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Abstract: The Serra da Bodoquena is a karst area situated on the southern edge of the Pantanal wetland region in the states of Mato Grosso and Mato Grosso do Sul, central-western Brazil. Morphological analysis, on a scale of 1:60,000, made it possible to identify such various karst features as dolines, caves, sinks and springs, as well as karst cones and corridors, among others, compartmentalized into six morphological units. To the west of the Serra, the labyrinth karst that was identified reflects a situation of extreme flattening and diffuse infiltration via vertical fractures, which is gradually limited by polygonal karst, to the extent that there is drawdown of the water level. To the north of the Serra, these features are obscured by a greater degree of fluvial incision, which develops in the form of canyons and alluvial plains. To the east, there is a predominance of karst plains with dolines in a thick soil covering, associated with residual hills. There are tufa deposits along the current fluvial drainage system, and extensive older deposits occur in Quaternary terraces. Sandstone plains with innumerable dolines occur to the southeast of the Serra, reflecting the presence of subjacent karst. Geomorphological mapping of this area will be able to contribute to the Serra da Bodoquena National Park management plan, or assist in the development of anthropic soil use/occupation plans.

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1. Introduction

The Serra da Bodoquena is one of the most extensive continuous karst areas in Brazil, located in the Mato Grosso do Sul State, in the central western part of Brazil (Figure 1A). It consists of a north-south plateau that extends for approximately 200 km, which forms an important water divide with an altitude of approximately 800 m (Figure 1B). It is unique in the context of the Brazilian Platform, because neotectonic activities have been recognized in the area that are related to the development of the Cenozoic Pantanal Basin (Figure 1B), which is still subsiding.

Few studies have been made of the geology and geomorphology of the Serra da Bodoquena karst (Almeida, 1965). The study reported herein involved the first geomorphological mapping to identify distinct morphological karst zones.

The Serra da Bodoquena karst is part of the system of plateaus and mountains (Ross, 2000) that surrounds the lower plains of the Pantanal Matogrossense Plain (Almeida, 1965) (Figure 1B), a regional base level with an altitude of 60 to 180 m a.s.l. The Serra da Bodoquena consists of a north-south plateau, which embraces both carbonatic and terrigenous rocks of the Corumbá Group (Neoproterozoic III) with open folds along a north-south axis and lowered plains that surrounds the plateau. The western part of this lowland consists of the granite/gneiss basement (Paleoproterozoic Eon); the eastern part, also known as the Miranda River Depression, is formed by terrigenous and carbonatic (mainly dolomitic) metamorphic rocks of the Corumbá and Cuiabá groups (Neoproterozoic III), with intense folding, and thrust faults to the West, as well as sedimentary rocks of the Paraná Basin (Paleozoic and Mesozoic).

The area has a humid tropical climate (Zavattini, 1992) with average temperatures between 22 and 24°C (Nimer, 1979) and an average annual rainfall of 1,419 mm, with 1-3 dry months.

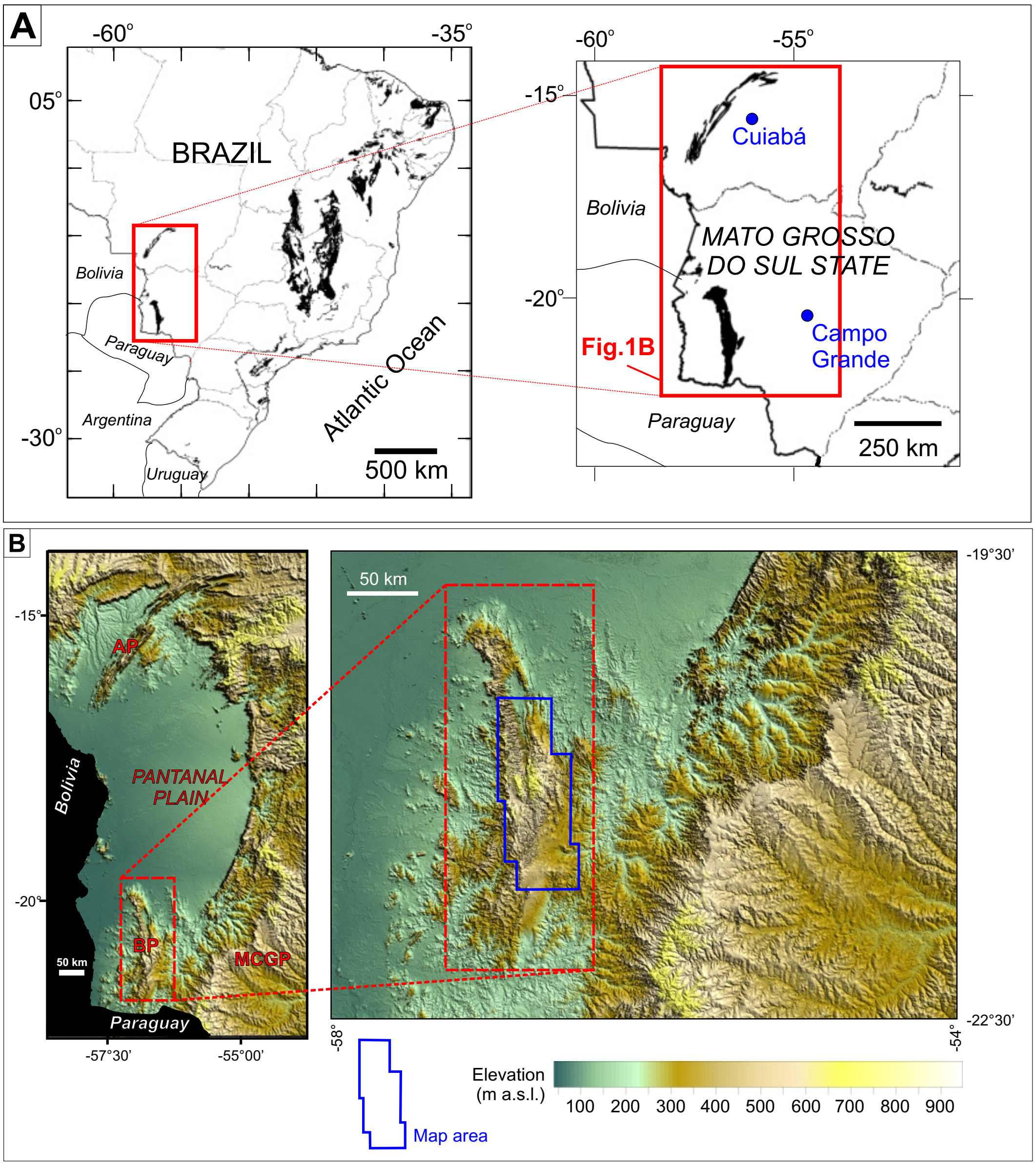
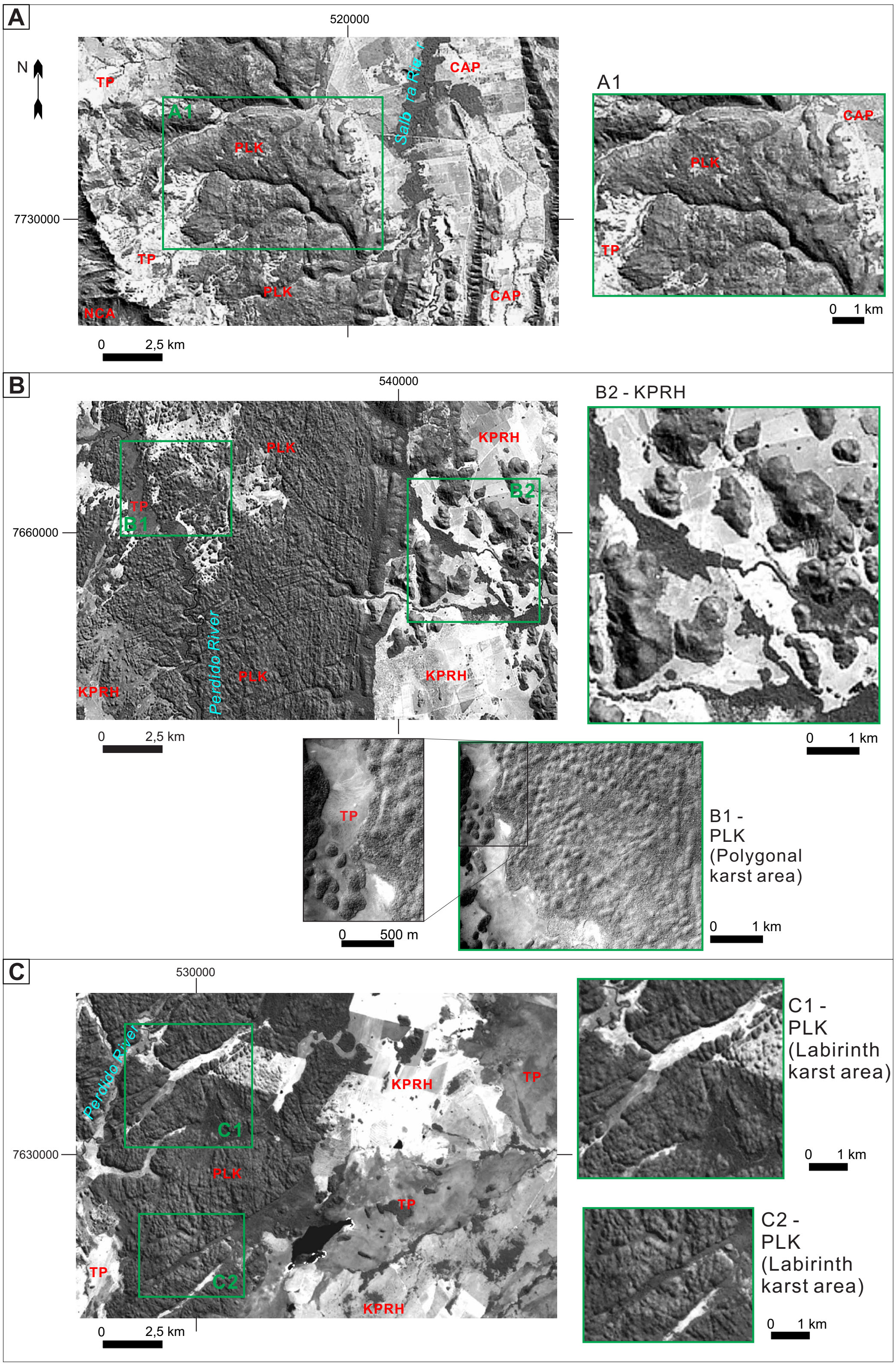


Figure 1 . Location map with the main carbonate rocks in Brazil (A) (modified from Bizzi et al. (2001)) and a digital elevation model (DEM) based on the Shuttle Radar Topography Mission (SRTM, 2006) (B). AP- Araras Plateau, BP- Bodoquena Plateau, MCGP (Maracaju-Campo Grande Plateau).

Figure 2 (next page) Landsat images of northern (A), central (B) and southern (C) portions of Serra da Bodoquena: (A) Noncarbonate area (NCA) in the Paraguai River Depression to the west contrasting with the Bodoquena Plateau where the transition zone plains (TZP) border the polygonal and labyrinth karst (PLK) in the area between tributaries cut in the east by the alluvial plains of the Salobra River (CAP zone) (A1); (B) Cone karst in the Perdido River area (PLK) with Tufa Plains (TP) (B1 - 1:60,000 aerial photograph), associated with karst plains with residual limestone hills in the KPRH zone (Limestone area) to the west on the Bodoquena Plateau and contrasting with the karst plains with residual hills on Dolomite area to the east (KPRH) (B2); (C) Labyrinth karst in the southern part of the Bodoquena Plateau (PLK - Perdido River area) with wide corridors.


A
520000
N
TP
CAP
A1
PLK
7730000
TP
PLK
CAP
NCA
0 2,5 km
A1
CAP
PLK
TP
0 1 km
B
540000
PLK
KPRH
B2
TP
B1
7660000
Perdido River
PLK
KPRH
KPRH
0 2,5 km
B2 - KPRH
0 1 km
TP
0 500 m
B1 -
PLK
(Polygonal
karst area)
0 1 km
C
530000
Perdido River
KPRH
TP
C1
7630000
PLK
TP
TP
C2
KPRH
0 2,5 km
C1 -
PLK
(Labirinth
karst area)
0 1 km
C2 -
PLK
(Labirinth
karst area)
0 1 km

2. Material and methods

The geomorphological zones were determined on the basis of the presence of specific karst features, drainage networks and lineaments, drawn on 1:60,000 aerial photographs and Landsat 7 ETM+ images (path 226, rows 74 and 75). A number of geomorphological indices were calculated for each morphological zone. The details of the zones were outlined using a Digital Elevation Model (DEM) based on topographical maps with a scale of 1:50,000 and the Shuttle Radar Topography Mission (SRTM, 2006). Details of the areas were identified by field work, which revealed the locations of caves, polygonal depressions, karst cones, residual hills, dolines, swallets and resurgences. The roughness index (surface area/planar area), was calculated according to Hobson (1972) on the basis of elevation contours using a scale of 1:50,000. The density of cones (Dc) and hills (Dh) was calculated using the number of cones and hills divided by the involved area (in km^2). For residual hills, the proportion of hills to plains (Rhp) was also calculated, obtained by dividing the area of hills by the total area of the involved unit. The karst landform zonation was based on terminology from EPA (2002).

3. Karst landform zonation on the map

Mapping the distribution of karst landforms led to the identification of six geomorphological units distributed in the Bodoquena Plateau (Highlands - greater than 500 m a.s.l.) and the Miranda River Depression (Lowlands - less than 500 m a.s.l.), forming exposed karst systems and part of a separate system of subjacent karst.

3.1 Polygonal and labyrinth karst zone (PLK)

This zone encompasses part of the Bodoquena Plateau and is divided into two distinct areas: (i) the southern sector (Perdido River area), which has mainly karst landforms; and (ii) the northern part (Salobra River area), which has more fluvial characteristics.

3.1.1 Perdido River area

This region consists of autogenic recharge, characterized by areas of (a) labyrinth karst (Brook and Ford, 1978) and (b) polygonal karst dominated by cones or cone karst (White, 1988). Superficial rivers are rare or absent and the Perdido River is the main drainage for the area. This area is distinguished by a large number of cones, with 5,657 in an area of 571 km^2, which constitutes a density of 9.9 cones per km^2 (Table 1).

The labyrinth karst areas consist of a flat surface interrupted by karren of various sizes. The most frequent karren involve fissures and straight corridors with vertical walls, with flat, relatively narrow bottoms with widths of a few metres to tens of metres, which extend for kilometres (Figure 2C). The largest corridors are found at the southern extremities of this zone, where they extend to up to 6.5 km in length, 500 m in width, and 100 m in depth (Figure 2C). The dissolution fissures and corridors follow the vertical fractures system, providing a crisscross pattern (Figure 2C). The surface is formed by the aligned flat tops between the karren and the tops of the cones (Figure 3C). It cuts the inclined bedding planes and so represents an ancient erosion surface. Near the Perdido River plain, this labyrinth karst fades gradually into cone-dominated areas of polygonal karst, with wide flat-bottomed polygonal depressions (depth of about 50 m) that provide centripetal drainage (Figure 2B). Both the polygonal and labyrinth karst have a roughness index of 1.0098.

3.1.2 Salobra River Area

This area has mixed, predominantly autogenic, recharge that is characterized by segments of both polygonal and labyrinth karst (similar to that found in the Perdido River area), and interrupted by river valleys, formed by tributaries of the Salobra River (Figure 2A), some of which flow underground.

The dendritic drainage pattern has impeded the development of polygonal and labyrinth karst and as a result, the few karst corridors are not as well developed as some other. The drainage goes from SW to NE, conditioned by a system of fractures as well as by dissolution fissures. The polygonal karst has higher cones than the karst in the Perdido River area and the depressions are deeper, with concave bottoms that form what White (1988) would call cockpit karst. Cones are also common, although fewer in number than in the Perdido River area; 1,400 were counted in an area of 808 km^2, which constitutes a density of 1.7 per km^2 (Table 1). The surface formed by the alignment of the tops of the hills follows the direction of the dip of the bedding planes (Figure 3A). The terrain here has more deeply incised valleys than the Perdido River area and so has a greater roughness index (1.0227).

3.2 Canyons and alluvial plains (CAP)

This area is characterized largely by fluvial processes of rivers passing over carbonate rocks, with the fluvial incision at times cutting down to the noncarbonate substrate. This compartment involves mainly the valley of the Salobra River and its tributaries, which are fed by the circulation of karst that is of mixed origin to the West of the valley and of allogenic origin to the East. The springs that give rise to this river arise in narrow valleys, which widen to form alluvial plains deposited by the Salobra River when it reaches its middle and lower courses.

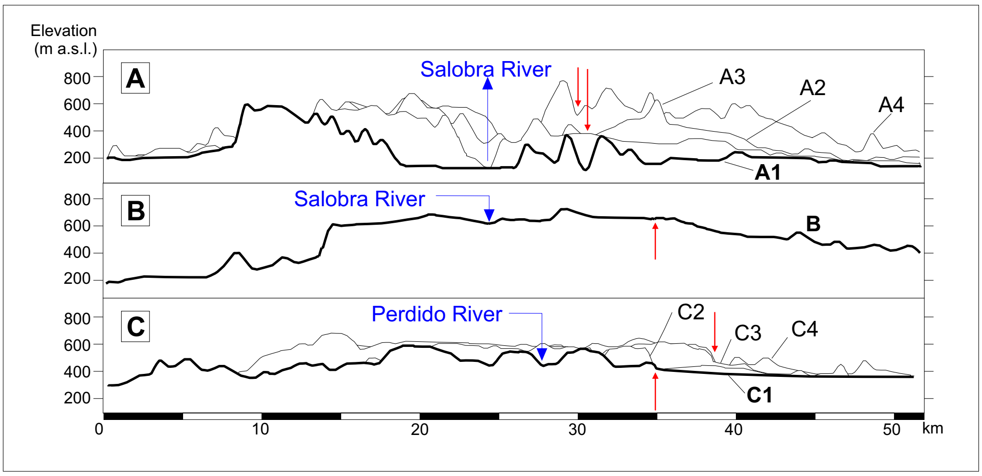


Figure 3 Topographic profiles transverse to Serra da Bodoquena (E-W): (A) Salobra River Basin in the northern area; (B) Central area; (C) Perdido River Basin in the southern area. Note the exaggerated vertical scale; red arrows indicate limits between limestones and dolomites; (D) Location of the topographic profiles.

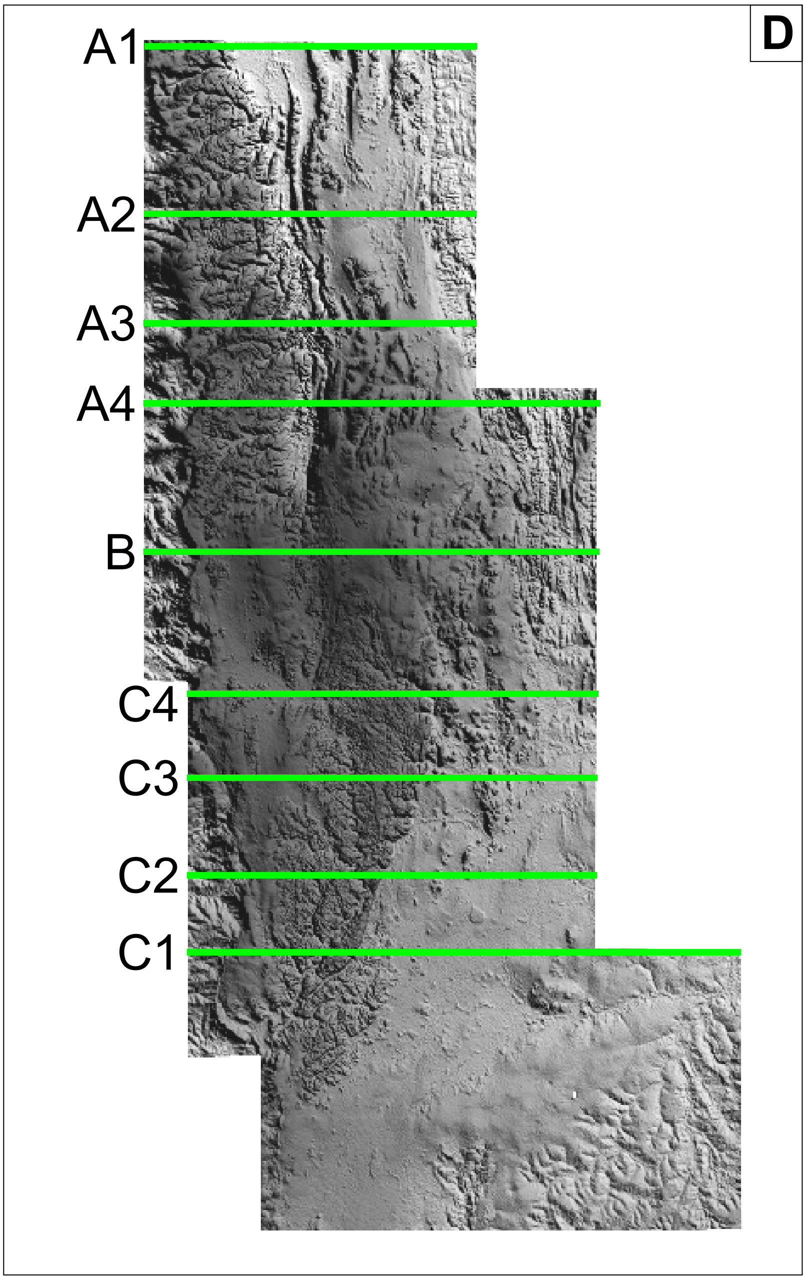


Figure 3D Location of the topographic profiles (A, B, C).

Zone		Lithology	Altitude (m)	Area (km^2)	Morphometric indices
PLK	Perdido River Area	Limestones	350-750	571	R= 1.0098 (1.0090-1.0111) Dc= 9.9
	Salobra River Area	Limestones	400-800	808	R= 1.0227 (1.0085-1.0380) Dc= 1.7
CAP	Canyons	Limestones and terrigenous rocks	120-700	83	—
	Alluvial plains	Sandy deposits	80-250	53	—
TZP		Terrigenous rocks, limestones and dolomites	400-500	622	R= 1.0013 (1.0012-1.0013)
KPRH	Dolomite Area	Dolomites, terrigenous rocks and limestones	250-800	2150 (total) ∼ 180 (hills)	R= 1.0022 (1.0001-1.0080) Dh= 0.17 Rhp= 0.08
	Limestone Area	Limestones and terrigenous rocks	560-720	311 (total) ∼ 65 (hills)	R= 1.0013 (1.0012-1.0013) Dh= 0.57 Rhp= 0.26
TP		Tufas	250-400 (PCMR) 450-550 (LKPK)	290	—
SPD		Sandstones (carboniferous Aquidauana Formation)	200-400	164 (at least)	R= 1.0003

Note: R = Average roughness; Dc = Density of cones; Dh = Density of hills; Rhp = Ratio of hills to plains.

Table 1. Physical characteristics and morphometric indices of the Serra da Bodoquena karst.

3.3 Transition Zone Plains (TZP)

This area forms an irregular strip along the western border of the Bodoquena Plateau. It represents the contact zone between carbonate and noncarbonate rocks. In the western part, the plains, with scattered carbonate hills, overlie the main carbonate substrate. Moving eastward, the thickness of the carbonate cover increases in a gradual transition to the PLK. The transition is marked by the presence of swallets, sometimes associated with contact poljes or blind valleys. This compartment includes areas of allogenic capture of water from the karst system to the East, especially from the Salobra River Basin in the northern part of the plateau.

3.4 Karst plains with residual hills zone (KPRH)

Two sectors have been distinguished in karst plains with residual hills: one in the east, which consists of dolomites, comprising part of the Miranda River Depression ($<$ 500 m of altitude), and the other in the west, developed mainly on limestones in the Bodoquena Plateau ($>$ 500 m).

3.4.1 Dolomite area

In the eastern sector of the KPRH, the plains present slightly undulating surfaces covered by thick reddish residual soil, which indicates a deeper epikarst than that in the PLK zone. Subsidence of the soil have developed frequent dolines with exposure of rounded karren. An isolated low-density superficial drainage network is associated with the karst springs on the western edge (Figure 2B) and in the interior of the zone. The recharge comes both from autogenic capture from its surface and partially allogenic groundwater flow from the PLK zone.

The 368 residual hills (30 to 220 m of altitude) commonly have steep slopes (7-33°) (Figure 3), and occur isolated, grouped, or as ridges. The hill density of 0.17 hills per km^2 is low in relation to the PLK zone. This represents only 8% of the total area (Rhp = 0.08), which reflects the low roughness index of 1.0022 (Table 1).

3.4.2 Limestone Area

In this part of the region, in contrast to what is found in the dolomitic area, the slightly undulating plains are covered with a relatively thin layer of soil (1-2 m) that overlies a shallow epikarst; no dolines have formed, and an incipient surface drainage network is under development. Although it receives a certain allogenic contribution from the TZP, the hydric recharge is predominately of autogenic nature. The residual hills are approximately 100 m high. They correspond to karst cones associated with polygonal depressions and dissolution fissures; hence, they represent fragments of the PLK zone. The hills, 180 of them, represent 21% of the total area, with a ratio of hills to plains (Rhp) of 0.26. The roughness index is similar to that obtained for the area of dolomites (1.0013), and constitutes a density of 0.57 hills per km^2 (Table 1).

3.5 Tufa Plains (TP)

This region corresponds to those areas of the Serra da Bodoquena with present-day or ancient deposits of tufa, along most of the rivers of the region. At present, the deposition of tufa occurs in the river beds and along their margins, forming dams (these are not represented on the map because of the scale involved.) Ancient tufas, with Quaternary age, are distributed widely throughout the Serra da Bodoquena, forming unconsolidated micrite deposits at least 290 km^2 in area (Table 1). The tufa plains can be identified adjacent to fluvial channels, presenting either smooth texture or one of irregular winding arcs. These arcs correspond to the edges of ancient tufa dams, whereas the smooth texture is associated with solid masses of tufa.

3.6 Sandstone plains with dolines (SPD)

This area is a relatively flat surface forming a gentle slope (200 to 400 m in altitude) formed by the sandstones of the carboniferous Aquidauana Formation (Maracaju-Campo Grande Plateau - Figure 1B). This surface forms a continuation of the plains with dolines of the dolomitic area of the KPRH zone, but here the carbonate plains are covered by sandstones that gradually increase in thickness to the East.

The surface developed in this area initially appears to be practically flat on a scale of 1:50,000 (roughness index of 1.0003 - Table 1). However, it has very large depressions, which were identified in the field, where the roughness index was 1.001 for the small area surveyed. The dolines vary in diameter (8 to 700 m) and depth (0.5 to 75 m). These features are typical of the collapse of sandstone after underground erosion and reveal the presence of a subjacent karst system in the carbonate rocks that underlie the Aquidauana sandstones.

4. Conclusions

Six geomorphological zones were defined for the Serra da Bodoquena karst based on interpretation of 1:60,000 aerial photographs, Landsat 7 ETM+ images, DEMs based on topographical maps with a scale of 1:50,000 and the Shuttle Radar Topography Mission (SRTM, 2006), and field work.

In the central zone the limestone plateau corresponds to a remnant of a flat erosion surface at a altitude of 760 m that is being entrenched.

To the south the labyrinth karst (PLK) is a product of epikarstic solutional entrenchment along vertical fracture zones. In contrast, the preferential solution along vertical fracture intersections is responsible for the development of sinkholes and polygonal karst with karst cones. In areas where the water table was very shallow, karst planes developed through hillslope retraction and alluviation leaving karst cones as residual hills.

As a result of a higher hydraulic gradient in the northern part of the PLK zone, due to the proximity of the Pantanal depression, the polygonal and labyrinth karst surface suffered a strong vadose entrenchment leading to a fluvial system which dissects the karst system.

The eastern sector of the Bodoquena karst, dominated by dolomites, exhibits a dominant morphology of karst plains with residual hills. This morphology is attributed to a subsidence of part of this block relative to the limestone plateau to the west.

The presented geomorphological map can be used for the Serra da Bodoquena National Park management and for the planning of soil use and human occupation of the region.

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Software

The morphological zones and the karst features were drawn over aerial photographs and digitized in Auto CAD r14. All data were imported into CorelDRAW 10, where the final layout work was done. The satellite imagery was processed in ER Mapper 6.3. The geomorphological indices were calculated using ArcView 3.2 and the roughness indices were calculated using the extension of Jenness (2002), from each 90 m grid cell of SRTM (2006).

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