tension fractures is expected

After broad subsidence and margin uplift during the Pliocene, the Pantanal basin block tilted to the west and underwent active fracturing with differential subsidence and uplift. The tilting has produced incised valleys, sediment reworking and terrace formation in the eastern part of the basin. In the west, tilting, in association with the Coimbra barrier in the Paraguay river bed, resulted in the drowning of plains and inselbergs (Amolar , Corumbá) and the transformed the Paraguay alluvial plain, at Cuiabá, Taquari Novo and Rio Negro distal fan plains, into anastomosed fluvial swampy and lacustrine areas.

The inferred southwest extension of the SW–NE lineament zone strongly interferes with basin organization, and recent changes imposed on the environment are notable. The most impressive deviation is the westward deviation, approximately fifty kilometers, of the Paraguay River from its early paleochannel, now the dead valley of the Nabileque Pantanal. Another noteworthy feature is the sill on the Paraguay

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River bed ("fecho dos Morros") due to the uplift of the Coimbra zone. This sill increase was responsible for the progressive increase in the phreatic level and the drowning of landscapes in the Rio Negro fan.

Some Pantanal environments are exceptional and sensitive to local activity of structures related to the active Andean tectonic. The environmental heritage, such as the paleodune fields (lunette type), composed of loose white sand, exhibits certain features that are particularly susceptible to resumption and deterioration. The more significant changes are the result of the humid reworking of the early Holocene environment, creating conditions highly favorable to special biomes: (1) the new fan lobes exhibit avulsion and flooding. (2) the western subsidence is evidenced by underfilling and drowning of the Paraguay River plain. (3) periodical seasonal and triennial floods and draughts have been amplified; (4)Decadal and multidecadal overfloods are also evident, with water levels rising. (5) The filling of valleys and the formation of disconnected paleo-channels, along with the waterflow in "corixos", "vazantes", and numerous lakes, have also been observed. (6) The interpreted warming trends in recent centuries with (7) an associated reduction in rainfall and a lowering of the water table may lead to (8) a significant increase in erosion processes and water restrictions on availability and salinization. Additionally, the current state of the Pantanal environment is severely threatened by human occupation and deforestation. The geological heritage and ongoing geological processes may have unexpected and irreversible consequences, asking for preventive regulations. The tectonic, depositional and erosive changes are occurring actively during human occupation. As example,

(1) An extensive sand plain and erosion occurred in the upper Taquari fan;

(2) There has been recurrent avulsion and deposition in the lower Taquari new lobe;

(3) Drowning areas have appeared the west side of the basin, on the Paraguay River plain, on the Negro River and on the lower Cuiabá River fan;

(4) There has been a forced change in the Paraguay River regime (Macedo et al. 2014) and direction NS to W-E, due to uplifting of southern side of Rio Negro EW fault in Corumbá

(5) Flow and navigation restrictions on the Paraguay River during the rainfall more frequent events over the Coimbra high river bed;

(6) Aeolian sands at the surface fixed by arboreal "cerrado" are susceptible to mobilizing under deforestation.

These changes constitute impositions associated with active tectonics, climate changes, anthropogenic occupations, depositional and water table responses.

## 4. ACKNOWLEDGEMENTS

This paper is the result of several research projects supported by funds from PADCT (065.95.0803), ERBIC18CT960073 (Pantanal-Chaco Project) and FAPESP (99/00326-4). The authors would like to thank the National Council for Scientific and Technologic Development (CNPq), for preliminary funds and for the scholarship granted to A. C. P. F. (Process 304122/2015-7). Some ideas have been previously discussed at conferences. Many colleagues and students did work on these projects and contributed to the data acquisition and processing and new ideas. Many theses and articles have been published, and some are in references. We express our gratitude to the reviewers for their careful, patient-related and thorough review and for providing valuable corrections and suggestions that made the article clearer and more suitable for publication

## 5. CONTRIBUTIONS

Planning and coordinating, discussing: LC, APF, PCS. Image interpretation, data processing, field and laboratory work: PCS, GL, APS, APF, LC, APF, EF. Text and figures: PCS. The text revision benefit from the use of AI (Curie and DeepL).

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boletim paranaense de Geociências
ISSN: 0067-964X

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