Paleolimnology in the Pantanal: Using Lake Sediments to Track Quaternary Environmental Change in the World's Largest Tropical Wetland

Michael M. McGlue, Aguinaldo Silva, Mario L. Assine, José C. Stevaux, and Fabiano do Nascimento Pupim

Abstract In spite of its global significance to biodiversity and biogeochemical cycles (e.g., as a methane source and carbon dioxide sink), the Pantanal of western Brazil remains underexplored from the perspective of Quaternary paleoecology, paleogeography, and paleoclimatology. Long in the scientific and cultural shadow cast by the Amazon Basin, recent research using lake sediment cores from different sites across the Pantanal lowlands has provided a glimpse at the sensitivity of this savanna floodplain wetland to climate-driven perturbations in the hydrologic cycle. Understanding the controls and feedbacks associated with this sensitivity is important, as the Pantanal is a critical freshwater resource situated in the headwaters of the immense Río de la Plata Basin. Published lake sediment archives have adopted a multi-indicator analytical approach, focusing on physical sedimentology, geochemistry, palynology, and siliceous microfossils. Such studies extend in time from the late Pleistocene to the present day, with the greatest emphasis placed on reconstruction of the Holocene environmental history. Several important transitions in effective precipitation have been inferred for the Holocene, which appear to be dominantly linked to variability in insolation and the South American Summer

---

M.M. McGlue (✉)
Department of Earth and Environmental Sciences, University of Kentucky, Lexington, KY 40506, USA
e-mail: michael.mcglue@uky.edu

A. Silva
Department of Geography, Federal University of Mato Grosso do Sul, Corumbá, Brazil

M.L. Assine and J.C. Stevaux
Applied Geology Department, Geosciences and Exact Sciences Institute, Paulista State University, Av. 24A, 1515, Rio Claro 13506-900, Brazil

F.d.N. Pupim
Geosciences Institute, University of São Paulo (USP), Rua do Lago, 562, São Paulo 05508-080, Brazil

I. Bergier and M.L. Assine (eds.), *Dynamics of the Pantanal Wetland in South America*, Hdb Env Chem (2016) 37: 51–82, DOI 10.1007/698_2015_350,

Monsoon system. By contrast, evidence of aridity in the Pantanal during the Last Glacial Maximum suggests that the wetlands also respond in a complex manner to Northern Hemisphere ice volume and that insolation forcing alone fails to fully explain patterns of environmental change. The great diversity of lacustrine ecosystems in the Pantanal warrant additional study and hold the potential to broaden our understanding of the response of tropical wetlands to global change. Such insights will be valuable for conservation planning, resource security, and sustainable management.

Keywords Brazil, Lakes, Sediment cores, Tropical paleoclimatology, Wetlands

Contents

1 Introduction

For centuries, the vast Pantanal wetlands of central South America have fascinated explorers and scientists, to include such luminaries as Theodore Roosevelt and Cândido Rondon, who famously conducted an expedition through part of the region in the early twentieth century. Responding sensitively to the flood pulse of the Upper Paraguay River, the landlocked Pantanal remains one of South America's great wilderness waterways (Fig. 1; [1]). The annual dynamics of Upper Paraguay River flooding are a key facet controlling the form and function of these wetlands, and pursuit of a deeper temporal understanding of the Paraguay River flood pulse is quite understandably a major goal of Pantanal research. The Pantanal is best characterized as a mosaic of seasonally inundated savanna floodplains with spectacular flora and fauna [2, 3]. Numerous studies have made it clear that the Pantanal is important to global biogeochemical cycles (particularly for the atmospheric trace gases CH_4 and CO_2 [4]; see also [5, 6]) and patterns of Neotropical biodiversity [3]. At the regional scale, the wetlands are socioeconomically vital by providing a host of ecosystem services to Brazil, Bolivia, and Paraguay, including nutrient

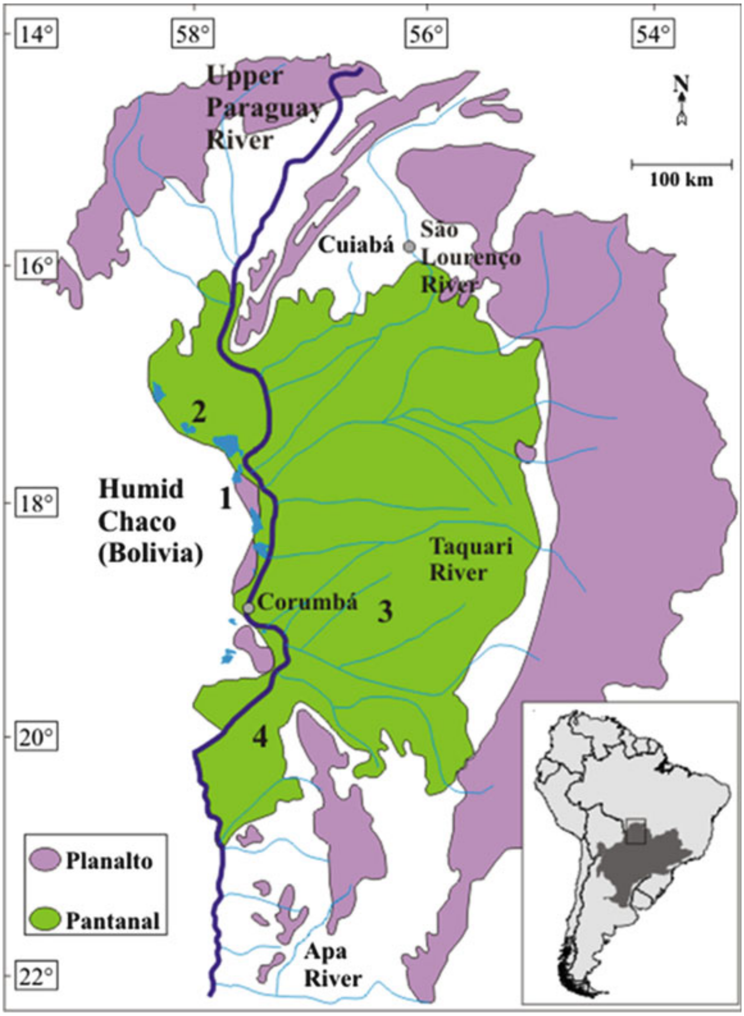

Fig. 1 Overview map of the Pantanal Basin. *Inset map* shows the location of the Pantanal in central South America (*light gray*), situated in the headwaters of the vast Río de la Plata watershed (*dark gray*). The Upper Paraguay River flows to the south along the western margin of the basin. (*1*) Location of the large floodplain lakes of the Pantanal, the subject of several recent paleolimnological studies. Some of these lakes are illustrated in detail on Fig. 5. (*2*) Location of large floodplain lakes along the distal toe of the Paraguay fluvial fan. These lakes are illustrated in detail on Fig. 6. (*3*) Nhecolândia region of the Pantanal, home to many thousands of deflation lakes; southern Nhecolândia is shown in Fig. 3. (*4*) Nabileque River megafan region. Oxbow lakes of the Nabileque River megafan are illustrated in Fig. 2

cycling, fish spawning grounds, rookery space, fertile agriculture, ranching, transportation, and recreation. Moreover, the Pantanal serves as the headwaters of the greater Paraguay-Parana River Basin, which acts as a freshwater resource for growing populations in southern South America, to include the large cities of the Mar de la Plata in Argentina and Uruguay.

Both natural and human-induced environmental changes threaten the ecologically sensitive Pantanal [1, 7], and these risks have motivated research aimed at understanding how the wetlands have responded to ancient changes in temperature and precipitation known to have affected the South American tropics [8–10]. However, efforts to study the Quaternary environmental history of the Pantanal wetlands are still in their infancy, due in large part to difficult operational conditions and the remote setting that renders acquisition of field data nearly as challenging as it was during the *Expedição Científica Rondon-Roosevelt* (1913–1914). However, this situation is improving, and a number of access points with infrastructure for logistical support now exist. Access to the heart of the Pantanal is best accomplished via the Upper Paraguay River from Corumbá, the frontier port in Mato Grosso do Sul state of western Brazil. Prospective international researchers are advised to establish collaborations with the community of Brazilian scientists working in the Pantanal to avoid potential legal complications (e.g., [11]). The Federal University of Mato Grosso do Sul State maintains a campus in Corumbá, which is growing into a center of excellence dedicated to geographic and environmental studies of the wetlands.

Most of the early hypotheses related to the influence of climate change on the Pantanal were developed using evidence gleaned from remote sensing data (e.g., [12, 13]), which is a tradition that continues today among many fluvial geomorphologists, albeit now with more highly resolved satellite imagery, the benefit of advanced computer processing, and improved access to sediment ground truth (e.g., [14–18]). Remote sensing techniques have the advantage of imaging large swaths of low-gradient floodplain, allowing scientists to discern difficult-to-access landforms, in some instances over different seasons and extents of fluvial inundation. To cite prominent early examples, Klammer [19] and Tricart [13] observed what appeared to be lunettes along the marginal fringes of shallow pans across parts of the Taquari River megafan, which they interpreted to have formed when the Pantanal experienced desertlike conditions during an interval of persistent aridity. Hamilton et al. [20] used a time series (1979–1987) of passive microwave remote sensing data to track inundation patterns across the Pantanal, which has obvious linkages to rainfall variability and wetland physiography. Assine and Silva [15] used satellite data to hypothesize about climatic influences on patterns of floodplain entrenchment and valley fill in the Paraguay River megafan, situated in the little-explored northern fringes of the Pantanal. Assine et al. [21] utilized remote sensing analysis to guide sediment coring and luminescence dating of different depositional landforms of the São Lourenço fluvial megafan (northeast Pantanal). This fully integrated approach allowed for a more comprehensive assessment of both geomorphology and Quaternary sediment accumulation history and provided a roadmap for future studies of this kind.

Whereas the aforementioned studies centered primarily on remote sensing techniques, other researchers have directly sampled geological materials. To date, archives of hydroclimatic and paleoecological information that have been assessed to probe the Pantanal's Quaternary history include lake sediments, alluvial/floodplain strata, terrestrial carbonates (speleothems, riverine tufas), and soil profiles [22–31]. A comprehensive review of all these studies is beyond the scope of this chapter, but many of the published records are either short or temporally punctuated, which is typical of many paleoclimate records from the South American lowlands [32]. Therefore, more is known about the Holocene (approximately 11.9 cal ka – present) than the Pleistocene evolution of the Pantanal wetlands.

Nonetheless, snapshots of Quaternary history can be recorded by the deposits accumulating in many of the Pantanal's lake basins. Ruddiman [33] highlighted the value of lacustrine sediments for understanding Earth's variable climate and its impact on the continents. Paleolimnology as a discipline operates from the premise that ancient lake sediments can, in certain instances, provide highly detailed and datable archives of environmental variability, albeit with the limitations imposed by so-called "hydroclimate filters," which themselves may vary over time [34]. Thus, the signal recorded by any individual geological, biological, or chemical indicator (e.g., carbonate content, particle size, diatom assemblages, pollen, among many others) recovered from a lake sediment core is potentially complex and ideally will be constrained by extensive modern limnogeological information. Because the Pantanal is very much a "land of lakes" [35], paleolimnological studies have inescapably played a role in constraining the effects of Quaternary climate change on the wetland mosaic. In fact, early maps (circa 1600) of tropical South America depicted the Pantanal as a single large lake referred to as *Laguna de los Xarayes*, after a supposed group of Indians inhabiting its margins [36]. This misconception among cartographers of the New World arose from the dramatic influence of Upper Paraguay River flooding during the austral summer, the process which exerts the single most important influence governing the hydroclimate filters of many of the Pantanal's lake systems today. Whether a large lake occupied the Pantanal Basin very early in its depositional history is not clearly known, although lithology logs developed from a few exploration wells drilled by Petrobras do not contain evidence for a widespread and persistent lacustrine system [37, 38]. Much more research is clearly needed to understand the early formation of the Pantanal – answers to questions related to basin geodynamics, linkages to Andean orogenesis and the South American Summer Monsoon, and biogeographic evolution await this future work.

In this chapter, we provide a review of paleolimnological records that have been published for the Pantanal, which in the past decade have appeared with greater frequency than in prior years. A number of important studies that use lake sediments have provided a more nuanced understanding of the Holocene hydrologic history of the wetlands and phytogeographic history of the basin, although much complexity marks these records and fertile ground exists for innovation. Only a few lakes have received detailed study, with most of these studies focusing on singular sediment cores recovered from the deepest regions of relatively shallow basins.

Core recovery techniques have emphasized either vibrocoring a desiccated landform or manual pushing or hammering of a piston coring device from a floating platform into the lake floor, either as a single drive or in overlapping segments (e.g., [22, 28, 30, 31]). The indicators or proxies used in these studies vary greatly (as do the techniques used to generate these data), from pollen and siliceous microfossils to organic matter geochemistry and siliciclastic sediments. In general, radiocarbon or optically stimulated luminescence dates have been used to develop the chronology of lake sediment cores in the Pantanal, although the sampling density and strategy usually vary a great deal. Our goal is to synthesize the information currently known, to consider the strengths and weaknesses of the data that have appeared, and to use this context to explore some fruitful future research directions for this fascinating and enigmatic wetland system.

2 The Pantanal: Overview

The reader is referred to other chapters in this volume for extensive details on the geology, hydrology, biology, and climate of the Pantanal. The overviews provided by Por [35] and Heckman [39], as well as the synthetic volume edited by Swarts [40], are other published resources that should be mined for an introduction to natural science in the Pantanal. We limit our remarks to a brief description of the Pantanal Basin and focus our attention on the environmental processes and gradients that notionally influence the interpretation of lake sediment records.

The Pantanal Basin is located in the Southern Hemisphere subtropics (~16–21°S latitude, ~55–58°W longitude; Fig. 1); the wetlands span the international borders of Brazil, Bolivia, and Paraguay, but the majority of this system lies within Brazil. The Pantanal Basin is a prominent feature in central South America due to its approximate "spoon shape" in map view [41, 42]. The center of the basin sits at low altitude (typically <200 m above sea level) and is comprised of Quaternary alluvium, whereas a prominent plateau ("planalto") that consists of resistant Devonian and Neoproterozoic rocks surrounds the basin on its eastern and northern margins [43]. In contrast, the western margin of the Pantanal, which borders the humid Chaco plains of eastern Bolivia, is much more diffuse. This region is largely defined by the position of the Upper Paraguay River, which flows from north to south in complex styles with meandering and anabranching patterns, making several sharp directional changes along its course (Fig. 1). Although not extensively studied, it is probable that intra-basinal faults and neotectonic deformation influence the position and geometry of the river along strike [42–44]. The geology of the western margin is notable for small remnants of a late Proterozoic fold-and-thrust mountain belt, whose strata host economically valuable iron ore deposits and are purported to contain glaciogenic features that date to the Cryogenian [45]. These remnants form the most prominent hills in the basin, but it should be emphasized that relief is otherwise limited. Because the age of the Pantanal is not rigorously constrained by absolute geochronometers, the total amount of time encompassed by the approximately 500 m of strata in the basin remains unknown. Most estimates suggest the basin is no older than Pliocene [43], which is consistent with what is currently understood about Andean geodynamics, assuming the Pantanal is indeed a back-bulge basin as has been suggested [41, 46, 47]. This major gap in our understanding of basin evolution is one of the great challenges confronting Quaternary scientists studying the evolution of the Pantanal wetlands from a geological perspective.

Several large rivers enter the Pantanal from the north and east, forming low-gradient megafans draining toward the Upper Paraguay River, which serves as the local base level (Fig. 1; [14]). Climate in the Pantanal is strongly influenced by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and the South American Summer Monsoon (SASM; [48]). Precipitation is heaviest during the austral summer (December, January, February [DJF]), when >1,000 mm of rain falls in the northern and central Pantanal in a single prolonged wet season that lasts approximately from October to April. The southern Pantanal receives slightly less rainfall, which produces a latitudinal climatic gradient in the basin. The mean annual temperature is ~25°C and evaporation exceeds precipitation during most of the year [35]. In terms of its vegetation, the Pantanal blends significant tracts of Planalto-derived *cerrado* (tropical savanna) with Amazonian semi-deciduous forest, seasonal dry forest of Chaco affinity, and aquatic plants [49]. Pinder and Rosso [50] have suggested that the spatial distribution of plants is controlled by patterns of flooding, elevation, and soil type (see also [51]).

The arrival of summer rainfall, and with it the Upper Paraguay River flood pulse, dramatically alters the hydrology of the Pantanal. The flood pulse is the defining hydrologic feature of the Pantanal because it causes the stage height of the Upper Paraguay River to rise by several meters across the basin [52]. Retention of the Upper Paraguay River flood pulse in the northern Pantanal (through floodplain storage processes; [1]) delays the onset of full inundation in the central and southern Pantanal by several months. The flood pulse is responsible for widespread inundation of megafan floodplains due to creation of a pronounced "backwater effect," as tributaries swollen with rainfall reverse flow after encountering the rising stage of the Upper Paraguay River. It is the basin's low-elevation and low-relief topography that makes the seasonal flooding of the Upper Paraguay River capable of covering an area in excess of 130,000 km^2 [52, 53]. The influence of the flood pulse on several of the large lake basins on the western margin of Upper Paraguay River (near the area of the Serra do Amolar) was discussed in the actualistic limnogeological analysis of McGlue et al. [54]. In these lakes, water levels and hydrologic closure tracked the flood pulse and were less sensitive to direct precipitation in DJF. McGlue et al. [30] demonstrated that changes in stage height of the Upper Paraguay River and arrival of flood waters strongly influenced lake levels, patterns of siliciclastic sedimentation, and sediment biogeochemistry. Thus, lakes with tie channels to the Upper Paraguay River and approximately continuous strata provide a means to evaluate ancient flood pulse dynamics sure to have influenced large tracts of the greater wetland system. Lakes or ponds lacking a well-defined physical connection to the Upper Paraguay River may still be impacted, if seasonal flooding enacts a change in water balance, sedimentation, or hydrochemistry indirectly through floodplain inundation, overland flow, or groundwater seepage.

3 Late Quaternary Paleolimnology in the Pantanal

Comprehensive mapping of the inland lentic waters of the Pantanal has not yet been undertaken, although a few studies have attempted to count and classify the small ponds of the Nhecolândia region of the southern Taquari River megafan [55, 56]. Nonetheless, even a cursory examination of satellite imagery from the Pantanal reveals a wide array of lakes throughout the basin. These extant lakes have served as the focal point for paleolimnological analysis. Outcrops of Quaternary-aged lacustrine deposits are presumed rare in the Pantanal wetlands, although Boggiani and Coimbra [57] suggest a possible lacustrine origin for some carbonates they have studied. Ab'Saber [58] recognized four different classes of lakes in the Pantanal: (a) oxbow lakes (Fig. 2); (b) small circular-ovate ponds, particularly focused on the Taquari River megafan (Figs. 3 and 4); (c) karst lakes (Fig. 2); and (d) large floodplain lakes (Figs. 5 and 6). From the perspective of paleolimnology, the large floodplain lakes have received the most attention. Our synthesis will focus on sediment records from these lakes, as well as the recent study of oxbow lake strata by Kuerten et al. [22]. The waters and supralittoral soils of ovate ponds of the Nhecolândia, which number in the many thousands, have been studied from chemical and biological perspectives (Fig. 3 [59, 60], see also [5]). However, paleolimnological data from these basins is scarce (see [61] for an exception) and in many instances is still in the early stages of development (R. Guerreiro 2014, personal communication). Readers are directed to the synthesis of Cohen et al. [47] for an in-depth examination of the controls on lacustrine deposystems and the formation of topographic closure in the central Andean foreland, which includes the Pantanal and humid Chaco as its distal back-bulge basin.

3.1 *Oxbow Lake Records*

Oxbows lakes form through lateral bank erosion and migration of meandering river systems [62]. The floodplains of many rivers in the Pantanal contain oxbows, making this class of lakes very common in the wetlands today (Fig. 2). Extant oxbows are not typical targets of paleolimnological study in South America and to our knowledge have not been specifically sampled for this purpose in the Pantanal. Abandoned channel lake deposits represent a unique challenge for paleolimnological analysis, principally because meandering rivers frequently rework and scavenge their floodplains. Therefore, poor preservation and overprinting are typical of these lake deposits, and their sedimentary record is usually no more than a

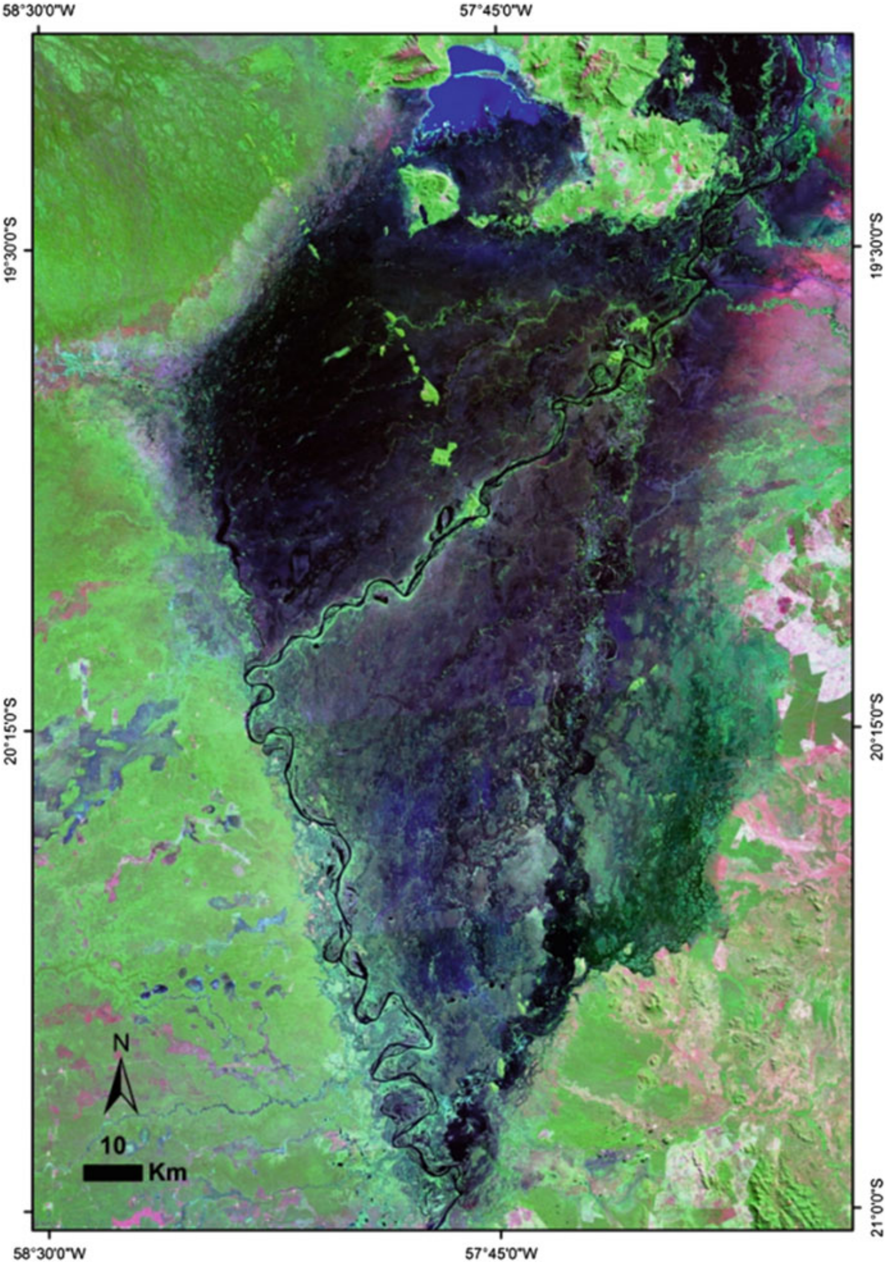

Fig. 2 NASA GeoCover Image Circa 2000 (band combination RGB: 742) of the Nabileque River megafan. Oxbow lakes are common features on the floodplains of several megafans within the Pantanal. The Nabileque River megafan contains some spectacular examples of oxbows, and oxbow lake deposits were recovered in the floodplain vibrocoring campaign and sponge spicule paleoecological analysis described in Kuerten et al. [22]. Lagoa Jacadigo, purportedly one of the Pantanal's karst lakes [35, 58], is visible at the top of the image

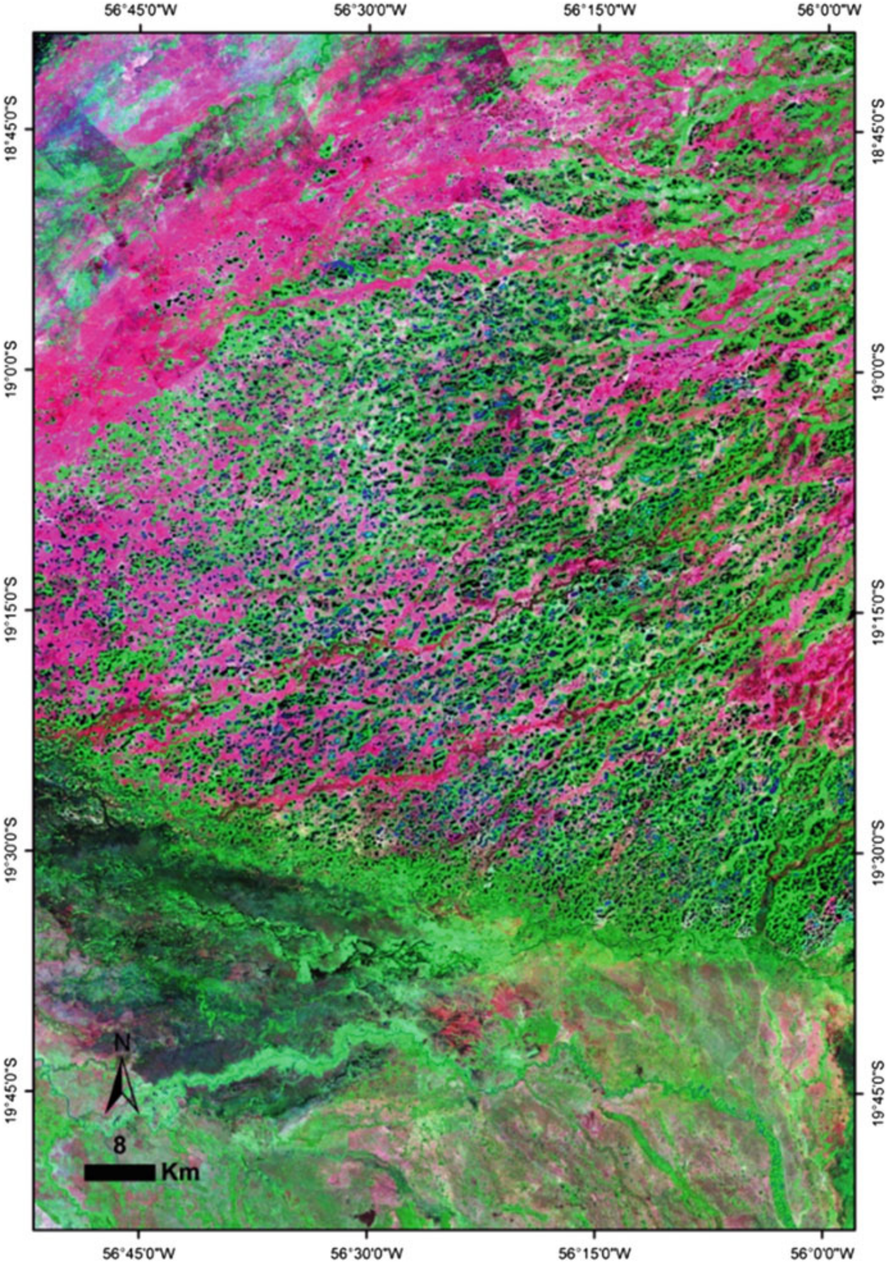

Fig. 3 NASA GeoCover Image Circa 2000 (band combination RGB: 742) of the many thousands of saline, oligo-saline, and dilute ponds juxtaposed in close proximity on the southern fringe of the Taquari River megafan, in a region known as the Nhecolândia. The ponds are believed to have formed through deflation during an interval of late Quaternary aridity. The sediments of these basins represent an underutilized paleolimnological archive for the southern Pantanal

Fig. 4 Overflight photos of the pond-rich landscape of the Nhecolândia. Saline and oligo-saline ponds are typically isolated and fringed by tree-covered sand ridges, whereas fresh ponds often become connected hydrologically during the flood season. Photo credit: Mario Assine

few thousand years in duration [34]. Oxbow lakes may also accumulate sediment in a nonlinear fashion, with a rapid early phase following levee buildup and isolation of the "U-shaped" basin, followed by episodic infill from overbank events and settling of clays from suspension. Thus, any paleolimnological records that might be obtained are likely to be marked by highly variable sedimentation rates. Finally, manually coring oxbows is often a difficult task, due to high clay content within strata and the possible presence of rooted macrophytes.

That said, short time slices of Quaternary history may be captured in oxbow lake deposits, as was demonstrated by Kuerten et al. [22]. In that study, the authors used vibracoring methods to sample the floodplain of the Nabileque River megafan in the southern Pantanal Basin (Fig. 1; approximately 20°S latitude, 57°W longitude). The Nabileque River megafan is among the most visually striking landforms in the entire Pantanal, and speculation about its Quaternary evolution has occurred for many years (Fig. 2; [58]). Casual observation of the Nabileque megafan reveals that the modern river is remarkably underfit for its channel, and Kuerten and Assine [63] used satellite images to hypothesize that the origins of the megafan were linked to a major avulsion event that led to the migration of the Upper Paraguay River to the west, near the border of the Chaco in eastern Bolivia. To test this hypothesis, Kuerten et al. [22] used a coupled geomorphological-paleolimnological assessment of the Nabileque River valley, which contains a high density of scroll bars and oxbow lakes (Fig. 2). Coring locations were determined using a surficial geological map produced by image analysis in Kuerten and Assine [63], with the main focus on a meander scroll environment, believed to be Holocene aged, situated adjacent to

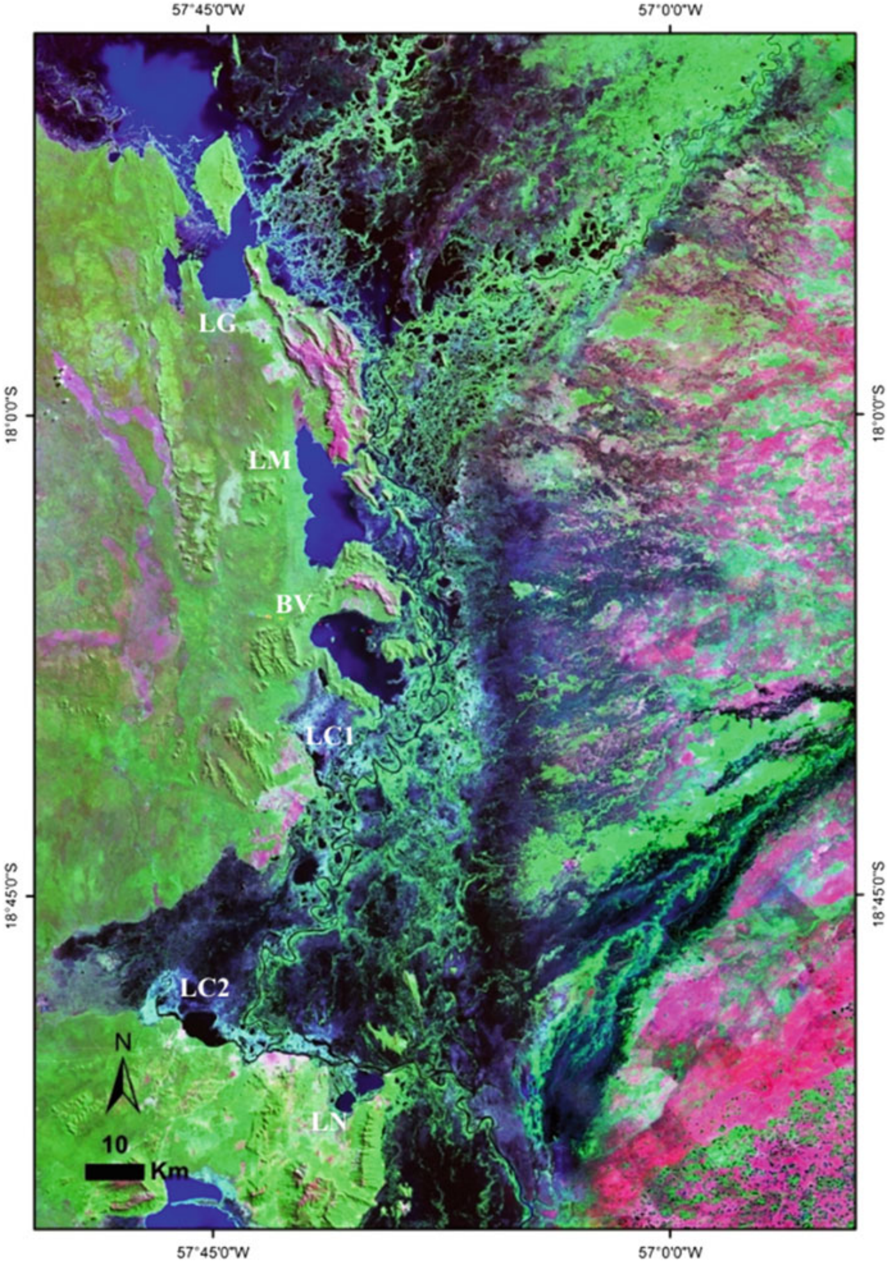

Fig. 5 NASA GeoCover Image Circa 2000 (band combination RGB: 742) of the large floodplain lakes of the central Pantanal. The lakes are interspersed among the ancient Serra do Amolar mountains. Note how these lakes are connected to the Upper Paraguay River, which flows along their eastern margins. *LG* Lagoa Gaíva, *LM* Lagoa Mandioré, *BV* Baía Vermelha, *LC1* Lagoa Castelo, *LC2* Lagoa Cáceres, *LN* Lagoa Negra

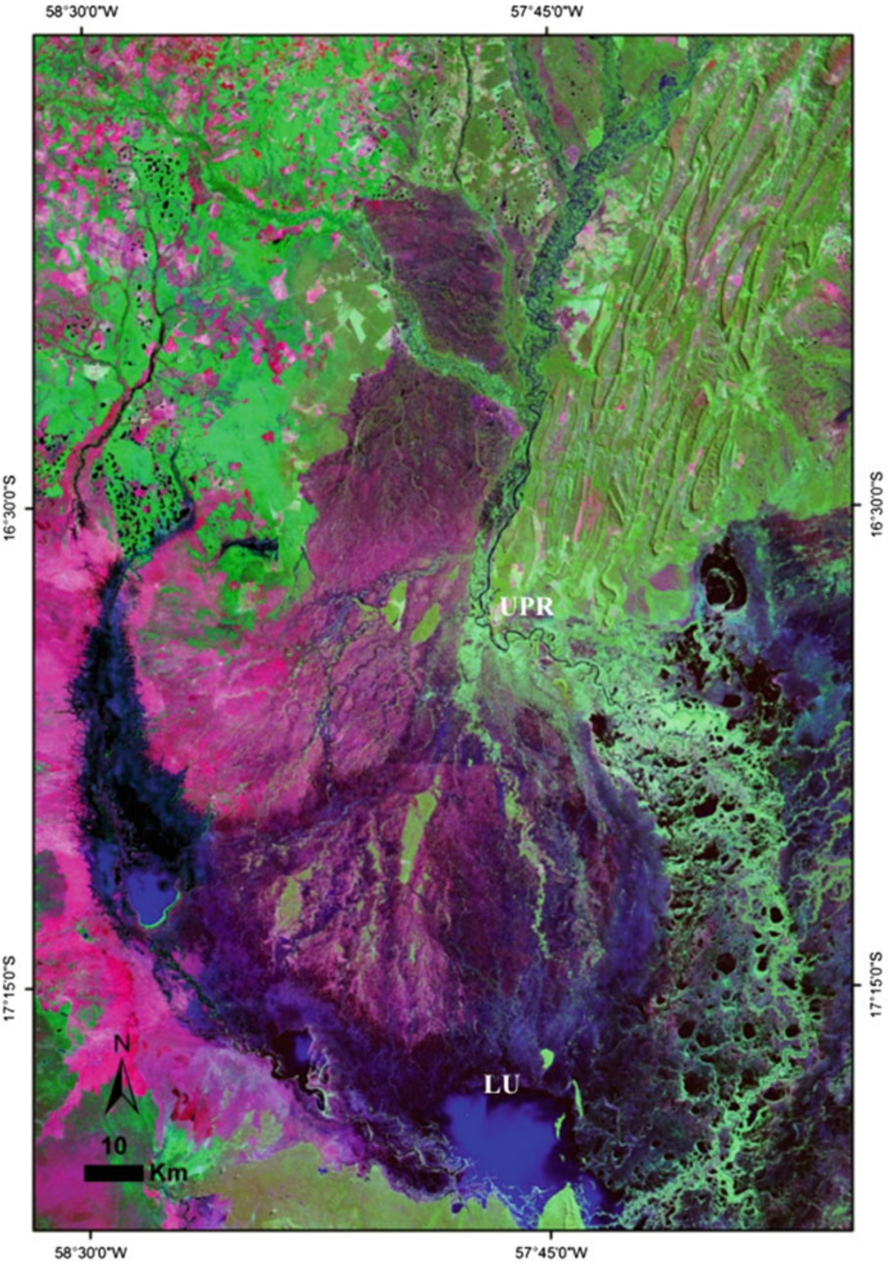

Fig. 6 NASA GeoCover Image Circa 2000 (band combination RGB: 742) of large floodplain lakes likely formed by competitive aggradation along the toe of the Paraguay fluvial fan. These lakes lack direct connections with the Upper Paraguay River (UPR) and represent new targets to obtain more continuous sedimentary records for paleolimnological analysis. *LU* Lagoa Uberaba

the extant Nabileque River. The depositional environment constrained the viable options for both geochronology and indicator materials, as the core sediments were dominated by inter-bedded sands and muds. Two dates, obtained near the top and base of the core using optically stimulated luminescence (OSL), provided a basic, albeit low-resolution, chronological framework for deposition. Those data indicated that at least 2,800 years of mid-late Holocene time was captured by the core, if sedimentation was uninterrupted in the interval between the two OSL anchor points. Kuerten et al. [22] developed a paleohydrological interpretation using sponge spicules, which are siliceous microfossils that can be identified to the species level under conditions of good preservation (Fig. 7; [64, 65]). The taxonomy of sponges is sufficiently well developed in central Brazil to allow the concept of “spongofacies” to spread through the Quaternary literature. Initially presented by Parolin et al. [66], the spongofacies concept links ancient assemblages of sponges, expressed through their spicules, with climatic and hydrologic environments through the use of modern analogs. Sponge spicules are especially valuable in the Pantanal because lotic and lentic species are relatively straightforward to unambiguously identify. For Kuerten et al. [22], lotic sponges near the base of the core suggested the presence of a large meandering river system with a significantly stronger flooding regime than the modern Nabileque River; this result was in accord with the possibility of the Upper Paraguay River flowing through the broad channel during the mid-Holocene. Delicate lentic sponge spicules (e.g., *Metania spinata*; Fig. 7) encased in muds reflected a transition to oxbow lake-type deposition around 3,700 years BP; this transition is interesting because it is one of the first paleolimnological datasets to capture apparent evidence of an avulsion event in the Upper Paraguay fluvial system. The timing of this transition is likewise important, because the extent of mid-late Holocene drought is not fully understood in the Pantanal. In his regional synthesis of soil and alluvial records, Stevaux [8] described a widespread drought in central South America from 3,500–1,500 cal year BP. Similarly, Latrubesse et al. [67] interpreted coeval alluvial and aeolian landforms in the Bolivian Chaco to reflect drought-related sedimentation. Many other areas of tropical South America likewise experienced a dramatic transition in vegetation and hydrology around this time [68]. The results of Kuerten et al. [22] suggest that aridity during this interval influenced fluvial dynamics by spurring migration of the Upper Paraguay River to its current course and abandoning the Nabileque valley.

3.2 Large Floodplain Lake Records

The origins of the large floodplain lakes of the central and northern Pantanal (e.g., Lagoas Mandioré, Gaíva, and Uberaba, Baía Chacororé) are not well studied. Wetzel [62] considered floodplain lakes as those that form either through fluvial erosion or deposition. Ponds may form within depression scours or paleo-channels after river levels recede and water drains from the floodplain, and such features may

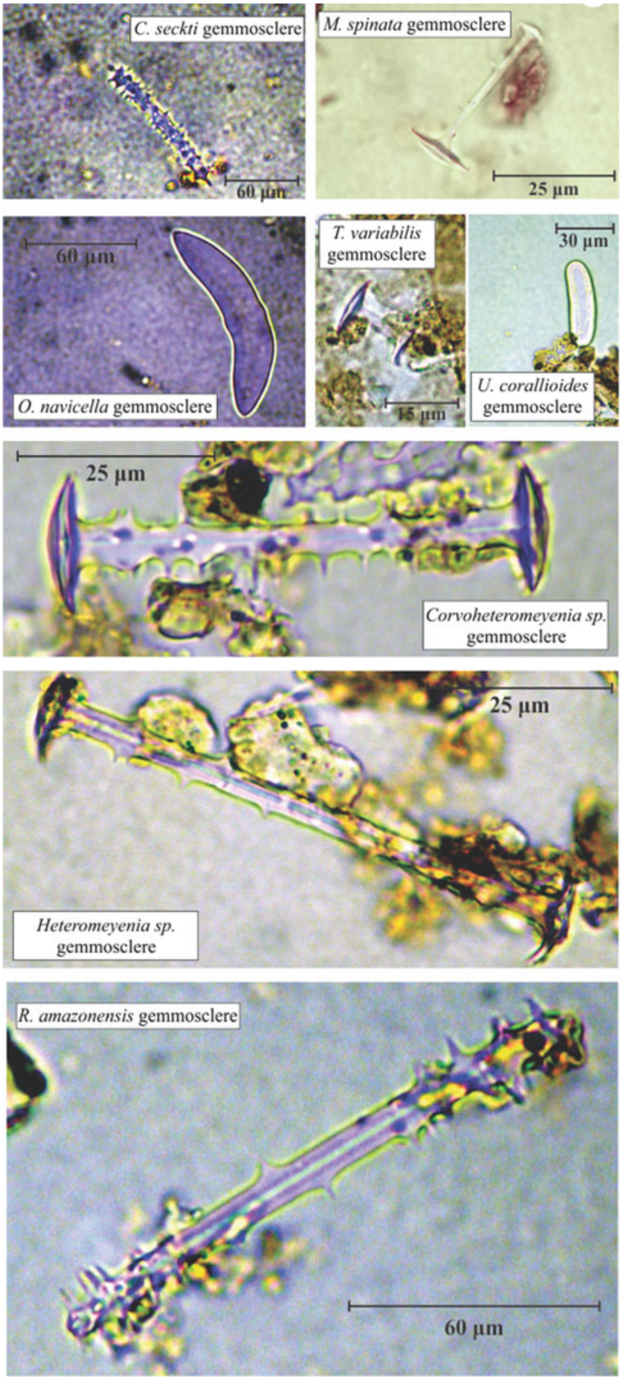

Fig. 7 Sponge spicules recovered from lake sediments in the Pantanal. Images adapted from Kuerten et al. [22] and McGlue et al. [54]. The siliceous spicules of both lotic and lentic species are frequently well preserved and can be used to infer conditions of paleohydrology

persist for thousands of years [34]. These lakes can remain connected to the river through a tie channel or be hydrologically closed and perched above the channel. Lateral lakes form through the obstruction (or damming) of tributary valleys by levee sedimentation [62] and hold the potential to contain moderately long paleolimnological records [34]. It is plausible that Lagoas Mandioré and Gaíva may represent lakes that formed in a paleo-tributary of the Upper Paraguay River (Fig. 5). Due to bathymetric patterns that deepen adjacent to shorelines with coincident topography, McGlue et al. [54] speculated on the potential for neotectonic controls influencing the limnogeology of Baía Vermelha and Lagoas Mandioré and Gaíva. More ground truth is needed to validate or refute this hypothesis. Another class of fluvial lakes is likely present in the Pantanal – lakes formed by competitive fluvial aggradation [34]. Differences in valley aggradation, subsidence patterns, and sediment accumulation rates can generate the topographic closure needed for lake formation, and a number of natural examples of these competitive processes appear along the distal fringes of the Paraguay fluvial fan (Fig. 6; [15]).

One of the earliest sediment core-based studies of the large floodplain lakes in the Pantanal was conducted by Bezerra and Mozeto [26]. These authors used gravity and vibracoring methods to recover sediments from Lagoas Negra and Castelo, which were dated using a combination of radiocarbon (expressed in ^{14}C years) and radioisotopes (Pb^{210}). Both lakes are located to the west of the Taquari River and its distal megafan, with Lagoa Castelo situated on the right margin of the Upper Paraguay River, south of Baía Vermelha by approximately 50 km [54]. Lagoa Castelo is remarkable due to its maximum depth (7.3 m), which makes it perhaps the deepest lake basin ever surveyed in the Pantanal, although it must be said that reliable bathymetric data is still not readily available for many of the wetland's lakes. Approximately 15 km south of Lagoa Cáceres, Lagoa Negra sits south of the Upper Paraguay River where it makes a sharp turn east, south of Corumbá, just before its confluence with the Taquari River. Bezerra and Mozeto [26] focus their analysis on lithostratigraphy, sediment accumulation rates, granulometry (sand content), and total organic carbon assays and attempt to discern fluvial versus lacustrine depositional patterns based on variability within these indicators. Some insights derived from pollen, C/N, and $\delta^{13}C_{OM}$ are also discussed, but these data are not presented in the paper. Although the study is constrained by a low number of radiocarbon dates and reliance on bulk elemental analysis, the authors are able to discern some interesting transitions which appear to have genetic relationships with late Quaternary climate and dynamics of the Upper Paraguay River. Core records from both lakes extend back in time to the late glacial period (>20,000 years BP) and capture the Pleistocene-Holocene transition. Deposition was assumed to be continuous over this interval, and Pb^{210} data attest to intact deposits from the past 100 years. Sedimentation rates vary in both lakes, with the terminal Pleistocene interval generally marked by faster accumulation versus a significant slowdown registered at the mid-Holocene. The lithostratigraphy of Lagoa Negra, which records a chronostratigraphically important change in sediment composition at the Pleistocene-Holocene transition, suggests that this basin is more sensitive to environmental change than Lagoa Castelo. The authors attribute this difference to fluvial dynamics and erosion, as Lagoa Castelo is marked by a strong connection to the Upper Paraguay River throughout the late Quaternary, whereas Lagoa Negra was partially isolated from the river due to the presence of channel-margin levees. Regardless, both lakes record markedly different sedimentation characterized by high percentages of sand in the late Pleistocene. The authors suggest greater humidity as one potential driver for organic-rich, sand-poor sediment accumulation in both lakes during the Holocene, and a major hydrodynamic transition is inferred for approximately 6,500 years BP. Lake level rise, coincident with a change in climate, is discussed by Bezerra and Mozeto [26] as a likely forcing mechanism for this pattern in sedimentation, as highstand conditions would likely limit the impact of fluvial sedimentation on these basins. The authors also considered basin morphometrics, floodplain geometry, and linkages to Taquari River megafan lobe construction as other potentially related controls that may have influenced late Pleistocene lacustrine deposition. These results are largely in accord with geomorphological and paleoecological studies from the region (e.g., [58, 69]). Sediment data from the past 100 years do not show high variability in sand or organic carbon content but do contain evidence for a shift to faster sediment accumulation rates in the 1980s [26]. The relationship between this shift and the stage height of the Upper Paraguay River is briefly considered by Bezerra and Mozeto [26], and although the linkages between flooding strength and sedimentation rates in these lakes are not well expressed in the data, the authors suggest that peaks may be related to floods that follow severe droughts.

A study of the late Pleistocene and Holocene paleoclimate in the Pantanal region was produced by Whitney et al. [28], using insights derived from a radiocarbon-dated lake sediment core (expressed in calendar years). This study used overlapping Colinvaux-type hammer piston cores collected from near the center of Lagoa Gaíva (also known as Laguna La Gaiba) to generate a record of pollen and diatoms, which are classic biological indicators frequently used in paleolimnological studies to express evidence of hydroclimatic change. The authors posit that water levels in this basin are sensitive to regional precipitation. For Whitney et al., the goal of the study was to better understand the South American Summer Monsoon and moisture carried from the Amazon Basin by the South American Low Level Jet into the central lowlands of western Brazil and eastern Bolivia. A sediment record from Lagoa Gaíva, due to its position on the western margin of the Upper Paraguay River, provided a vehicle for this analysis, as evidence of change on the lake's catchment vegetation could be used to reconstruct temperature and precipitation (especially when paired with a probabilistic plant-climate computational model). This study also uses a network of lake-floor sediment samples from different water depths and sub-environments to provide a baseline of modern data in order to inform interpretation of the proxies. Deposition was assumed to be continuous throughout the approximately 45,000 cal year record, with largely invariant sedimentation rates over the Holocene (constrained by four radiocarbon dates) and more variable sedimentation over the late Pleistocene (fourteen radiocarbon dates), with a marked reduction in accumulation rates near the end of the glacial period

[28]. Intriguingly, many of the changes observed in the pollen stratigraphy are abrupt. Based on the absence of tree pollen, the presence of herb macrofossils, and abundant shallow water diatoms, the authors conclude that the late glacial period (45,000–19,500 cal year BP) in central South America was likely relatively dry and cool and Lagoa Gaíva was much smaller. Evidence of a major transition (most likely driven by warmer annual temperatures) that occurred at 19,500 cal year BP comes from the appearance of floodplain arboreal pollen in the core sediments; these data, coupled with macrofossils and diatom assemblages, suggest invasion of a favorable habitat along the southern lake margin while lake levels were low, rather than initiation of much stronger rainfall from 19,500–12,200 cal year BP. Tree pollen types, grass pollen abundance, faster sedimentation rates, and "deep water" diatom assemblages reveal a transition to higher rainfall and widespread floodplain inundation around Lagoa Gaíva after 12,200 cal year BP. Whitney et al. [28] explained that although water levels clearly rose at the Pleistocene-Holocene transition, a modest drought affected the region until approximately 3,000 cal year BP. In agreement with paleo-records from the Andes, the climate reconstruction provided by Whitney et al. [28] suggests that interglacial warming in the Southern Hemisphere tropics began several thousand years sooner than the same response in the Northern Hemisphere. Importantly, these authors confirmed early geomorphic hypotheses related to widespread aridity in the central South American lowlands during the Last Glacial Maximum, which contrasts the climate response of the high Andes at the same time (e.g., [70, 71]). This led Whitney and colleagues to interpret that glacial-interglacial cycles and associated boundary conditions in the North Atlantic are at least one important control on lowland environmental response during the late Pleistocene. Adding to the complexity, the Holocene pollen and diatom data presented by Whitney et al. [28] are consistent with a critical role for insolation varying at the beat of orbital precession on hydroclimate variability in the Pantanal over the past 12,200 cal year, which is coherent with precipitation proxy records from southeastern Brazil [10].

The study by McGlue et al. [30] was the first that explicitly set out to reconstruct late Quaternary Upper Paraguay River flood pulse dynamics using radiocarbon (expressed in calendar years)- and radioisotope (Pb^{210})-dated lake sediment cores. That study examined the strata of two large floodplain lakes in the central Pantanal: Lagoas Gaíva and Mandioré. The sites were selected based on earlier limnogeological studies by the same group of researchers who indicated that water levels in both basins were controlled by passage of the flood pulse [54]. As a consequence, the potential for stratigraphic sensitivity to climate or geomorphic change that might influence the hydrologic connection between the lakes and the river was high. Moreover, examination of two basins provided some opportunity for cross-validation of interpretations and, in concert with an assessment of other published Quaternary studies from the Pantanal, the chance to separate local versus regional paleoenvironmental signals. The sediment core from Lagoa Gaíva encompassed the Holocene, whereas the temporal record captured in the Lagoa Mandioré was much shorter but provided compelling evidence of an important depositional hiatus in the mid-late Holocene. Deposition was shown to be

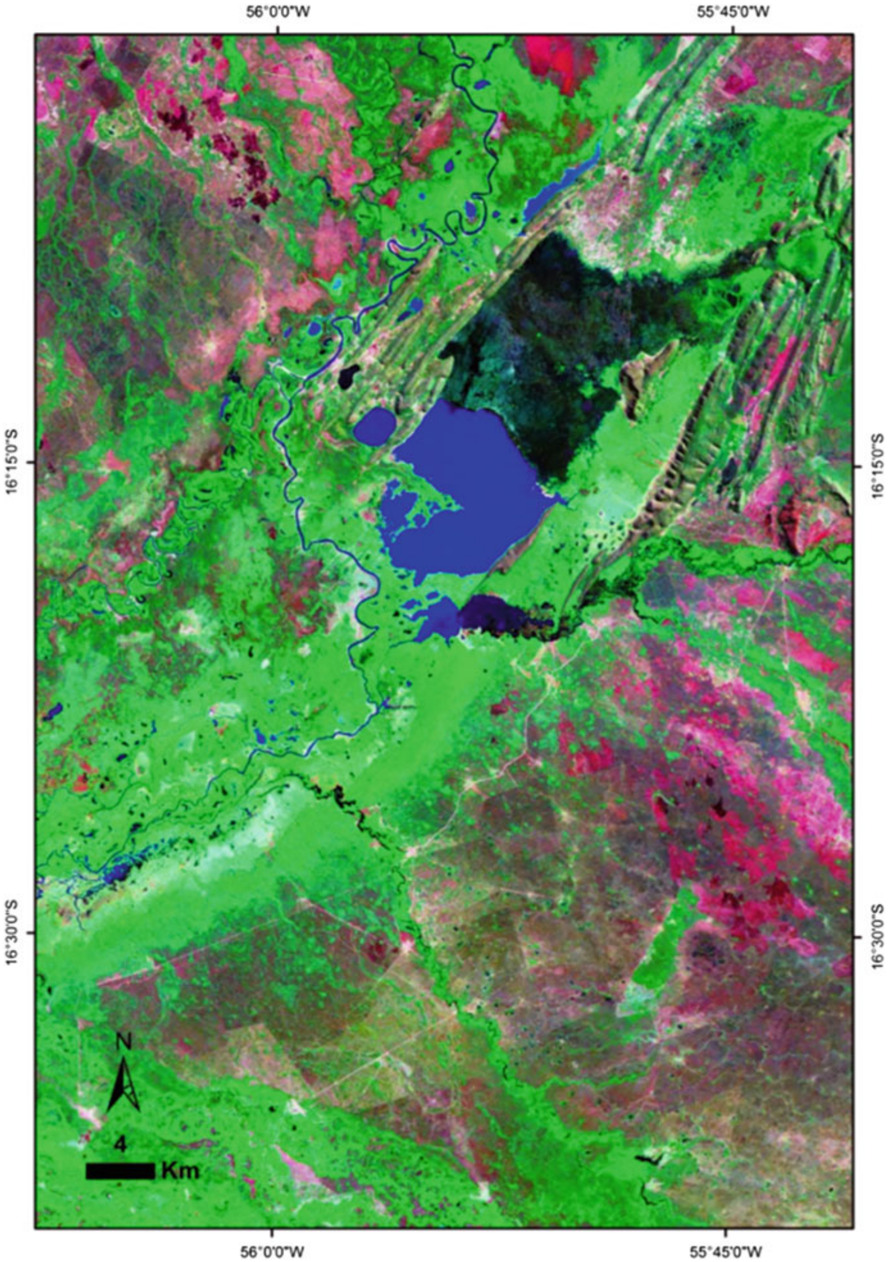

Fig. 8 NASA GeoCover Image Circa 2000 (band combination RGB: 742) of Baía do Chacororé and the Cuiabá River. Paleolimnological records from the northern Pantanal are particularly scarce, and Baía do Chacororé represents a potential target for future limnogeological analysis. As with most of the large floodplain lakes of the Pantanal, Baía do Chacororé is shallow (<3.5 m maximum depth; [87])

discontinuous over the Holocene in Lagoa Gaíva, but Pb^{210} data attest to continuous sedimentation over the past 100 years. The strata of Lagoa Gaíva were the primary focus, and the authors adopted a multi-indicator approach that centered on physical sedimentology (detrital particle size), organic geochemistry (total organic carbon [TOC], C/N, $\delta^{13}C_{OM}$), biogenic silica, and microfossils (sponge spicules and fish remains). The actualistic facies data of McGlue et al. [54] served as valuable constraints on interpretation of these indicators by providing a snapshot of lake sediment physical properties and biogeochemistry influenced by a strong seasonal flood pulse. The study results showed that inception of depositional patterns similar to modern did not occur until the late Holocene (approximately 2,600 cal year BP, with modern depositional conditions achieved around the Little Ice Age), which suggests that a fully realized Upper Paraguay River flood pulse triggered by austral summer precipitation is a transient feature in the Pantanal. Sediment composition at Lagoa Gaíva during the early Holocene, by contrast, was much more consistent with deposition in a very shallow lake with less direct influence of riverine flooding (Fig. 9). One of the most important findings of the study was the identification of a stratigraphically subtle hiatus from approximately 5,300–2,600 cal year BP. This was accomplished using a high density of radiocarbon dates, coupled with the response of multiple indicators that were consistent with inundation of a previously desiccated lake floor (e.g., a spike in productivity, signaled in biogenic silica and fish fossil abundance, perhaps associated with mixing and nutrient release [72]). The timing of this hiatus is consistent with a severe drought that impacted the Upper Parana watershed [8, 67] and correlates in time with terrestrial carbonates from Bodoquena and Aquidaban (southern Pantanal) that record reduced precipitation [24, 25]. Most importantly, the sediment core from Lagoa Mandioré clearly showed that the southern end of that basin was completely desiccated at 4,700 cal year

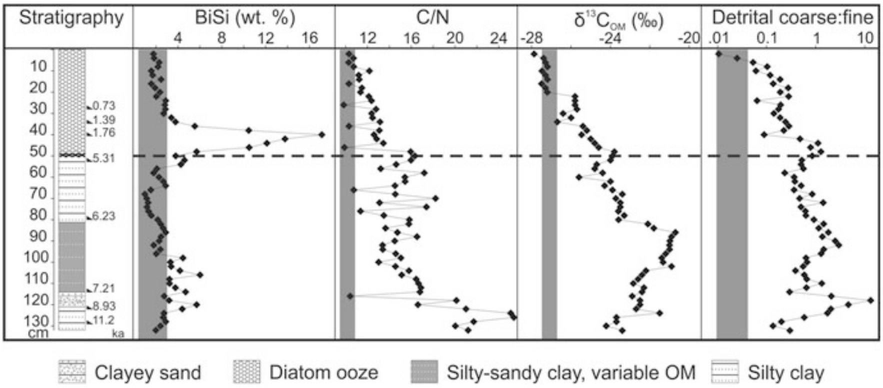

Fig. 9 Lagoa Gaíva sediment core stratigraphy, biogenic silica (BiSi), atomic carbon to nitrogen ratio (C/N), carbon isotope ($\delta^{13}C_{OM}$), and detrital grain size, expressed as a ratio of sand to silt plus clay (modified from [30]). The sample interval is 2 cm. Vertical shading represents values from modern sediment samples measured near the core site. The dashed horizontal line marks the position of a subtle hiatus

BP. The Lagoa Gaíva TOC record bears some similarity to the core data from Lagoa Castelo presented in Bezerra and Mozeto [26] around 6,500 cal year BP. As previously mentioned, Bezerra and Mozeto [26] argue for a "climatic optimum" in the middle Holocene on the basis of higher TOC values and diminished sand deposition, but the interpretations of McGlue et al. [30] suggest that changes in climate within the Pantanal are difficult to fully appreciate using paleo-indicators with limited sensitivity to the full range of environmental change that might influence a shallow floodplain lake. Nonetheless, there is evidence for more frequent floods from 6,200 to 5,300 cal year BP, which is broadly consistent with a more vigorous fluvial system inferred for the region by Assine and Soares [14] around this time.

Metcalfe et al. [31] have produced the most recent lake sediment core-derived analysis of late Pleistocene-Holocene hydroclimatic conditions for the Pantanal. This study again focused on the strata of Lagoa Gaíva and leveraged the sediment core and radiocarbon chronology initially described by Whitney et al. [28]. The authors present a wide variety of paleoenvironmental indicators (X-ray fluorescence-derived inorganic sediment chemistry, particle size, magnetic susceptibility, loss on ignition (LOI) insights on organic and inorganic carbon content, C/N, and carbon isotope data), but the main focus of the discussion is on diatom assemblages. The authors suggest that the pollen record presented by Whitney et al. [28] may be less sensitive to hydrologic change than the diatoms, in part because of the unique and unstable habitat of floodplain forest. In other words, a lake level threshold must be crossed in order to impact the shallow floodplain environment south of the lake, and as a result, the pollen data may not faithfully record the full range of possible hydroclimatic variability in the late Quaternary. Interpretation of diatom paleoecology also benefited from constraints provided by modern sediment samples (presented in [28]), whereas the other indicators presented in this study do not. Ultimately, Metcalfe et al. [31] suggest a complex response for Lagoa Gaíva to climate over the past 25,000 cal year BP, mostly in accord with the findings of Whitney et al. [28] and partially in agreement with the findings of McGlue et al. [30]. The Last Glacial Maximum through the late glacial interval (24,500–12,200 year BP) was interpreted as a relatively dry environment, marked by infrequent floods. Importantly, an abrupt transition occurs in the diatom stratigraphy from 12,200 to 11,800 year BP (encompassed within the latter part of the Younger Dryas), which suggested that Lagoa Gaíva deepened and freshened due to a higher frequency of floods, which may in turn have produced some erosion within the basin. This response is similar to some lake records on the Altiplano [70]. At approximately 10,000 cal year BP, perhaps the most distinct transition is registered in the diatom stratigraphy, with a dominance of the planktonic *Aulacoseira ambigua* and a marked decline in species of the genus *Staurosira* [31]. Based on small peaks in benthic and aerophilous taxa, in concert with indications from LOI regarding the presence of carbonate, the authors suggest that the period from 9,000 to 5,000 cal year BP was one of highly variable hydrology at Lagoa Gaíva, with a distinct and perhaps lengthy dry season. Intriguingly, Metcalfe et al. [31] found no evidence of discontinuous sedimentation from 5,000 to 2,100 cal year BP, in contrast to the conclusions of McGlue et al. [30]. Rather, the diatoms across this interval indicated persistent "deep water" conditions. After 2,100 cal year BP, diatoms and other indicators were interpreted by Metcalfe et al. [31] to signal a stable lake system perhaps influenced by increasingly wet conditions. In terms of climate-forcing mechanisms, Metcalfe et al. [31] noted the incoherent response of Lagoa Gaíva to insolation over the late Pleistocene and Holocene and suggested the potential influence of Northern Hemisphere ice volume, considering the evidence of hydrologic variability in the later part of the Younger Dryas chronozone. Metcalfe et al. [31] suggested that climate modeling would help elucidate the major controls on the lowland environmental response, which might be tied to ITCZ position and the regional influence of convective rainfall.

Environmental variability can be natural or induced by humans, and under certain circumstances lake cores may provide archives of geomorphic processes, such as those associated with changes in land cover and development. Bonachea et al. [73] used Pb^{210}-dated sediment cores from Lagoas Jacadigo, Negra, and Castelo to probe anthropogenic and climatic influences on sedimentation rates over the past approximately 100 years. Those authors found a marked increase in sedimentation rates following the 1970s, which was attributed to higher rainfall and greater soya cultivation. The vast majority of land cover changes related to agriculture took place on the plateaus surrounding the basin, where the deforestation rate was ~59% until 2008 [74]. The marginal plateaus are highly sensitive to erosion, due the sandy soils and steep slopes that enhance anthropogenic impacts on the sediment budget and hydrologic regime. Bonachea et al. [73] suggested government policies enacted in the 1970s designed to expand agriculture and stimulate livestock production had an influence on soil erosion in the northern Pantanal through removal of natural vegetation. Human activity evidently blossomed in the Pantanal during this same period, and modifications of the land with population growth may have allowed for greater erosion with the increase in rainfall. Godoy et al. [75] also found an increase in sedimentation rates in the 1970s and 1980s in cores collected from floodplain lakes on the Taquari River megafan. Godoy et al. [75] suggested that as the Pantanal emerged from a relative dry period between 1958 and 1972, denudation of native vegetation associated with agriculture, coupled with higher annual rainfall, led to an intensification of erosion and therefore faster siltation rates on the floodplain. The flux of contaminants such as mercury (Hg) to lake basins appears to have been captured in lake sediment archives for some areas of the Pantanal [75]; higher sediment mass accumulation rates after 1970, however, may influence the expression of contaminant variability. Direct runoff of leachate associated with artisanal gold extraction (in open cast mines or small pits [76]) and atmospheric deposition are two potential pathways for mercury contamination in the Pantanal's lakes [77]. In the Poconé region (northern Pantanal), Lacerda et al. [77] discovered high relative Hg concentrations in the upper 3–7 cm of sediment cores recovered from shallow floodplain lakes and attributed this to atmospheric delivery from far afield gold mines. The results of Godoy et al. [75] suggested that Hg concentrations on the Taquari River megafan were essentially invariant over the ^{210}Pb-dated interval, but the flux of Hg has increased due to higher sediment mass accumulation rates associated with greater erosion after 1970.

4 Knowledge Gaps and New Questions for Lakes and Lake Cores from the Pantanal

It is clear that during the Last Glacial Maximum and deglacial transition, virtually all available paleo-records from the Pantanal indicate arid conditions. The start of the Holocene witnessed the emergence of the wetlands from persistent drought into an interval of more variable rainfall that was still very unlike the modern environment, which is characterized by austral summer rainfall and pronounced Upper Paraguay River flooding. This modern-like condition appears to have initiated after 2,600 cal year BP. Interpretations of the middle Holocene environment are far more equivocal, with some records indicating drought and others indicating a wet climate.

This synthesis of environmental change inferred from lake sediment cores provokes a number of questions to be addressed by future studies. The Pantanal is an important yet underappreciated tropical wetland system, and more research is needed to expand our current level of understanding on how the wetlands will respond to global change. Lake studies will likely play a major role, but more limnogeological research is required in order to constrain the temporal resolution and "hydroclimate filter" associated with each lake. Science-based management and conservation planning will undoubtedly be critical in order to sustain the Pantanal and protect its freshwater resources and biodiversity in the future.

4.1 Was the Pantanal Impacted by Mid-Late Holocene Drought?

Sustained drought can have severe ecological consequences in the Pantanal, because so much of the wetlands' form and function rely on arrival of the annual Upper Paraguay River flood pulse. Available paleolimnological records from Lagoa Gaíva [28, 30, 31] conflict regarding the water levels in the mid-Holocene environment, which may have resulted from (1) differences in coring location (which seems unlikely, considering the basin's bathymetry), (2) coring artifacts, (3) density of radiocarbon age dates, or (4) sensitivity of indicator materials. Future research should revisit the Whitney et al. [28] coring site, which is suggested to be fully continuous. New coring methods (e.g., Uwitec percussion piston coring [78]) and seismic profiling could help to establish whether or not the lake persisted through intervals of a much diminished SASM. If water level in Lagoa Gaíva is indeed a useful indicator of effective precipitation and flood pulse dynamics in the wetlands, this basin may hold the most valuable stratigraphic record available in the Pantanal. The total stratal thickness contained within this lake is still unknown. As a consequence, the amount of geologic time archived in the strata is likewise a mystery, although the Whitney et al. [28] dataset makes clear that dramatic changes in sedimentation rate exist in the basin. Longer records that extend to the penultimate glaciation or even the Eemian interglacial would be of tremendous value for clarifying the complex response of the basin to Northern Hemisphere ice volume and low-latitude insolation. A long sediment record from Lagoa Gaíva may warrant analysis using biomarkers, which could provide insights on amounts of precipitation, vegetation change, and methane cycling (e.g., [79, 80]).

4.2 What Types of Paleoenvironmental and Sedimentological Information Are Archived in Some of the Less Studied Lakes of the Pantanal?

It remains unclear if Lagoa Gaíva is the most complete and sensitive lacustrine stratal archive available in the Pantanal. Several other large and comparably deep lakes (e.g., Lagoa Uberaba, Baía Chacororé; Figs. 6 and 8) that lack direct connection to the Upper Paraguay River are attractive potential targets for future limnogeological analysis. How sediment delivery and the “hydroclimate filter” operate in these lakes is less certain, and these characteristics must be analyzed first in order to make the most of cores recovered from the basins. Do these lakes record flooding as discrete event beds or lamination bundles? What is the temporal resolution of the strata? Answers to these important questions are unknown. Bioturbation is seemingly high in these basins, because of shallow maximum depths and oxygenated lake floors – massive bedding in strata from the large floodplain lakes attest to this. These boundary conditions notionally limit paleolimnological records from most of Pantanal’s lakes to multi-centennial resolution. Nonetheless, much can be learned from such records, especially when a multi-indicator approach is adopted. It remains to be seen if the influence of higher-frequency climate modes, like the El Niño-Southern Oscillation (ENSO) or the North Atlantic Oscillation, is recorded in any of the Pantanal’s lakes (e.g., [81]). Adequately addressing the knowledge gap surrounding annual- to decadal-scale climate variability in the wetlands will likely require other proxy methods. Modeling, perhaps in tandem with tree ring-stable isotope studies, provides potentially fertile opportunities to explore the Pantanal’s ecohydrological responses to ENSO.

Thousands of ovate ponds, both saline and dilute, dot the landscape of the Nhecolândia (Fig. 3). Geological evidence presented by Soares et al. [82] suggests that these lakes formed by floodplain deflation during an arid interval in the late Quaternary. The strata of these lakes are an untapped resource for expanding our understanding of environmental change in the southern Pantanal. Preliminary results from lake sediment cores collected from Nhecolândia's ponds indicate the presence of a sharp lithostratigraphic shift from fine sand and silt to organic-rich mud (R. Guerreiro 2014, personal communication); future radiocarbon dating will help to clarify the chronological and environmental context for this transition. Floodplain trenching results presented in Furian et al. [60] reveal a similar transition, which suggests this change may be widespread across Nhecolândia. Sediment cores from Nhecolândia's ponds also afford the opportunity to test recently developed facies models, to include the potential for lacustrine carbonate accumulation on dominantly siliciclastic floodplains [83].

4.3 Were Large Lakes Present in the Early Basin History of the Pantanal?

Diamond wireline coring is increasingly being utilized on the continents to recover long, well-preserved sediment cores for scientific study [84]. The time is opportune to consider what value scientific drilling in the Pantanal could provide. Drilling operations in the Pantanal would surely present logistical challenges, but a number of important knowledge gaps could be addressed with an offset transect of drill cores designed to sample the approximately 500 m of sediment in the basin. Dating techniques from radiocarbon, OSL, paleomagnetics, and cosmogenic nuclides could be leveraged to date these cores, which would most likely consist of fluvial and floodplain strata, perhaps with intervals of lacustrine deposits. If large lakes were present throughout the basin's history, their strata could be continuously sampled and analyzed for fossil content, geochemistry, and sedimentology. Scientific drill cores offer the opportunity to constrain the age of the basin and thus provide much needed context for studies focused on the geodynamic evolution of the Andean foreland basin and the paleogeography of central South America. Scientific drill cores also afford the opportunity to track the history of floral biodiversity through pollen studies and the evolution of freshwater fauna via microfossil analysis. A number of basic questions related to the sedimentological and chronological development of distributary fluvial systems in tropics could also be addressed with scientific drill cores from the Pantanal.

4.4 Lakes as Sentinels of Global Change

Because climate change is widely regarded as a severe threat to both aquatic ecosystems and the human populations that rely upon them, the value of instrumented lakes to provide a geographically distributed signal of global change is clear [85, 86]. As regional "sinks" on the landscape, the water and sediment columns of permanent lakes register climate variability in ways that can be recorded. Routine data logging of lake water physical, chemical, and biological properties to track "real-time" responses to climate changes currently under way would make for an evocative long-term experiment. This type of monitoring might focus on automated logger collection of water temperature, water level, transparency, and dissolved organic carbon data. These physical and chemical indicators, although complex, provide ground truth that can explain variability in solar radiation, air temperature, and precipitation patterns. Such data could be critical for sustainable management and development of the Pantanal in the coming decades. A number of sites elsewhere in Brazil are already participating in the Global Lake Ecological Observatory Network (www.gleon.org). The community of Pantanal scientists should consider exploring the possibilities for this type of field experiment applied to the large floodplain lakes.

5 Conclusions

Persistent droughts are one of the most intimate ways humankind can experience climate change. For most areas of the developing world, droughts have particularly devastating consequences, because so much of population lives off the land. This is particularly true of the lowland tropics, which are currently experiencing explosive population growth but still lack the infrastructure to adequately address the impacts of anthropogenic global change. Unfortunately, we still do not have a complete picture of how numerous lowlands tropical regions will respond to greater variability in the water cycle, which many models predict will accompany the "new normal" of an atmosphere with higher concentrations of greenhouse gases. The Pantanal is no different, but the sense of urgency for new scientific discoveries that can explain the sensitivity of the basin to climate is growing, due to valuable ecosystem services provided by the wetlands.

Lake sediment core studies have led to many insights regarding the response of the Pantanal to late Quaternary climate change, but several key questions are still unanswered. Severe widespread drought appears to be the response of the Pantanal to high-latitude glaciation, perhaps due to linkages among effective precipitation, ITCZ position, and North Atlantic sea surface temperatures. Likewise, drought appears to characterize the wetlands during low levels of Southern Hemisphere insolation. This complex response warrants further investigation using new proxies from longer and perhaps more complete lacustrine stratigraphic records. Because of the strong coupling between most lakes and the Upper Paraguay River flood pulse, paleo-records that can constrain the influence of fluvial landscape evolution on patterns of lacustrine sedimentation will likely be most successful. Other geological archives must be mined to fully assess the influence of higher-frequency climate modes, such as those originating in the Pacific Ocean (e.g., ENSO). Insights from paleo-records like these can play a vital role in shaping strategic planning, both for mitigation of environmental degradation and to inform sustainable development.

Acknowledgments We thank the many colleagues, students, family members, and friends who assisted and supported our field and laboratory research in the Pantanal from 2006 to 2014. The authors thank the Mato Grosso do Sul Research Foundation - FUNDECT (23/200.628/2012), the National Council of Technological and Scientific Development – CNPq (447402/2014-5) and Federal University of Mato Grosso do Sul for financial support to our research in the Pantanal Basin. The National Council of Technological and Scientific Development – CNPq is acknowledged for grants to AS (312386/2014-1). We thank the Laboratório de Geoprocessamento at CPAN for assistance with figures. Discussions with R. Guerreiro, E. Lo, and C. Gans improved the quality and direction of the manuscript, and reviews by the editors are gratefully acknowledged.

References

1. Hamilton SK (1999) Potential effects of a major navigation project (Paraguay-Parana Hidrovia) on inundation in the Pantanal floodplains. Regul Rivers Res Manag 15:289–299
2. Pott A, Pott VJ (2004) Features and conservation of the Brazilian Pantanal wetland. Wetl Ecol Manag 12(6):547–552
3. Junk WJ, Nunes Da Cunha K, Wantzen KM, Petermann P, Strussmann C, Marques MI, Adis J (2006) Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil. Aquat Sci 68 (3):278–309
4. Bastviken D, Santoro AL, Marotta H, Pinho LQ, Calheiros DF, Crill P, Enrich-Prast A (2010) Methane emissions from Pantanal, South America, during the low water season: toward more comprehensive sampling. Environ Sci Technol 44:5450–5455
5. Bergier I, Krusche A, Guérin F (2015) Alkaline lake dynamics in the Nhecolândia landscape. Hdb Env Chem. doi:10.1007/698_2014_327
6. Bergier I, Silva APS, Monteiro H, Guérin F, Macedo HA, Silva A, Krusche A, Sawakuchi HO, Bastviken D (2015) Methane and carbon dioxide dynamics in the paraguay river floodplain (pantanal) in episodic anoxia events. Hdb Env Chem. doi:10.1007/698_2014_353
7. Bergier I (2013) Effects of highland land-use over lowlands of the Brazilian Pantanal. Sci Total Environ 463:1060–1066
8. Stevaux JC (2000) Climatic events during the Late Pleistocene and Holocene in the Upper Paraná River: correlation with NE Argentina and South-Central Brazil. Quat Int 72:73–85
9. Cruz FW, Burns SJ, Karmann I, Sharp WD, Vuille M, Cardoso AO, Silva Dias PL, Ferrari JA, Viana O (2005) Insolation driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. Nature 434:63–66
10. Cruz FW, Vuille M, Burns SJ, Wang X, Cheng H, Werner M, Edwards RL, Karmann I, Auler AS, Nguyen H (2009) Orbitally driven east–west antiphasing of South American precipitation. Nat Geosci 2(3):210–214
11. Arini J (2009) Nos labirintos da bioparanoia. Época 68–70
12. Braun EHG (1977) Cone aluvial do Taquari, unidade geomórfica marcante na planície quaternária do Pantanal. Rev Bras Geogr 39(4):164–180
13. Tricart J (1982) El Pantanal: Un ejemplo del impacto de la geomorfologia sobre el medio ambiente. Geografia 7(13–14):37–50
14. Assine ML, Soares PC (2004) Quaternary of the Pantanal, west-central Brazil. Quat Int 114:23–34
15. Assine ML, Silva A (2009) Contrasting fluvial styles of the Paraguay River in the northwestern border of the Pantanal wetland, Brazil. Geomorphology 113:189–199
16. Buehler HA, Weissmann GS, Scuderi LA, Hartley AJ (2011) Spatial and temporal evolution of an avulsion on the Taquari River distributive fluvial system from satellite image analysis. J Sediment Res 81(8):630–640
17. Makaske B, Maathuis BH, Padovani CR, Stolker C, Mosselman E, Jongman RH (2012) Upstream and downstream controls of recent avulsions on the Taquari megafan, Pantanal, south-western Brazil. Earth Surf Process Landf 37(12):1313–1326

18. Zani H, Assine ML, McGlue MM (2012) Revealing geoforms in Pantanal wetland (Brazil) with remote sensing: a method to enhance SRTM-DEM for megafan environments. Geomorphology 161–162:82–92
19. Klammer G (1982) Die Paleowueste des Pantanal von Mato Grosso und die pleistozaene Klimageschichte der brasilianischen Randtropen. Zeitschrift Geomorphol NF 26:393–416
20. Hamilton SK, Sippel SJ, Melack JM (2002) Comparison of inundation patterns among major South American floodplains. J Geophys Res 107(D20):8038
21. Assine ML, Corradini FA, Pupim FDN, McGlue MM (2014) Channel arrangements and depositional styles in the São Lourenço fluvial megafan, Brazilian Pantanal wetland. Sediment Geol 301:172–184
22. Kuerten S, Parolin M, Assine ML, McGlue MM (2013) Sponge spicules indicate Holocene environmental changes on the Nabileque River floodplain, southern Pantanal, Brazil. J Paleolimnol 49(2):171–183
23. Victoria RL, Fernandes F, Martinelli LA, Piccolo MC, Camargo PB, Trumbore S (1995) Past vegetation changes in the Brazilian Pantanal-Grassy Savanna ecotone by using carbon isotopes in the soil organic matter. Glob Chang Biol 1:65–71
24. Bertaux J, Sondag F, Santos R, Soubies F, Casse C, Plagnes V, Le Cornec F, Seidel F (2002) Palaeoclimatic record of speleothems in a tropical region: study of laminated sequences from a Holocene stalagmite in Central-West Brazil. Quat Int 89:3–16
25. Boggiani PC, Coimbra AM, Gesicki ALD, Sial AN, Ferreira VP, Ribeiro FB, Flexor JM (2002) Tufas Calcárias da Serra da Bodoquena, MS: cachoeiras petrificadas ao longo dos rios. In: Schobbenhaus C, Campos DA, Queiroz ET, Winge M, Berbert-Born M (eds) Sítios Geológicos e Paleontológicos do Brasil. Brasília-DF, DNPM, pp 249–259
26. Bezerra MAO, Mozeto AA (2008) Deposição de carbono orgânico na planície de inundação do Rio Paraguai durante o Holoceno médio. Oecologia Brasiliensis 12(1):155–171
27. Sallun-Filho W, Karmann I, Boggiani PC, Petri S, Souza Cristalli P, Utida GA (2009) Deposição de Tufas Quaternárias no Estado de Mato Grosso do Sul: Proposta de Definição da Formação Serra da Bodoquena. Revista do Instituto de Geociências USP 9:47–60
28. Whitney BS, Mayle FE, Punyasena SW, Fitzpatrick KA, Burn MJ, Guillen R, Chavez E, Mann D, Pennington RT, Metcalfe SE (2011) A 45 kyr palaeoclimate record from the lowland interior of tropical South America. Palaeogeogr Palaeoclimatol Palaeoecol 307:177–192
29. Whitney BS, Mayle FE (2012) Pediastrum species as potential indicators of lake-level change in tropical South America. J Paleolimnol 47:601–615
30. McGlue MM, Silva A, Zani H, Corradini FA, Parolin M, Abel EJ, Cohen AS, Assine ML, Ellis GS, Trees MA, Kuerten S, Gradella FS, Rasbold GG (2012) Lacustrine records of Holocene flood pulse dynamics in the Upper Paraguay River watershed (Pantanal wetlands, Brazil). Quat Res 78(2):285–294
31. Metcalfe SE, Whitney BS, Fitzpatrick KA, Mayle FE, Loader NJ, Street-Perrott FA, Mann DG (2014) Hydrology and climatology at Laguna La Gaiba, lowland Bolivia: complex responses to climatic forcings over the last 25 000 years. J Quat Sci 29(3):289–300
32. Ledru MP, Bertaux J, Sifeddine A, Suguio K (1998) Absence of last glacial maximum records in lowland tropical forests. Quat Res 49:233–237
33. Ruddiman WF (2001) Earth's Climate: past and future. W. H. Freeman, New York, 465 pp
34. Cohen AS (2003) Paleolimnology: the history and evolution of lake systems. Oxford University Press, Oxford
35. Por FD (1995) The Pantanal of Mato Grosso (Brazil). Kluwer, Dordrecht
36. Costa MF (2007) De Xarayes ao Pantanal: a cartografia de um mito geográfico. Revista do Instituto de Estudos Brasileiros 45:21–36
37. Weyler G (1962) Relatório final dos Poços perfurados no Pantanal Matogrossense. Projeto Pantanal. Distrito de Expl. Sedimentar do Paraná, Petrobrás, Ponta Grossa-PR, 27 pp
38. Catto AJ (1975) Análise geológica e geofísica da Bacia do Pantanal Matogrossense. Rio de Janeiro, Petrobrás (DEPEX/SEDOT n° 5296)
39. Heckman CW (1998) The Pantanal of Poconé. Kluwer, Den Haag

40. Swarts FA (ed) (2000) The Pantanal: understanding and preserving the world's largest wetland. Paragon House, St. Paul
41. Horton BK, DeCelles PG (1997) The modern foreland basin system adjacent to the central Andes. Geology 25:895–898
42. Ussami N, Shiraiwa S, Dominguez JML (1999) Basement reactivation in a sub-Andean foreland flexural bulge: the Pantanal wetland, SW Brazil. Tectonics 18(1):25–39
43. Assine ML (2003) Sedimentação na Bacia do Pantanal Mato-Grossense. Centro-Oeste do Brasil, Rio Claro
44. Assumpção M, Schimmel M, Escalante C, Barbosa JR, Rocha M, Barros LV (2004) Intraplate seismicity in SE Brazil: stress concentration in lithospheric thin spots. Geophys J Int 159:390–399
45. Alvarenga CJS, Boggiani PC, Babinski M, Dardenne MA, Figueiredo MF, Dantas EL, Uhlein A, Santos RV, Sial AN, Trompette R (2011) Glacially influenced sedimentation of the Puga Formation, Cuiabá Group and Jacadigo Group, and associated carbonates of the Araras and Corumbá groups, Paraguay Belt, Brazil. Geological Society, London, Memoirs 36(1):487–497
46. Chase CG, Sussman AJ, Coblentz DD (2009) Curved Andes: Geoid, forebulge, and flexure. Lithosphere 1:358–363
47. Cohen AS, McGlue MM, Ellis GS, Zani H, Swarzenski PW, Assine ML, Silva A (2015) Lake formation, characteristics and evolution in retroarc deposystems: a synthesis of the modern Andean orogen and its associated basins. In: DeCelles PG, Ducea MN, Carrapa B, Kapp P (eds) Geodynamics of a cordilleran orogenic system: the central Andes of Argentina and Northern Chile, Geological Society of America Memoir 212. doi:10.1130/2015.1212(16)
48. Zhou J, Lau KM (1998) Does a monsoon climate exist over South America? J Clim 11:1020–1040
49. Prance GT, Schaller GB (1982) Preliminary study of some vegetation types of the Pantanal, Mato Grosso, Brazil. Brittonia 34:228–251
50. Pinder L, Rosso S (1998) Classification and ordination of plant formations in the Pantanal of Brazil. Plant Ecol 136:151–165
51. Pott A, Silva JSV (2015) Terrestrial and aquatic vegetation diversity of the Pantanal wetland. Hdb Env Chem. doi:10.1007/698_2014_352
52. Hamilton SK, Sippel SJ, Calheiros DF, Melack JM (1997) An anoxic event and other biogeochemical effects of the Pantanal wetland on the Paraguay River. Limnol Oceanogr 42:257–272
53. Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. Can Spec Publ Fish Aquat Sci 106:110–127
54. McGlue MM, Silva A, Corradini FA, Zani H, Trees M, Ellis G, Parolin M, Swarzenski PW, Cohen AS, Assine ML (2011) Limnogeology in Brazil's "Forgotten Wilderness:" a synthesis from the floodplain lakes of the Pantanal. J Paleolimnol 46(2):273–289
55. Costa MP, Telmer KH (2006) Utilizing SAR imagery and aquatic vegetation to map fresh and brackish lakes in the Brazilian Pantanal wetland. Remote Sens Environ 105(3):204–213
56. Costa M, Telmer KH, Evans TL, Almeida TI, Diakun MT (2015) The lakes of the Pantanal: inventory, distribution, geochemistry, and surrounding landscape. Wetl Ecol Manag 2015:1–21
57. Boggiani PC, Coimbra AM (1995) Quaternary limestone of the Pantanal area, Brazil. An Acad Bras Cienc 3(67):343–349
58. Ab'Saber AN (1988) O Pantanal Mato-Grossense ea teoria dos refúgios. Rev Bras Geogr 50 (2):9–57
59. Barbiéro L, Queiroz Neto JP, Ciornei G, Sakamoto AY, Capellari B, Fernandes E, Valles V (2002) Geochemistry of water and ground water in the Nhecolândia, Pantanal of Mato Grosso, Brazil: variability and associated processes. Wetlands 22(3):528–540
60. Furian S, Martins ERC, Parizotto TM, Rezende-Filho AT, Victoria RL, Barbiero L (2013) Chemical diversity and spatial variability in myriad lakes in Nhecolândia in the Pantanal wetlands of Brazil. Limnol Oceanogr 58(6):2249–2261

61. Fávaro DIT, Damatto SR, Silva PSC, Riga AA, Sakamoto AY, Mazzilli BP (2006) Chemical characterization and 210 Pb dating in wetland sediments from the Nhecolândia Pantanal Pond, Brazil. J Radioanal Nucl Chem 269(3):719–726
62. Wetzel RG (2001) Limnology: lake and river ecosystems. Academic, San Diego, 1006 pp
63. Kuerten S, Assine ML (2011) O rio Paraguai no megaleque do Nabileque, sudoeste do Pantanal Mato-Grossense, MS. Rev Bras Geosci 41(4):642–653
64. Volkmer-Ribeiro C, Turcq B (1996) SEM analysis of siliceous spicules of a freshwater sponge indicate paleoenvironmental changes. Acta Microsc 5:186–187
65. Volkmer-Ribeiro C, Motta JFM, Callegaro VLM (1998) Taxonomy and distribution of Brazilian spongillites. Sponge sciences, multidisciplinary perspectives. Springer-Verlag, Tokyo, pp 271–278
66. Parolin M, Volkmer-Ribeiro C, Stevaux JC (2008) Use of spongofacies as a proxy for river-lake paleohydrology in Quaternary deposits of central-western Brazil. Revista Brasileira de Paleontologia 11(3):187–198
67. Latrubesse EM, Stevaux JC, Cremon EH, May J-H, Tatumi SH, Hurtado MA, Bezada M, Argollo JB (2012) Late Quaternary megafans, fans and fluvio-aeolian interactions in the Bolivian Chaco, Tropical South America. Palaeogeogr Palaeoclimatol Palaeoecol 356:75–88
68. Marchant R, Hooghiemstra H (2004) Rapid environmental change in African and South American tropics around 4000 years before present: a review. Earth Sci Rev 66:217–260
69. Parolin M, Volkmer-Ribeiro C, Stevaux JC (2007) Sponge spicules in peaty sediments as paleoenvironmental indicators of the Holocene in the upper Parana River, Brazil. Revista Brasileira de Paleontologia 10:17–26
70. Baker PA, Seltzer GO, Fritz SC, Dunbar RB, Grove MJ, Tapia PM, Cross SL, Rowe HD, Broda JP (2001) The history of South American tropical precipitation for the past 25,000 years. Science 291:640–643
71. Fritz SC, Baker PA, Seltzer GO, Ballantyne A, Tapia P, Cheng H, Edwards RL (2007) Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. Quat Res 68:410–420
72. Talbot MR, Jensen NB, Lærdal T, Filippi ML (2006) Geochemical responses to a major transgression in giant African lakes. J Paleolimnol 35(3):467–489
73. Bonachea J, Bruschi V, Hurtado MA, Forte LM, da Silva M, Etcheverry R, Cavallotto JL, Dantas M, Pejon O, Zuquette LV, Bezerra MA, Remondo J, Rivas V, Gomez-Arozamena J, Fernandez G, Cendrero A (2010) Natural- and human-forcing in recent geomorphic change: case studies in the Rio de la Plata basin. Sci Total Environ 408:2674–2695
74. Silva JSV, Abdon M, Silva SMA, Moraes JA (2011) Evolution of deforestation in the Brazilian Pantanal and surroundings in the timeframe 1976–2008. Geografia 36:35–55
75. Godoy JM, Padovani CR, Guimarães JR, Pereira JC, Vieira LM, Carvalho ZL, Galdino S (2002) Evaluation of the siltation of River Taquari, Pantanal, Brazil, through 210Pb geochronology of floodplain lake sediments. J Braz Chem Soc 13(1):71–77
76. Hylander LD, Meili M, Oliveira LJ, Castro E, Silva J, Guimarães RD, Araujo DM, Neves RP, Stachiw R, Barros AJP, Silva GD (2000) Relationship of mercury with aluminum, iron and manganese oxy-hydroxides in sediments from the Alto Pantanal, Brazil. Sci Total Environ 260:97–107
77. Lacerda LD, Salomons W, Pfeiffer WC, Bastos WR (1991) Mercury distribution in sediment profiles from lakes of the high Pantanal, Mato Grosso State, Brazil. Biogeochemistry 14 (2):91–97
78. Schultze E, Niederreiter R (1990) Palaolimnologische Untersuchungen an einem Bohrkern aus dem Profundal des Mondsees (Oberosterreich). Linzer Biol Beitr 22:231–235
79. Zheng Y, Zhou W, Meyers PA, Xie S (2007) Lipid biomarkers in the Zoigê-Hongyuan peat deposit: Indicators of Holocene climate changes in West China. Org Geochem 38(11):1927–1940
80. Zhou W, Zheng Y, Meyers PA, Jull AJ, Xie S (2010) Postglacial climate-change record in biomarker lipid compositions of the Hani peat sequence, Northeastern China. Earth Planet Sci Lett 294(1):37–46

81. Bergier, I., 2010. River level sensitivity to SOI and NAO in Pantanal and Amazonia. 30. Simpósio de Geotecnologias do Pantanal
82. Soares AP, Soares PC, Assine ML (2003) Areiais e lagoas do Pantanal, Brasil: herança paleoclimática? Braz J Geol 33(2):211–224
83. Gierlowski-Kordesch E, Finkelstein DB, Holland JJT, Kallini KD (2013) Carbonate lake deposits associated with distal siliciclastic perennial-river systems. J Sediment Res 83 (12):1114–1129
84. Soreghan GS, Cohen AS (2013) Scientific drilling and the evolution of the earth system: climate, biota, biogeochemistry and extreme systems. Sci Drill 16:63–72
85. Adrian R, O'Reilly CM, Zagarese H, Baines SB, Hessen DO, Keller W, Livingstone DM, Winder M (2009) Lakes as sentinels of climate change. Limnol Oceanogr 54(6):2283
86. Williamson CE, Saros JE, Vincent WF, Smol JP (2009) Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnol Oceanogr 54(6):2273
87. Pacheco EB, Da-Silva CJ (2009) Fish associated with aquatic macrophytes in the Chacororé-Sinhá Mariana lake system and Mutum River, Pantanal of Mato Grosso, Brazil. Braz J Biol 69 (1):101–108