



Paleoenvironmental Evolution of Continental Carbonates in West-Central Brazil

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ABSTRACT

This paper presents a sedimentological and stratigraphical study of Quaternary (Middle to Late Pleistocene/Holocene) continental carbonates outcrops inside Pantanal Basin and its surroundings, especially in Serra da Bodoquena, Pantanal do Miranda and Corumbá/Ladário plateau, in the state of Mato Grosso do Sul, as well as in Serra das Araras, in the state of Mato Grosso. The aim is to understand the depositional paleoenvironments and analyse climate and tectonic influences in their genesis and evolution. The results show that the deposition of these continental carbonates started in the Middle to Late Pleistocene and have continued, with some interruptions, until the present days. Sedimentary successions were identified in the different areas, without complete correlation. Two sedimentary successions separated by an erosional surface were described in Serra da Bodoquena and Serra das Araras. In Corumbá and Pantanal do Miranda, only one succession was described. These successions were deposited in elongated lakes parallel to fault planes; small lakes, related plains and plateaus; springs related to cliffs produced by faulting; rivers conditioned by topographic variation. The climatic interpretation, without proper temporal resolution, obtained by the stable-isotope composition and stratigraphic interpretation, indicates alternation of dry and wet periods. The Neoproterozoic faults with their neotectonics and the subsidence of the Pantanal Basin, are the major control for carbonated water flow and development of depositional areas, gradually turning plateaus into slight tilted areas, allowing the evolution of depositional systems from lakes to rivers.

Key words: central Brazil, continental carbonates, Holocene, paleoenvironments, Pantanal Basin, Pleistocene.

INTRODUCTION

Continental carbonates have particular sedimentological, geomorphological and chemical characteristics and commonly form a significant

component of the continental successions (Alonso-Zarza and Tanner 2010). The use of continental carbonates for local and global paleoclimate analysis is common in many environments, including tropical ones (Carthew et al. 2003, 2006), where it is possible to correlate their types to regional climatic history, tectonic setting and carbonated water sources. However, field

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* Contribution to the centenary of the Brazilian Academy of Sciences.

interpretation of tropical carbonate facies and their paleoenvironments can be difficult, especially where weathering, pedogenesis or shallow burial have erased the main geomorphic, stratigraphic and textural details. In particular, subaerial exposure and pedogenesis can result in extensive modification to the form, texture and composition of the original deposit (Alonso-Zarza 2003, Wright and Tucker 1991). Field interpretations can be enhanced significantly if local tectonic and climatic factors are well understood, as these control the types and nature of the deposits and their paleoenvironments.

There are many studies of the paleoenvironmental evolution of Quaternary continental carbonates in temperate and semi-arid settings, describing tufas, lacustrine, palustrine, travertines and calcrete facies in active and inactive tectonic settings (e.g. Alonso-Zarza et al. 2012, Arenas et al. 2014, Capezzuoli et al. 2014). However, there are few studies of continental carbonates in Brazil despite significant occurrences in the Pantanal Basin and its surroundings, in west-central Brazil (Boggiani et al. 1999, Boggiani and Coimbra 1995, Corrêa et al. 2011, Sallun Filho et al. 2009a), in the northern part of the state of Bahia (Auler and Smart 2001, Wang et al. 2004), in São Paulo state (Almeida et al. 2011, Basilici et al. 2009, Fernandes and Basilici 2009) and in the state of Rio Grande do Sul (Horn et al. 2013).

Although studies in temperate and semi-arid settings have produced models to interpret the evolution of continental carbonates, the development of specific models for this type of tropical setting, as presented by Carthew et al. (2003), which includes the influence of tectonic activity, is essential to correctly interpret continental carbonate sequences. Continental carbonate deposits developed in the Pantanal Basin and its surroundings, particularly in the Serra da Bodoquena, Pantanal do Miranda and Corumbá/Ladário plateau, in the state of Mato Grosso do Sul, as well as in the Serra das Araras, in the state

of Mato Grosso. The Pleistocene, Holocene and contemporary deposits provide a scenario where the paleoenvironmental characteristics of a tropical setting can be studied and compared to similar researches on temperate and semi-arid settings.

Thus, the aims of this paper are (i) to describe the depositional paleoenvironments of the continental carbonates in the Pantanal Basin vicinity and (ii) to analyse the influence of climate and tectonics in their genesis during the Quaternary.

REGIONAL SETTING

The region studied in this article is located in west-central Brazil, and includes the southwest part of the Pantanal Basin and the Paraguay Fold Belt (Fig. 1). The relief is characterized by a depression, the Pantanal Basin, surrounded by plateaus and ranges (*serras*). The basement rocks and sediments for the Quaternary continental carbonates of the area comprises low-grade metamorphic rocks, including limestone, dolomite and claystone (Corumbá and Araras Groups) from the Neoproterozoic, in the Paraguay Fold Belt (Boggiani and Alvarenga 2004, Teixeira et al. 1989) and siliciclastic sediments, mostly quartz sand and clay, in the Pantanal Basin (Assine et al. 2015, Assine and Soares 2004). The continental carbonate occurrences are related to present-day and former springs, fluvial and palustrine and lacustrine systems in the plateaus and ranges, with the formation of carbonate-rich water in these systems related to weathering and dissolution of the host rock around the Pantanal Basin, and clast within the oldest lobe of the Taquarí Megafan, the biggest sedimentary structure of the basin, formed by Taquarí river sediments and avulsion process (Assine et al. 2015, Assine and Soares 2004).

In the Serra das Araras, basement outcrops can reach 800 m above sea level, where they form cliffs resulting from NE-SW folds, faults and lineaments (Fig. 1a). Gaps of approximately

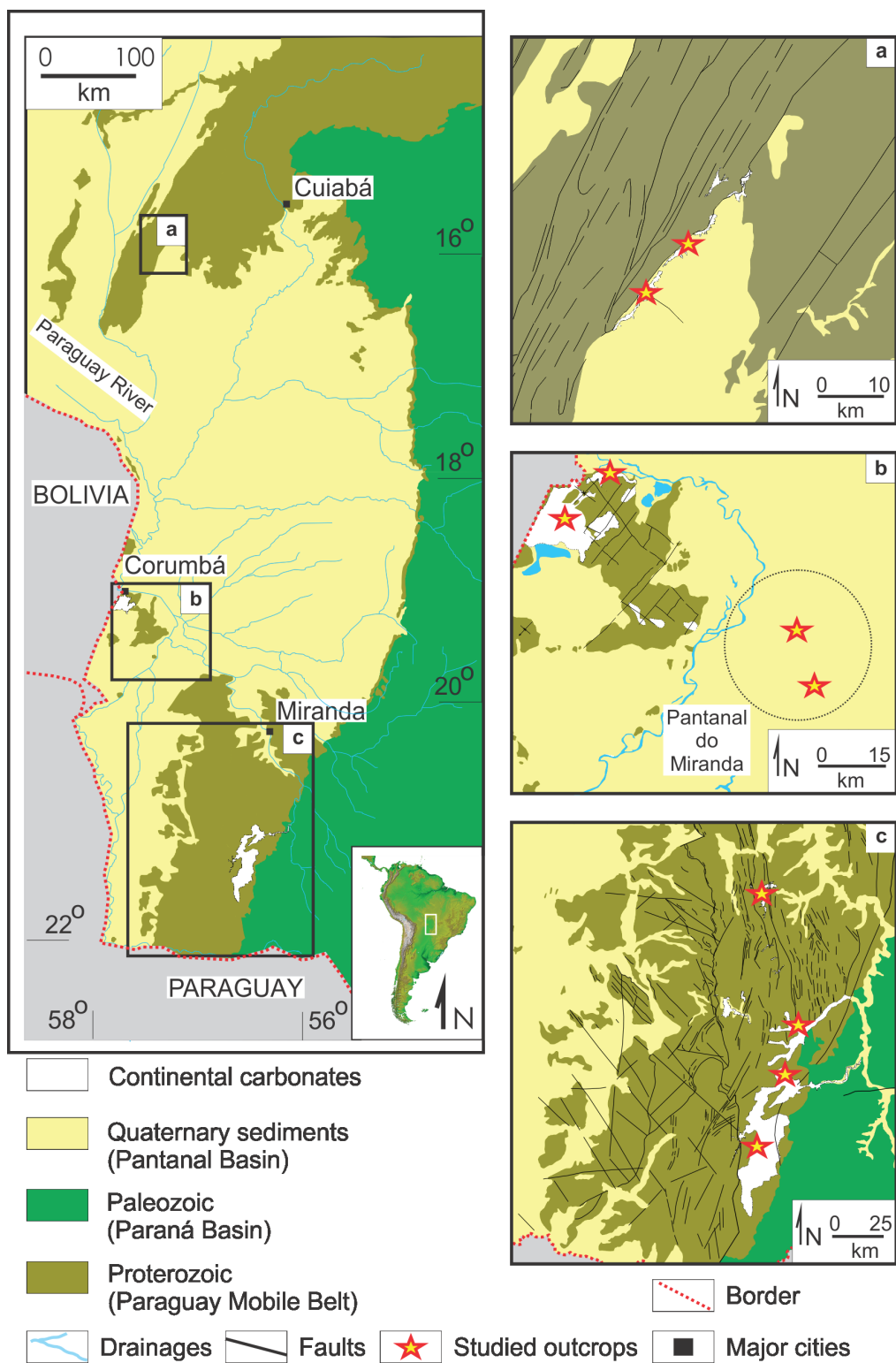


Figure 1 - Simplified geological map of Paraguay's Mobile Belt indicating location of studied areas: **a**: Serra das Araras; **b**: Corumbá/Ladário plateau and Pantanal do Miranda; **c**: Serra da Bodoquena (modified from Lacerda Filho et al. 2004a, b, Valente et al. 2004).

300 m have been recorded on a narrow plateau composed of Quaternary deposits of the Xaraiés Formation (Corrêa et al. 2011) and siliciclastic debris, which is 300 m above sea level. In this context, the occurrence of continental carbonates is associated with the scarp of the range, and four narrow elongated bodies are developed along faults which puts them in lateral contact with basement rocks (Fig. 1a). The Corumbá/Ladário plateau, with average altitude of 120 m, is characterized by a relatively flat area, associated with high mountains formed by NE-SW and NW-SE normal faults (Fig. 1b). It consists of basement rocks which are overlain by continental carbonates (Almeida 1945, Boggiani and Coimbra 1995). In the Serra da Bodoquena, a mountain range of Neoproterozoic strata reaching 600 m above sea level, controlled by NNW-SSE normal faults in the north and NW-SE, NE-SW and NS directions in its south-central portion, there are remarkable occurrences of continental carbonates. Finally, in the Pantanal do Miranda located in the Pantanal Basin, with an altitude of approximately 90 m, lenses of continental carbonates occur directly on the oldest lobe (Pleistocene) of the Taquarí river megafan (Assine and Soares 2004).

The origin of Pantanal Basin, averaging 135,000 km² with altitudes between 80 m and 200 m, is related to the Early Quaternary tectonic reactivation, which occurred during the last Andean compressive event (Ussami et al. 1999). It's filling was controlled by alluvial, fluvial and lacustrine sedimentary systems, with the Taquarí river megafan covering more than 37% of the basin area (Assine et al. 2015, Assine and Soares 2004). The ranges and plateaus are characterized by outcrops of basement limestones and dolostones associated with fluvial plains (Almeida 1945, Boggiani et al. 1999, Corrêa et al. 2011).

The climate in the region is tropical monsoonal (Alvares et al. 2013, Soto et al. 2006), strongly influenced by the South American Summer Monsoon (SASM) and by the South American

Converge Zone (SACZ) (Rao et al. 1996). Winter temperatures are around 22°C, and summer temperatures are around 27.5°C, with significant contrast in seasonal rainfall, with 900 mm during the summer months and around 100 mm during the winter (Gan et al. 2004). Temperature is influenced by continentality and relief, with high temperatures in the low lands and low temperatures in the high lands. During the winter, some Antarctic air masses raise humidity some days with intense temperature cooling (30°C in less than 12 hours) (Marengo et al. 2012, Vera et al. 2006).

Climate reconstructions for south-eastern Brazil, during the Late Pleistocene, suggest periods of higher water abundance, related to the intensification of South American summer monsoon (Cruz et al. 2005). This climatic context persisted throughout the Holocene, with an incidence of more frequent and more abrupt events, such as BOND Events in the North Atlantic and solar forcing, which have been recorded in central Brazil deposits (Bertaux et al. 2002, Strikis et al. 2011, Vuille et al. 2012, Novello et al. 2016).

Some studies in this area (Boggiani et al. 1999, 1998, Corrêa et al. 2011, Ribeiro et al. 2015, Sallun Filho et al. 2009b, Turcq et al. 1987, This study) were successful in dating the continental carbonates, providing 37 ages, ranging from more than 600,000 years before present (600 kyr BP) to 0.65 kyr BP (Table I), suggesting that the deposition of carbonates was not continuous. Serra das Araras presents the oldest stages of deposition, in the Middle Pleistocene (probably 2 stages) and ending in the Late Pleistocene (probably 1 stage): 525 to 440 kyr BP, 288 to 223 kyr BP, 111 to 75 kyr BP. Deposits on the Corumbá plateau also have a Middle Pleistocene age: 312 kyr BP. Pantanal do Miranda carbonates represent only one Holocene stage; 3.9 kyr BP. Occurrences in the Serra da Bodoquena give intermediate to modern ages, with Late Pleistocene (2 stages) and Holocene,

continuing to the present day (1 stage): 118 kyr BP, 75 to 51 kyr BP, 5.8 kyr BP to 0.65 kyr BP.

In the Serra das Araras two facies of continental carbonates were recognized (Almeida 1954, Corrêa et al. 2011): directly overlying the basement limestones there is a basal layer of conglomerates, described as pinkish micritic calcite conglomerate with quartz and limestone pebbles, and local occurrence of gastropods; a top layer of tufas directly overlying the basal conglomerate, described as tufas related with springs, cascades, pendants and perched springline types, rich in detrital components as well as in plant and gastropods remains. On the Corumbá/Ladário plateau two facies were recognized (Almeida 1945, Boggiani and Coimbra 1995): directly overlying the carbonate-rich basement; there is a basal layer of conglomerates, 0.5 to 9 m thick, described as polymictic conglomerate with a micritic matrix, and a layer of brecciated wackestone, 0.5 to 1 m thick, described as limestone rich in plant and shells remains. In the Pantanal do Miranda area only one facies of continental carbonates has been recognized (Boggiani and Coimbra 1995): directly overlying quartz sands of the Pantanal Formation (Assine and Soares 2004), some lenses, 100 to 300 m² and 1 to 1.5 m thick, of quartz sand rich wackestone, described as sub-rounded fine-grained quartz sand supported by fine calcite matrix, rich in gastropod shells. In the Serra da Bodoquena two facies were recognized (Almeida 1965, Boggiani et al. 1999, Sallun Filho et al. 2009a): overlying the carbonate basement there is a basal layer of fossiliferous wackestone, described as micritic sediment, rich in fossil gastropods; a top layer of tufas (barrage, stromatolite, cascade types), directly overlying the basal wackestone. The stratigraphy of the continental carbonates of the Pantanal Basin and its surroundings can be seen in Figure 2.

In the first studies (Almeida 1945, 1954) all continental carbonates of the Pantanal Basin and its surroundings were considered as one unique

geological unit, the Xaraiés Formation, despite the distances and stratigraphic characteristics between the occurrences (Fig. 1). More recently, Sallun Filho et al. (2009a) proposed the term Serra da Bodoquena Formation to describe the Upper Pleistocene and Holocene deposits of this area, related to lacustrine and fluvial settings. In the Serra das Araras, Corrêa et al. (2011) used Xaraiés Formation to name the Middle to Upper Pleistocene spring, fluvial and lacustrine deposits.

MATERIALS AND METHODS

The field and laboratory analysis of the stratigraphy and sedimentology of the continental carbonates combined with the available dates for the main outcrops led to the assessment of the time of deposition of the various continental carbonates. Four stratigraphic sections were measured in each studied area.

The cartographic representation of the continental carbonate occurrences was produced by associating field data, existing maps and images from the Shuttle Radar Topography Mission (S 15 to 23; W 54 to 60; version 3 - SRTM3). The SRTM data were combined into a Digital Elevation Model (DEM) and then associated with the field data, using 52° north ILWIS 3.8 free software. Maps from other authors (Boggiani and Coimbra 1995, Corrêa et al. 2011, Sallun Filho and Karmann 2007) were digitalized and combined with the DEM images to generate an initial continental carbonate map. All the maps were finished in Inkscape free software.

Several tens of samples of the different carbonate facies were collected for analysis of their sedimentological features and to support field descriptions and interpretations. A set of 58 samples was subjected to conventional optical petrographic analysis on a Zeiss AXIOPLAN 2 microscopy. In view of the fragility of some samples, these were previously submerged in a resin containing Epofor EX 401 and Epofor E 432 in a vacuum system.

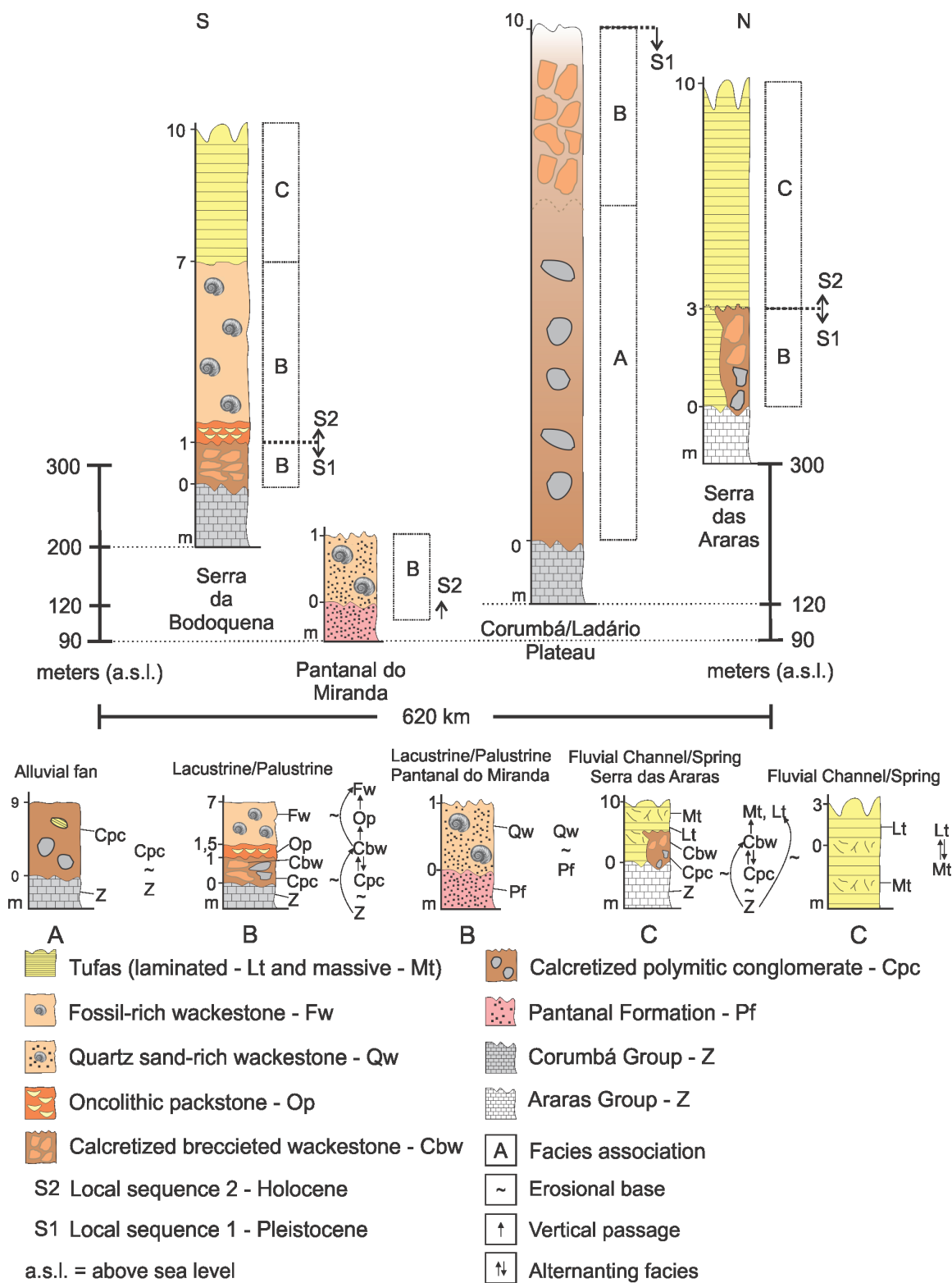


Figure 2 - Composite stratigraphic sections of the studied areas, with facies association representative of the different environments present in the studied area, without stratigraphic correlation.

Characteristics such as mineralogy, textures, siliciclastic components, structures, matrix type and paleontology were analysed to interpret their genesis. The classification scheme of Dunham (1962), modified by Embry and Klovan (1971) and Wright (1992), and applied by Della Porta (2015) to classify continental carbonates, based on texture, was applied to name the sedimentary facies.

A set of 66 samples was selected for bulk sample analyses of carbon and oxygen stable isotopes. Extraction was made with a microdrill. Isotopic determinations were carried out on a DeltaPLUS Advantage mass spectrometer at the Stable Isotope Analysis Laboratory of the Geosciences Institute of the University of São Paulo (Brazil). All the analytical processes followed the standard methods (McCrea 1950), and the analytical precision and replica analyses were better than 0.05‰ for carbon and 0.07‰ for oxygen. The results are expressed in ‰ units and reported against the Vienna Pee Dee Belemnite (VPDB) standard (Table II).

As a result of the impure nature of the carbonate samples, with high concentrations of initial ^{230}Th , only one sample, a conglomerate from the Corumbá/Ladário plateau, was dated by the U-series method, at the Geochronology Laboratory of the Geology Department of the University of Minnesota (USA), applying a Thermo Finnigan Element I magnet-sector inductively coupled plasma mass spectrometer (ICP-MS), according to standard chemical and analytical methods (Shen et al. 2002). This dated sample yields an error (2σ) <1%.

RESULTS

STRATIGRAPHY

The continental carbonates described in this study were deposited directly upon the carbonate basement, with an angular unconformity which also represents an erosional surface, in Serra das Araras, Corumbá/Ladário plateau and Serra da

Bodoquena and, in Pantanal do Miranda, with an abrupt contact over Pleistocene sediments of the Pantanal Formation (Fig. 2). The sections range from 1 m in Pantanal do Miranda, to almost 9 m on the Corumbá/Ladário plateau, and consist of lacustrine (wackestone) and fluvial (tufa) carbonates deposited over debris flow carbonate sediments (conglomerate) and/or brecciated lacustrine (wackestone and packstone) carbonates in all studied areas, except in Pantanal do Miranda, where the lacustrine (wackestone) carbonates lie over quartz sands of Pantanal Formation. Thus, it is possible to identify 2 sedimentary successions that are physically and stratigraphically disconnected. The chronology presented here (Table I) uses data from many regional papers (Boggiani et al. 1998, Boggiani et al. 1999, Corrêa et al. 2011, Ribeiro et al. 2015, Sallun Filho et al. 2009a, Turcq et al. 1987).

PLEISTOCENE DEPOSITS

The Serra das Araras occurrence is composed only of Pleistocene carbonates, with conglomerate and wackestone in the lower part of the sequence and tufas, which in some places are related to the basement and elsewhere crop out above the conglomerate or wackestone (Fig. 2). The relations between the different carbonates are always associated with erosional surfaces. The tufas are generally associated with the scarps of the Serra das Araras, forming numerous elongated bodies along the main fault. The chronological data (Table I) indicate several stages of tufa deposition: 525 to 520 kyr BP; 490 to 440 kyr BP; 312 kyr BP; 285 kyr BP; 228 to 223 kyr BP; 111 to 102 kyr BP; 75 kyr BP, and the conglomerates and wackestones are older than 600 kyr BP (Corrêa et al. 2011). On the Corumbá/Ladário plateau, the succession is composed only of Pleistocene carbonates with conglomerates occurring directly on the basement, pass up into wackestones (Fig. 2). These sediments

TABLE I

Compiled ages of Quaternary continental carbonates of Serra da Bodoquena, Corumbá plateau, Serra das Araras and Pantanal do Miranda. Symbols: Rock Type: Tf = Tufa; Wc = Wackestone; Cl = Conglomerate; Area: SB = Serra da Bodoquena; Pantanal do Miranda = PM; SA = Serra das Araras; CO = Corumbá/Ladário Plateau.

Ages (kyr BP)	Rock type	Area	Method	Author	Ages (kyr BP)	Rock type	Area	Method	Author
0.65±0.04	Tf	SB	¹⁴ C	Sallun Filho et al. 2009b	102±10	Tf	SA	U/Th	Corrêa et al. 2011
0.80±0.1	Tf	SB	OSL	Ribeiro et al. 2015	111±5	Tf	SA	U/Th	Corrêa et al. 2011
2.13±0.06	Tf	SB	¹⁴ C	Boggiani et al. 1999	118.6±10	Tf	SB	OSL	Ribeiro et al. 2015
2.15±0.5	Wc	SB	¹⁴ C	Turcq et al. 1987	223±8	Tf	SA	U/Th	Corrêa et al. 2011
2.42±0.7	Tf	SB	¹⁴ C	Boggiani et al. 1999	223±8	Tf	SA	U/Th	Corrêa et al. 2011
2.63±0.06	Wc	SB	¹⁴ C	Sallun Filho et al. 2009b	227±7	Tf	SA	U/Th	Corrêa et al. 2011
3.41±0.07	Tf	SB	¹⁴ C	Boggiani et al. 1999	228±7	Tf	SA	U/Th	Corrêa et al. 2011
3.91±0.11	Wc	PM	¹⁴ C	Boggiani et al. 1998	285±10	Tf	SA	U/Th	Corrêa et al. 2011
4.20±0.04	Wc	SB	¹⁴ C	Sallun Filho et al. 2009b	288±10	Tf	SA	U/Th	Corrêa et al. 2011
4.20±0.7	Tf	SB	OSL	Ribeiro et al. 2015	302±57	Cl	CO	U/Th	This study
5.20±0.24	Wc	SB	¹⁴ C	Turcq et al. 1987	312±19	Tf	SA	U/Th	Corrêa et al. 2011
5.50±0.4	Tf	SB	OSL	Ribeiro et al. 2015	440±60	Tf	SA	U/Th	Corrêa et al. 2011
5.65±0.05	Wc	SB	¹⁴ C	Sallun Filho et al. 2009b	470±30	Tf	SA	U/Th	Corrêa et al. 2011
51.9±4.8	Tf	SB	OSL	Ribeiro et al. 2015	490±30	Tf	SA	U/Th	Corrêa et al. 2011
55.8±13.7	Tf	SB	OSL	Ribeiro et al. 2015	520±40	Tf	SA	U/Th	Corrêa et al. 2011
75.0±14.0	Tf	SB	OSL	Ribeiro et al. 2015	525±50	Tf	SA	U/Th	Corrêa et al. 2011
75.2±0.9	Tf	SA	U/Th	Corrêa et al. 2011	> 600	Cl	SA	U/Th	Corrêa et al. 2011
75.2±1.2	Tf	SA	U/Th	Corrêa et al. 2011	> 600	Cl	SA	U/Th	Corrêa et al. 2011

TABLE II
 $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ compositions for different facies associations of Quaternary continental carbonates of Serra da Bodoquena, Corumbá plateau, Serra das Araras and Pantanal do Miranda.

Facies Assoc.	$\delta^{13}\text{C}$ (‰PDB)	$\delta^{18}\text{O}$ (‰PDB)	Facies Assoc.	$\delta^{13}\text{C}$ (‰PDB)	$\delta^{18}\text{O}$ (‰PDB)	Facies Assoc.	$\delta^{13}\text{C}$ (‰PDB)	$\delta^{18}\text{O}$ (‰PDB)
A	-7.13	-6.97	B	-6.67	-6.64	C	-2.80	-8.87
A	-6.89	-6.48	B	-7.08	-5.33	C	-2.66	-8.40
A	-6.70	-7.72	B	-7.05	-4.21	C	-4.88	-7.09
A	-7.70	-7.15	B	-5.93	-6.84	C	-4.71	-6.65
A	-7.31	-7.64	B	-7.03	-5.43	C	-5.10	-7.23
A	-7.31	-6.36	C	-3.98	-8.11	C	-4.89	-6.62
A	-7.03	-8.33	C	-3.11	-7.81	C	-4.98	-7.16
A	-7.23	-8.10	C	-1.38	-8.60	C	-5.17	-6.95
A	-7.12	-4.78	C	-2.28	-8.06	C	-5.08	-7.43
A	-7.50	-9.70	C	-5.25	-8.43	C	-4.95	-7.27
A	-5.96	-7.96	C	-3.50	-7.38	B	-7.01	-7.00
A	-6.03	-6.34	C	-3.25	-7.30	B	-7.38	-7.64
A	-6.87	-7.59	C	-4.22	-7.48	B	-7.77	-7.65
A	-4.51	-6.35	C	-5.71	-6.75	B	-7.47	-7.79
A	-5.97	-8.32	C	-6.09	-7.82	B	-6.54	-7.29
A	-4.68	-7.49	C	-5.51	-7.08	B	-6.98	-6.86
A	-6.87	-4.65	C	-6.00	-6.98	B	-7.06	-7.15
A	-7.02	-6.18	C	-9.26	-7.88	B	-7.05	-7.01
A	-6.68	-5.98	C	-3.19	-8.60	B	-7.12	-6.97
B	-6.04	-7.13	C	-3.12	-8.46	B	-6.88	-7.57
B	-6.41	-7.37	C	-2.67	-8.46	B	-5.38	-7.87
B	-5.25	-7.84	C	-2.51	-8.78	B	-3.54	-8.53
B	-6.37	-8.01	C	-2.34	-9.44	B	-3.23	-8.42
B	-7.03	-7.45	C	-2.31	-8.95	B	-7.38	-7.64

are related to the scarps and the plain area of the plateau. There is only one age (Table I) for this area: 302 kyr BP. The Serra da Bodoquena succession is composed of Pleistocene and Holocene carbonates, with tufas and brecciated wackestones in the basal part, overlying the basement (Fig. 2). These tufas crops out in several places of the ridge, always with sharp erosional contact, with the basement and with the carbonates above, related to the main faults of the Serra da Bodoquena, and the brecciated

wackestones crop out in just a few areas, with a sharp erosional contact with the basement. The chronological data (Table I) show several stages of tufa deposition: 118 kyr BP; 75 kyr BP; 55 to 51 kyr BP.

HOLOCENE DEPOSITS

The Holocene deposits occur only in the Serra da Bodoquena and Pantanal do Miranda, with a basal erosional surface (Fig. 2). The Pantanal

do Miranda carbonates are quartz sand-rich wackestones which overlie the quartz sands of the Pantanal Formation, forming numerous of carbonate lenses. The chronological data are poor (Table I), with only one age: 3,9 kyr BP. In Serra da Bodoquena, the Holocene carbonates covering the Pleistocene deposits include oncolithic packestone and fossil-rich wackestones that, with a sharp erosional contact, are overlain by tufas (Fig. 2). The chronological data (Table I) indicate several stages of carbonate deposition: 5.6 to 2.1 kyr BP; 0.8 ky BP to the present-day.

FACIES

The occurrences of continental carbonates reported here from the Serra da Bodoquena, Pantanal do Miranda, Corumbá/Ladário plateau and Serra das Araras are similar (Fig. 2), and they can be separated into seven sedimentary facies: Calcretized polymitic conglomerate – Cpc; Calcretized brecciated wackestone – Cbw; Oncolithic packestone – Op; Fossil-rich wackestone - Fw; Quartz sand-rich wackestone - Qw; Laminated tufa – Lt; Massive tufa – Mt. Despite the particularities of the studied region, most facies described here have been identified in other continental carbonate environments elsewhere (Arenas-Abad et al. 2000, 2007, Arenas et al. 2014, Carthew et al. 2003, Gandin and Capezzuoli 2008, Pla-Pueyo et al. 2009, Pla-Pueyo et al. 2015).

CALCRETIZED POLYMITIC CONGLOMERATE – CPC

The calcretized conglomerates (Cpc, Fig. 3a and 3b) were identified in Serra das Araras and in Corumbá/Ladário plateau, commonly outcropping in direct contact, an angular unconformity, with the basement, forming tabular beds that vary from 0.5 to 9 m thick, and can be observed in the Corumbá/Ladário section (Fig. 2). It mostly consists of non-oriented, millimeter in diameter, quartz and feldspar grains along with lithic limestone clasts, which can

be millimeters to centimeters in diameter (Fig. 3a), with ostracods fossils and micritic calcite between the grains, in a matrix-supported framework. (Fig. 3a). Some pedogenic features are observed, such as concentric cracks and root cavities, along with diagenetic features such as calcite spar and microspar cements and recrystallized matrix (Fig. 3b).

CALCRETIZED BRECCIATED WACKESTONE – CBW

The only facies which can be recognized in all studied areas, except in Pantanal do Miranda, are the calcretized wackestones (Cbw, Fig. 3c and 3d), which crop out in direct contact, an angular unconformity, with the basement or directly overlying the facies Cpc, with a gradational contact, forming tabular or lenticular beds that are 0.5 to 1 m thick. In the Serra das Araras section (Fig. 2) it can be observed that the facies Lt and Mt overlies some Cbw beds, and in Corumbá/Ladário plateau (Fig. 2), Cbw facies overlie some beds of Cpc. In Serra da Bodoquena (Fig. 2), Cbw crops out in direct contact, an angular unconformity, with the carbonate basement, and is commonly covered by facies Op and Fw, in gradational contact. This facies consists of quartz grains and limestone lithic fragments, ranging from sand to pebble, floating on a micritic matrix, grading upwards to a intraclastic wackestone, represented by centimetric micritic clasts (Fig. 3c). Displacive/replacive texture can be observed as calcite spar filling textures, along with pisolithic and nodular textures (Fig. 3d), similar to beta-texture patterns. It also occurs matrix recrystallization and Fe/Mn cementation (Fig. 3d).

ONCOLITHIC PACKESTONE – OP

The oncolithic packestones (Op, Fig. 3e and 3f) are restricted to Serra da Bodoquena, and form lenticular bodies, up to 0.5 m thick, which are positioned, with gradational contact, between facies Cbw and Fw, as shown in Serra da Bodoquena

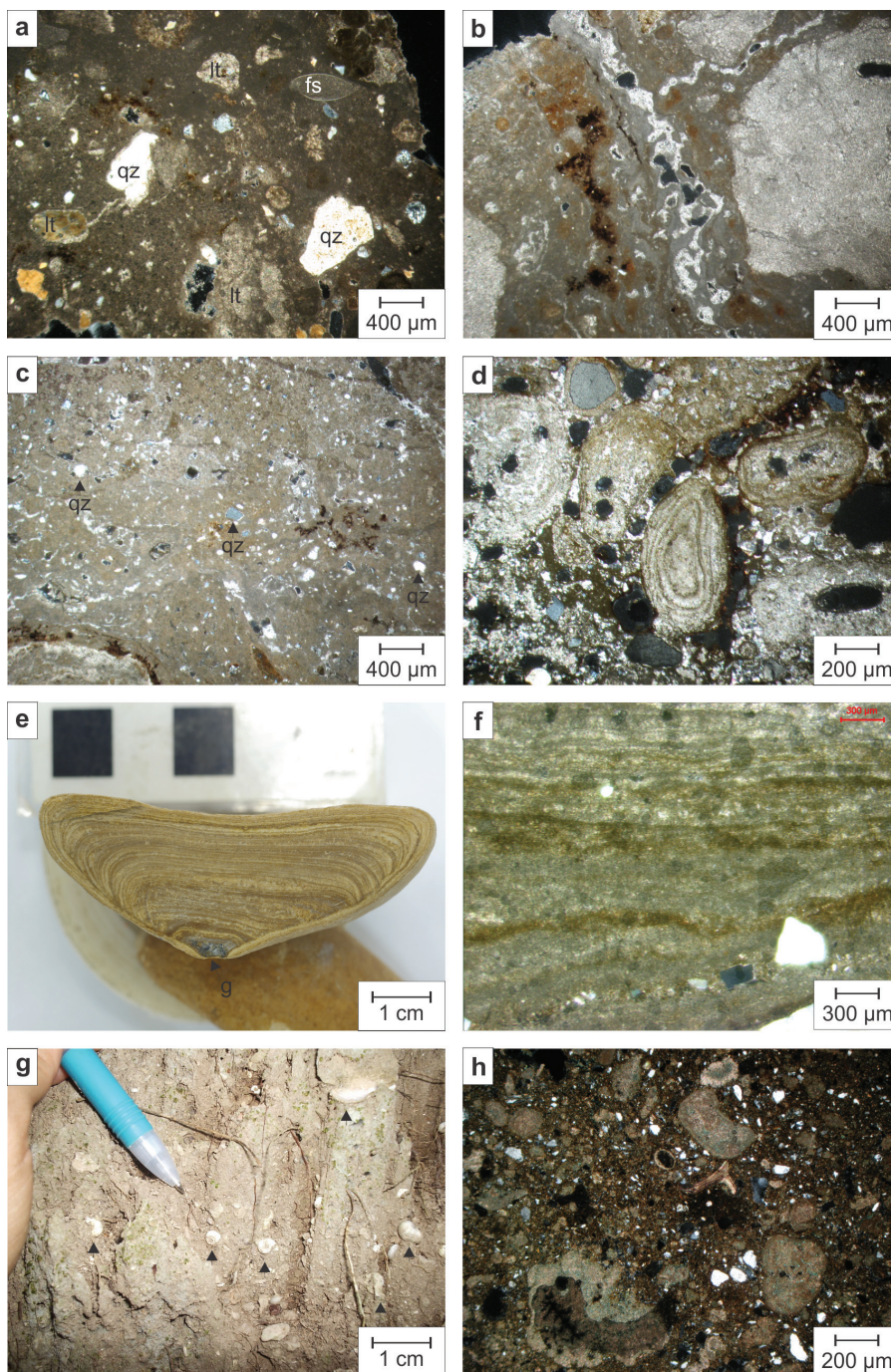


Figure 3 - Plate showing photographs and microscopic photographs (optical microscope) of lower facies. **a**: Microscopic photograph (polarized) of wackestone with fossils (calcrete), clasts are quartz (qz), lithics (lt) and fossils of ostracods (fs) (Corumbá, MS). **b**: Microscopic photograph (polarized) of wackestone with fossils (calcrete), root cavity (Corumbá/Ladário plateau). **c**: Microscopic photograph (polarized) of wackestone (calcrete), clasts are quartz (qz) and lithics (lt) (Serra das Araras). **d**: Microscopic photograph (polarized) of asymmetric coated grains with Fe cementation (Serra das Araras). **e**: Photograph of internal structures of an asymmetric oncolite with highlighted start up grain (g) (Serra da Bodoquena). **f**: Microscopic photograph (polarized) of asymmetric oncolite showing planar depositional structures (Serra da Bodoquena). **g**: Photograph of fossiliferous wackestone with gastropods fossils highlighted (arrows) (Serra da Bodoquena). **h**: Microscopic photograph (polarized) of low crystallized fossiliferous wackestone (Serra da Bodoquena).

section (Fig. 2). It consists of concave-convex calcitic oncolites, 4 cm in diameter (Fig. 3e), dense laminated, but not concentrically, with the micritic laminae covering an initial sand grain of quartz or limestone. They are always found with the same orientation, with the convex side turned down (Fig. 3f). An unconsolidated micritic matrix is present between the oncolites. All the depositional features are preserved, with no sign of pedogenic or diagenetic modifications.

FOSSIL-RICH WACKESTONE – FW

The fossil-rich wackestones (Fw, Fig. 3g and 3h) are an exclusive facies of Serra da Bodoquena in the form of tabular and lenticular beds, which are 0.5 to 3 m thick. This facies always crop out over facies Cbw and Op, and are commonly covered by facies Lt and Mt, which can be observed in Serra da Bodoquena section (Fig. 2). The fossil content of this facies is notable in macroscopic observation, with many mollusk shells widespread in the sediment (Fig. 3g). This wackestone is composed by unconsolidated micrite sediment, with low content (~10%) of quartz, feldspar and lithic limestones grains, along with fossil plant fragments and bivalve and gastropods fossil shells (Fig. 3h). A low (~1%) portion of the micrite of this wackestone is recrystallized, and just traces of Fe/Mn cement can be found.

QUARTZ SAND-RICH WACKESTONE - QW

This facies can only be recognized in Pantanal do Miranda area, and are composed by wackestones (quartz sand rich) (Qw, Fig. 4a and 4b), which form lenses, 0.5 to 1 m thick. The contact between Qw and Pantanal Formation is abrupt, as shown in Pantanal do Miranda section (Fig. 2). It consists of wackestone, with micritic matrix and high content (~30%) of quartz sand grains and macroscopic notable content fossils of gastropods and algae (Fig. 4a). Pedogenic features were observed, such

as root cavities and empty cracks (Fig. 4b). Despite some recrystallized portions of the matrix can be identified, no representative occurrence of cement was noted.

TUFAS - LAMINATED – LT AND MASSIVE – MT

The tufas facies (Lt and Mt, Fig. 4c to 4f) commonly appear isolated or interbedded (filling fractures), in direct contact, with the carbonate basement forming an angular unconformity, as lenses 0.5 to 3 m thick related to springs and fluvial channels. Facies Lt and Mt can also overlie facies Cbw and Fw with erosional contact which can be observed in Serra da Bodoquena and Serra das Araras sections (Fig. 2). The Lt facies is composed by microspar calcite stromatolitic lamination, with presence of encrusted microbes and macrophytes fossils and icnofossils (Fig. 4c). The presence of clay-minerals associated with the calcite spar is common, and occurs more concentrated in some laminae. Diagenetic features are represented by calcite cement, in an intense (~20%) cementation of fossil pores (Fig. 4d). The Mt facies occurs associated with facies Lt, and also occurs only in Serra da Bodoquena and Serra das Araras (Fig. 4e). It consists of stems, levees and seeds, ranging from 0.5 mm to 20 cm in major axis, encrusted or substituted by microspar calcite (Fig. 4f). High porosity (~20%) is the characteristic feature due to organic matter decomposition (encrusted fossils). No pedogenic features were observed and low (~10%) calcite cementation can be observed.

FACIES ASSOCIATIONS

It was possible to group the facies recognized in the studied areas into facies associations, related to each location which represents depositional paleoenvironments. Three facies associations were described in the field (Fig. 2): alluvial fan (A), lacustrine/palustrine (B) and fluvial channel/springs (C).

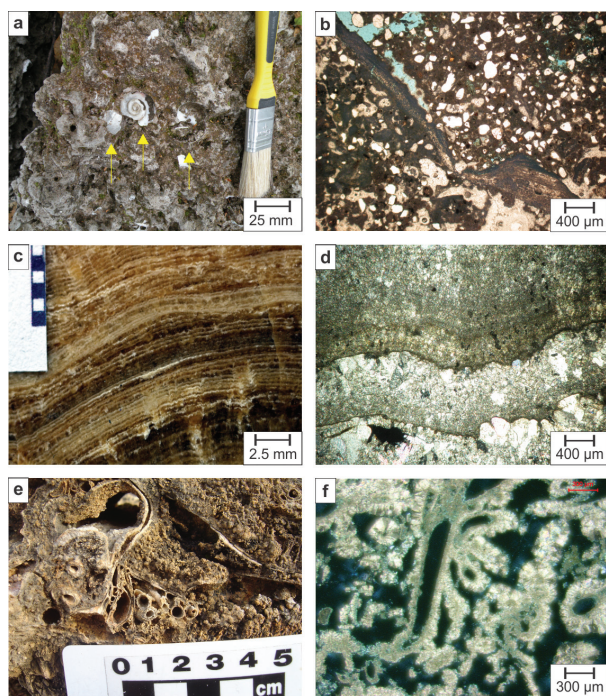


Figure 4 - Plate showing photographs and microscopic photographs (optical microscope) of upper facies. **a**: Photograph of quartz wackestone with gastropods fossils (arrows) (Pantanal do Miranda). **b**: Microscopic photograph of quartz wackestone with fossils (calcrete) with preserved root cavity (Pantanal do Miranda). **c**: Photograph of laminated boundstone (tufa, with well-marked stromatolitic lamination (Serra da Bodoquena). **d**: Microscopic photograph (polarized) of laminated boundstone (tufa) showing cementation and recrystallization (Serra da Bodoquena). **e**: Photograph of massive boundstone (tufa) showing macrophytes fossils (Serra da Bodoquena). **f**: Microscopic photograph (polarized) of massive boundstone (tufa) with biological porosity (macrophytes and microphytes) (Serra da Bodoquena).

ALLUVIAL FAN (A)

This facies association is present in Serra das Araras and in Corumbá/Ladário plateau and is composed of facies Cpc (Fig. 3a and 3b) and the Neoproterozoic carbonate basement (Fig. 2). Besides a coarse grained lithological composition, an important feature of these deposits is the actual outcrop position close to scarps, upon the basement, with a variable thickness from 15 cm to 10 m, and also variable in extent from 100 m² to 50 km². These deposits are cut by sub-vertical normal

faults (E-W), parallel to the plateau scarps. Some textures and structures, especially the displacive calcite filling (Fig. 3b), related to the near-surface parts, are the result of pedogenic alteration. The characteristics of facies association A indicates deposition from high-energy debris flows, with sufficient energy to erode the basement and previous lacustrine carbonate deposits. The poor sorting of clasts, in a fine matrix with fossils, is similar to conglomerates deposited by gravity in proximal, submerged areas of lacustrine systems (Fig. 3a).

LACUSTRINE/PALUSTRINE (B)

This facies association includes facies Cbw (Fig. 3c and 3d), Op (Fig. 3e and 3f) and Fw (Fig. 3g and 3h) and occurs in Serra do Bodoquena, with facies Cbw, Op and Fw, and Corumbá/Ladário plateau, with facies Cbw, which has a gradational contact with facies association A (Fig. 2). The thickness of this association ranges between 15 cm to 6 m and its area ranges between 50 m² and 20 km². Facies association B is compatible with lacustrine environment because it is dominated by micritic carbonate (Cbw, Op, Fw), with ostracods, gastropods and bivalves in facies Fw (Fig. 3h), located in flat areas at the foot of the hills, in form of discontinuous and elongated lenses. The facies Op is related to the development of oncolites in shallow and low-energy environments, as suggested by the asymmetry and texture of laminae (Fig. 3f). The facies Qw (Fig. 4a and 4b) is related to a palustrine environment that formed small water bodies exclusively in Pantanal do Miranda, with thickness ranging between 1.5 and 5 m, and average area around 200 m². The textures include rhizoliths and mud cracks (Fig. 4b) and the well-rounded and well sorted quartz grains. The biological activity in this environment was high, with remarkable fossil gastropods and preserved roots (Fig. 4a and 4b).

FLUVIAL CHANNEL/SPRINGS (C)

Facies association C includes facies Lt (Fig. 4c and 4d) and Mt (Fig. 4e and 4f) and is related to the basement (Fig. 2). The channels show typical concave-up erosional morphology, filled with clastic carbonate sediments. The geometry in Serra das Araras is related to lenses, 3 m thick, distributed in an elongated area, with an average width of 75 m and extension of up to 2 km. In Serra da Bodoquena these deposits vary in thickness, from 15 cm to 6 m, and in area, from 20 m² to 1 km², and are always associated with active and inactive fluvial channels. Some tufas textures, such as petrified waterfalls geometry, appears related to the carbonate scarps (Ford and Pedley 1996). The tufas, resulting from carbonate precipitation associated with springs, with laminated tufa (Lt) deposited next to spring areas, and fine carbonate (Cbw) (Fig. 3c) deposited downstream. The petrified waterfalls geometry of facies Lt suggests high hydraulic energy (Corrêa et al. 2011). This association is not observed in the Corumbá/Ladário plateau, but some tufa clasts, similar to facies Lt, were identified.

STABLE ISOTOPE COMPOSITION

The various carbonate facies of Serra das Araras, Corumbá/Ladário plateau, Pantanal do Miranda and Serra da Bodoquena (n = 71) have stable isotope compositions that range between -9.44‰ and -4.20‰ V-PDB (mean = -7.14 ± 0.90‰) for δ¹⁸O, and between -9.26‰ and -1.39‰ V-PDB (mean = -5.79 ± 1.53‰) for δ¹³C (Table II; Fig. 5).

These results are similar to those obtained for other continental carbonates (Andrews et al. 2000, 1997, Arenas and Alonso-Zarza 2004, Boggiani et al. 1999, Buccino et al. 1978, Chafetz and Lawrence 1994, Fritz 1965, Horvatincic et al. 2003, Sinha et al. 2006). In detail, the average δ¹³C for the Pleistocene samples is more negative than the Holocene samples (Pleistocene n = 24; mean δ¹³C = -6.64 ± 0.59‰; Holocene n = 49; mean

δ¹³C = -5.38 ± 1.78‰), with less variation. The average δ¹⁸O values are similar (-6.99 ± 0.97‰ for Pleistocene and -7.21 ± 1.24‰ for Holocene), with a wider range for Holocene samples.

Another difference is the most negative δ¹³C mean value for the lacustrine facies association (C) in the Holocene (-7.31 ± 0.48) compared to the same facies association in the Pleistocene (-6.64 ± 0.59). These results could suggest an increase in vegetation (Andrews 2006), perhaps the consequence of an increase in rainfall during the Holocene, which is in accordance with paleoclimatic data for the region (Bertaux et al. 2002, Whitney et al. 2011).

The correlation between the δ¹³C and δ¹⁸O values for the Pleistocene samples is $r = 0.01$ and for the Holocene samples is $r = 0.68$. The lack of a correlation in the Pleistocene data could be a reflection of sedimentation in a hydrologically closed system, with a strong groundwater influence (Arenas-Abad et al. 2000, 2007, Garnett et al. 2006). However, in spite of such a poor correlation, the set of Holocene samples shows a moderately good covariation, with $r = 0.68$; this could also indicate a hydrologically open system, but with more evaporation and/or CO₂ degassing (Andrews 2006). It was not possible to analyse the isotopic variation through time, because the sampling for stable isotopes was not related to the sampling for dating. The only remarkable fact is the large variation in the δ¹³C and δ¹⁸O values in the Pleistocene, probably related to changing residence time of the water in lakes and the influence of organic matter, possibly due to variations in precipitation and evaporation during this epoch (Arenas et al. 2014).

DISCUSSION

The described facies associations of the continental carbonates of Serra das Araras, Corumbá/Ladário plateau, Pantanal do Miranda and Serra da Bodoquena are similar to other Quaternary

sequences described in different sedimentary settings (Arenas-Abad et al. 2000, Arenas-Abad et al. 2007, Pimentel et al. 1996, Pla-Pueyo et al. 2009, 2015). However, the combination of sedimentary systems described here by the facies associations and the prevailing tropical climate for the region during the Quaternary is rare.

The characteristics of facies association A is interpreted as deposition by debris flows into lakes. This interpretation is consistent with the fact that the facies association A has a transitional contact with facies association B, related to lacustrine sedimentation, and with the fossil content. Similar features are described in alluvial environments in Spain, Sorbas basin, where conglomerates similar to facies Cpc were attributed to debris flows (Candy et al. 2003). The interruption of deposition is marked by an erosional surface, which also indicates sub-aerial exposure and soil formation, generating displacive textures (Fig. 3b) similar to calcretes exposed to biological activity (Alonso-Zarza 2003). The facies association A is only related to the Pleistocene occurrences, which might be related to changes in the environmental conditions, especially in geomorphology and climate, which is discussed below.

The facies association B is interpreted as formed by lacustrine deposition due to textural characteristics and fossil content, similar to the lacustrine deposits of wackestones described in the Madrid basin (Spain) (Wright et al. 1997). The deposits of this facies association can be related to the Pleistocene sequences (facies Cbw) or to the Holocene (facies Op and Fw), and the contact between these sequences is marked by an erosional surface, which also indicates sub-aerial exposure (Figs. 3c and 3d). The occurrence of the facies Op is also related to lacustrine environments, due to the asymmetrical characteristics of the oncoids, which are similar to the oncoids described in the Mainz Basin, Germany (Leinfelder and Hartkopf-Fröder 1990). The characteristics of the facies association

B, in Pantanal do Miranda, is interpreted as the deposition in palustrine settings, due to the carbonate lenses form and their fossil content (Figs. 4a and 4b). The inclusion of quartz sand can be related to wind transport during the deposition of the carbonates, due to the quartz sand composition of the Pantanal Formation, leading to specific facies that can also be found in the Atacama Basin, Chile (Bell 1989) and in the Sado Basin, Portugal (Pimentel et al. 1996).

For the facies association C, in Serra das Araras, the interpretation of springs, related to the basement and/or to the facies Cpc and Cbw, the tufas formed over these rocks as speleothems and perched spring lines (Ford and Pedley 1996), in a similar situation to what is observed in Denizli Province, Turkey (Özkul et al. 2010). The facies Cbw also present textures compatible with sub-aerial exposure and soil formation (Figs. 3c and 5d), also with displacive texture. The development of tufas in Serra da Bodoquena, related to channels is interpreted as fluvial deposition for the facies association C, in a common setting in different fluvial environments (Arenas et al. 2014, Emeis et al. 1987, Martini and Capezzuoli 2014). The two facies, Mt and Lt, are related to specific environments: the facies Lt is related to high energy water flow environments, where the CO₂ degassing has a major control, leading to the precipitation of laminated tufas (Arenas et al. 2014, Chen et al. 2004); the facies Mt is related to the low energy environments, where the incrustation of algae, mosses and plants is possibly due to the low energy of water flow (Zhang et al. 2001, Arenas et al. 2014).

FACTORS CONTROLLING THE CONTINENTAL CARBONATES GENESIS AND EVOLUTION

The south-central region of the Pantanal Basin and its surroundings have a geological, geomorphological and environmental situation that favoured the deposition of carbonates towards the

end of the Quaternary and which, at least in part, are continuing to form at the present time.

These carbonate deposits do not show any particular features that allow an interpretation of a pure climatic control on their deposition. For example, no evaporitic minerals were identified in the lacustrine deposits, which could indicate deposition under dry conditions, as has been recorded in many lacustrine successions of arid regions (Camoïn et al. 1997). An element that could be used as an indicator of paleoclimatic changes is the erosional surface with modifications produced by subaerial exposure, present at the top of Pleistocene section. Although calcretes can develop under many climatic conditions (Alonso-Zarza and Wright 2010), the features identified in this study are not conclusive regarding how deep these modifications were and how representative the calcrete generation is in terms of a paleoclimatic interpretation. This is particularly revealed by the presence of beta texture, whose formation involves biogenic activity in pedogenic profiles (Alonso-Zarza 2003, Wright and Tucker 1991), which can occur in different climatic environments.

The values of stable isotopes are compatible with sub-humid/humid conditions during the development of tufas (Lt and Mt) and lake sediments (Op and Fw) (Fig. 5). Some samples of lake sediments (facies Qw) have values positioned between tufa and calcretes fields, but with more negative $\delta_{13}\text{C}$ (Fig. 5) (Alonso-Zarza 2003). This occurred, probably, because these sediments are exposed to subsequent dry periods, which eventually could lead to calcretization processes (Wright and Tucker 1991). For the facies with sub-aerial modification (Cpc and Cbw), the results are not as consistent as expected for calcretes in other parts of the world (Alonso-Zarza 2003), since the results showed a concentration of values in an area between carbonates with sub-aerial exposure and mature calcretes (Fig. 5). This might be related to exposure to subsequent humid and arid periods,

which would have caused the precipitation of carbonate cements in diverse climatic conditions.

Climate change events might have conditioned the carbonate sedimentation in the Pantanal area where a more humid climate led to the formation of lakes and river systems, and a drier climate led to the development of erosional surfaces and sub-aerial exposure. Thus, a period of higher humidity would have favoured the establishment of lakes that were later dried under conditions related to arid climate, culminating in the formation of the erosional surfaces with sub-aerial exposure features.

After this arid event, a humid event would have again favoured the development of lakes and river systems. This alternation might have been occurring since the Middle Pleistocene. Tectonics is another factor that was probably significant in the genesis of carbonates in the Pantanal region. This is suggested by the direct association between the carbonate deposits and tectonic structures, normal faults and folds originated in the Brasiliano tectonic cycle, in the Neoproterozoic (Almeida et al. 2000), and reactivated with the Andean orogeny and the subsidence of the Pantanal (Ussami et al. 1999). The tectonic activity could have modified the relief, generating scarps and depressed areas, which controlled the location of rivers and lakes. The faults were the conduits for carbonated water derived from the basement and, when generating high-gradient scarps, provided a turbulent flow with consequent high CO_2 degassing, similar to the situation in the Iberian Range (Peña et al. 2000). The evolution of the local geomorphology was mostly conditioned by tectonics and weathering, creating plateaus, scarps and ranges (*serras*), allowing the development of fluvial and lacustrine systems.

In the Serra das Araras, the influence of the structures on the genesis of carbonates is demonstrated by their geometry and position, characterized by elongated bodies of Cpc, Cbw, Lt and Mt facies parallel to the base of a fault

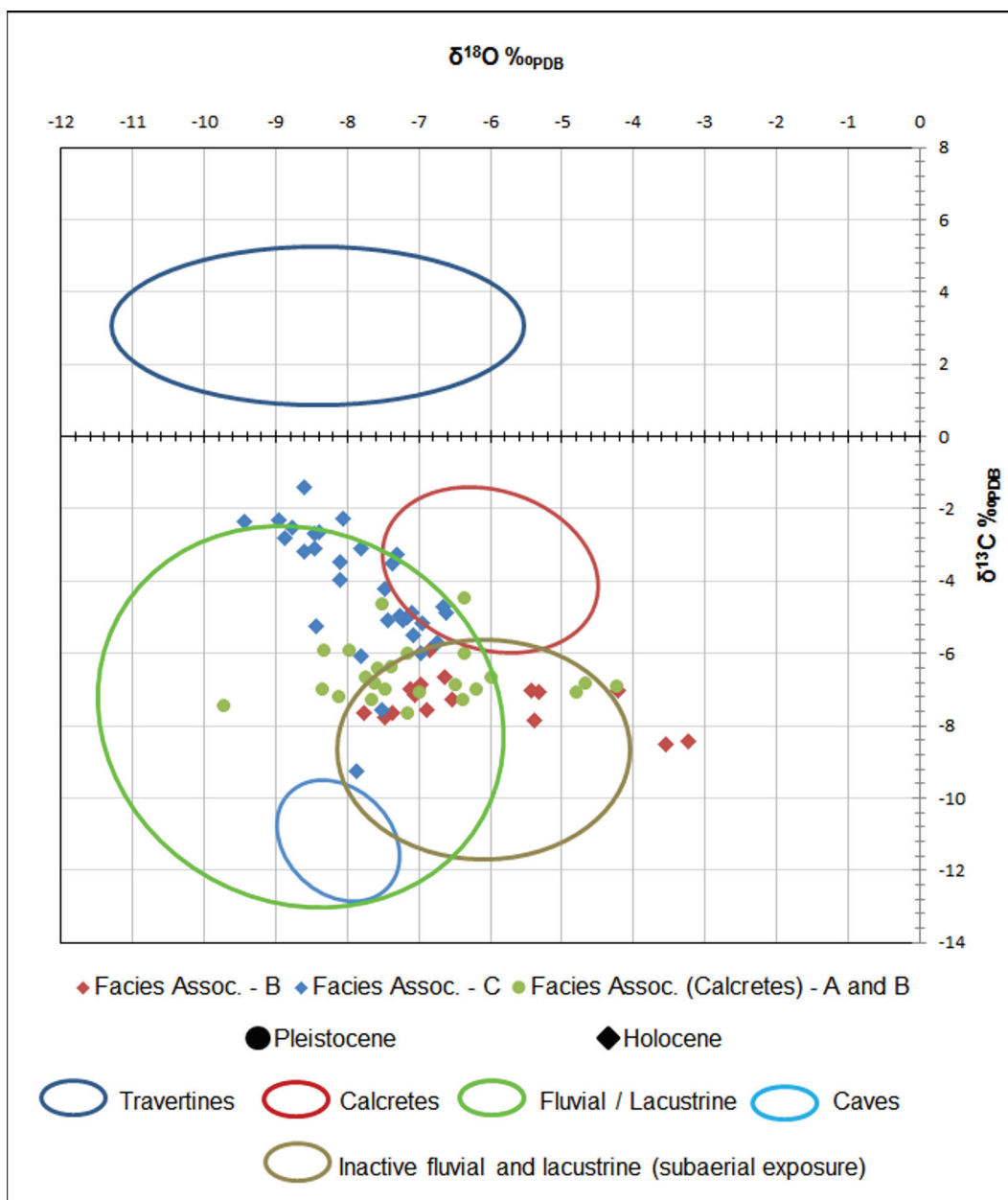


Figure 5 - Isotopic composition ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of different facies associations and combined plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data from other continental carbonates. Data sources: Andrews et al. 1997, 2000, Arenas et al. 2004, Boggiani et al. 1999, Buccino et al. 1978, Chafetz and Lawrence 1994, Fritz 1965, Horvatinčić et al. 2003, Sinha et al. 2006.

scarp (NE-SW). In the Corumbá/Ladário plateau the occurrence of several small elongated bodies of Cpc and Cbw facies related to faults (NE-SW in the north and NW-SE in the south) is also observed. In the Serra da Bodoquena the most significant deposits of Fw, Lt and Mt facies that form an elongated body bordered in the east by a fault (NE-SW), with thickness (~ 10 m) deposited in less than 6,000 years ago. According to the tectonic hypothesis, elongated lakes were created during the subsidence of areas along tectonic structures where debris flows were also common in marginal areas. With the tectonic evolution, the faults produced significant topographical variation with plateaus and steep cliffs allowing the development of riverine systems with springs, waterfalls and channels.

PALEOENVIRONMENTAL EVOLUTION

The analysis of the depositional record in the studied area indicates that the first phase of development of lacustrine systems occurred directly on the carbonate basement, in the Middle Pleistocene (Table I). The formation of these lakes occurred after an extended period of non-deposition and/or erosion, during which there was the development of an unconformity on the surface of the basement. The greater thickness of lacustrine deposits was recorded on the Corumbá/Ladário plateau, where the marginal areas of the lakes received sediments transported by gravitational flows, which reworked previously deposited sediments and carbonates of the basement. In the Serra das Araras, there was also development of tufas curtains on the cliffs, in association with springs, along with the development of elongated lakes, associated to the base of the cliffs, with restricted debris flows sediments. The development of packages with deposits of subaqueous debris flows on the Corumbá/Ladário plateau and Serra das Araras may have also been promoted by gravity instabilities in low-energy environments such as lakes, due to

the accumulation of sediment near the base of the fault scarps. Generation of the fault scarps or its reactivation was caused by the subsidence events of the Pantanal Basin.

In the Serra da Bodoquena, the fluvial and spring tufa (Late Pleistocene), occurring immediately over the basement, and in the Serra das Araras the sedimentation took place exclusively in springs. In the Corumbá/Ladário plateau, no carbonate sedimentation occurs during the Holocene. The evolution of regional tectonics, with the subsidence of the Pantanal Basin, probably captured the drainages of the region, shifting the course of the main river, the Paraguay, to the surroundings of the Corumbá/Ladário plateau. In Serra da Bodoquena, the Holocene deposits are represented by the occurrence of lacustrine carbonate sediments and fluvial tufas until late Holocene when, probably due to geomorphological and climatological changes, the lacustrine systems disappeared and only the riverine systems remained active. The Pantanal do Miranda area only presents deposits related to the middle-late Holocene boundary (Walker et al. 2012). The observed palustrine system might be related to a change in the water table during the recent evolution of the Pantanal Basin, and is probably linked with climatic variations (Assine and Soares 2004). These lacustrine systems are still active in the neighbouring area of Nhecolândia (Furquim et al. 2010), in a distal part of the Taquarí river alluvial fan, although evaporitic sediments were described.

CONCLUSIONS

The mapping of Quaternary continental carbonates in the Pantanal Basin and its surroundings, along with sedimentological, stratigraphic, isotopic and petrographic studies have allowed the proposal of a reconstruction of the depositional environments and the main factors involved in its genesis.

The analyses of facies associations indicate deposition under continental conditions within subaqueous debris flows, springs, lakes and river channels. The stratigraphic correlation reveals that the deposits are not geographically or chronologically related, but the sedimentological similarities indicate repetition of environmental conditions in different times and areas in the studied region.

The presence of an erosional surface, formed due to sub-aerial exposure, indicates that the climatic regime was not stable during the development and evolution of these deposits. Considering climate hypothesis, higher humidity would have favoured the establishment of lakes that were later dried, generating the erosional surface and the sub-aerial exposure features in the sediments. After this, the hydrological regime would have again favoured the development of lakes and river systems, in a more humid climate. This alteration of arid and humid climate has occurred since the Middle Pleistocene.

The geological structures associated with active tectonic are a key factor in the formation of the studied Quaternary carbonates. These deposits do not occur randomly in the areas studied, but are related to fault zones. The occurrence of subaqueous debris flows in lacustrine environment, as described in the Corumbá/Ladário plateau, may have also been related to gravitational instability during sedimentation. Additionally, there was deposition in springs and waterfalls in river channels due to the presence of topographic variations related to tectonic activity.

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