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The Río Parapetí – Holocene megafan formation in the southernmost Amazon basin

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1 Introduction

Megafans may potentially store long records of regional uplift, denudation and climate history over long geologic timescales due to their extensive surface areas and large sediment volumes (HORTON & DECELLES 2001; UBA et al. 2007). On much shorter timescales, however, they are characterized by highly dynamic fluvial processes of severe flooding and frequent avulsions (CHAKRABORTY et al. 2010; WELLS & DORR 1987). The spatial and temporal variability of these processes ultimately determine the environmental, hydrological and ecological properties across extended foreland areas (WILKINSON et al. 2006). The Andean foreland in eastern Bolivia is characterized by three megafans: the Río Grande (Guapay), Río Parapetí and Río Pilcomayo (HORTON & DECELLES 2001; IRIONDO 1993; MAY 2006), the latter being among the largest known megafans of the world (HARTLEY et al. 2010). For all of these, large-scale channel shifts have been identified based on remotely sensed detection of paleochannels (HORTON & DECELLES 2001; WERDING 1977a), illustrating that the Río Parapetí has become part of the southernmost Amazon catchment only in the late Quaternary, and formerly drained towards the Paraná and La Plata basins in the south (BARBOZA et al. 2000; LATRUBESSE 2003). Today, the Parapetí contributes surface water to the Amazon only occasionally, and terminates in the Bañados de Izozog wetlands (ARGOLLO 2006). As a function of seasonal flooding, these wetlands sustain a highly diverse wildlife and flora (NAVARRO & MALDONADO 2002), and were consequently declared a «Ramsar» protection site in 2001 (Convention on Wetlands of International Importance, www.ramsar.org). For the local indigenous Guaraní people, who inhabit the area at least since the 15th century, this peculiar setting is of fundamental cultural and economic importance, allowing for fishing, irrigation and agriculture within the otherwise dry environment of the Gran Chaco (ORTIZ et al. 2008). Even though the link between these highly fragile wetland habitats and the larger-scale processes operating on the megafan may be obvious, as yet there is no sound geoscientific understanding of the geomorphic history of the Río Parapetí, and a number of relevant questions remain to be answered: Which are and were the geomorphic processes operating on the megafan, what are their variabilities and controls, and how have

they contributed to the evolution of the Río Parapetí over different late Quaternary timescales? In order to address these questions, this paper intends to (i) present a detailed description of landforms along the Río Parapetí and its megafan, (ii) provide first stratigraphic and chronological data for the Bañados de Izozog, and (iii) discuss these data within the larger-scale framework of late Quaternary and Holocene megafan and wetland evolution in the eastern Bolivian foreland.

2 Regional setting

The Chaco plain (Gran Chaco) encompasses most of the modern Andean foreland in eastern Bolivia (Fig. 1a) and is bordered by the fold-and-thrust belt of the Subandes to the west (BABY et al. 1992), and the «Alto de Izozog» to the east (MAY 2006; UBA et al. 2006). Compared to the adjacent Río Grande and Pilcomayo megafans, the Río Parapetí occupies a much smaller catchment area of ~7500–8000 km² almost exclusively situated in the Subandean Zone and rising to ~3300 m asl in the upper catchment (BARNES & HEINS 2009). Below, the antecedent Río Parapetí cuts through multiple anticlines and reaches its catchment outlet at the megafan apex at ~600 m asl in the vicinity of San Antonio de Parapetí. From here, its megafan covers an area of at least 5800–6800 km² in the Chaco plain with average gradients ranging from 0.003 to 0.0014 (BARNES & HEINS 2009).

Climatically, eastern Bolivia is situated in a transitional setting between the tropical humid Amazon basin to the north and the semi-arid Chaco plain to the southeast, leading to strong hydroclimatic seasonality (Fig. 1a, b). Most annual precipitation falls during the wet season from December to March through convective storms related to the South American Summer Monsoon (SASM), averaging less than 700 mm/a in the semi-arid Chaco plain, but locally exceeding 1000 mm/a in the Parapetí catchment due to orographic effects along the main anticlines of the Subandes (AGTECA 2010; BOOKHAGEN & STRECKER 2008; VERA et al. 2006). Moisture is transported southward by a low level jet (South American Low-Level Jet - SALLJ), which is responsible for very strong northerly winds in the Bolivian Chaco throughout the year with a peak during the dry season (Fig. 1b; AGTECA 2010; BERRI & INZUNZA 1993). Catchment vegetation is characterized by various semi-deciduous forest types, but anthropogenic impacts have caused some degra-

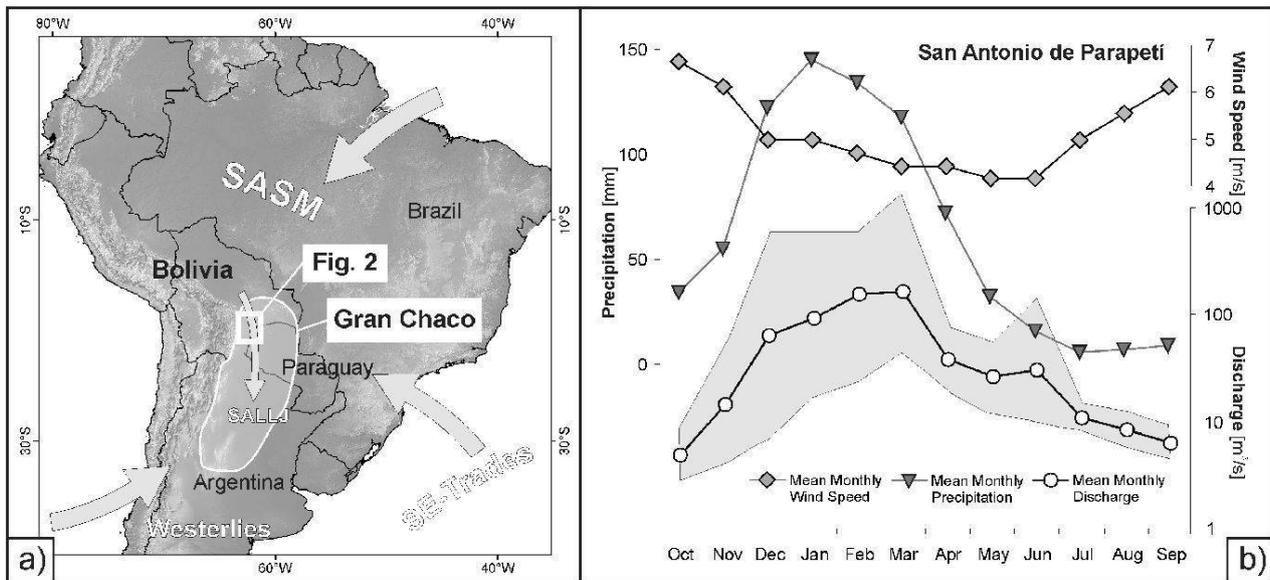


Fig. 1: Geographic and hydroclimatic setting of the study area: a) location of the Gran Chaco in South America; b) hydroclimatic variables as measured at San Antonio de Parapetí

Geographischer und hydroklimatischer Rahmen des Untersuchungsgebietes: a) Lage des Gran Chaco in Südamerika; b) hydroklimatische Parameter gemessen in San Antonio de Parapetí

Conditions géographiques et hydroclimatiques de la zone d'étude: a) localisation du Gran Chaco en Amérique du Sud; b) variables hydroclimatiques mesurées à San Antonio de Parapetí

Source: a) RIVEROS 2004; b) AGRAR- UND HYDROTECHNIK GMBH 1974; AGTECA 2010

dation and soil erosion (GEROLD 1985). On the plains, the semi-deciduous Chaco dry forest of variable density is interspersed with patches of palm forests and savannah type vegetation (IBISCH et al. 2004; NAVARRO & MALDONADO 2002). The resulting vegetation pattern commonly reflects local differences in soils and lithology (GEROLD 2004), and thereby mimics the larger-scale geomorphic pattern of relict landforms on the megafan.

Only very limited data exist regarding the average annual discharge of the Río Parapetí, and reported values range between ~ 38 and $90.9 \text{ m}^3/\text{s}$ (AGRAR- UND HYDROTECHNIK GMBH 1974; GUYOT et al. 1994). More importantly, however, discharge is characterized by very high seasonal and intra-annual variability with a pronounced flood peak in February or March, when discharges in excess of $4000 \text{ m}^3/\text{s}$ have been observed (Fig. 1b; AGRAR- UND HYDROTECHNIK GMBH 1974). Interestingly, the Parapetí carries 40% of the total annual sediment load as sandy bedload, a much higher value than $\sim 0.5\%$ in the adjacent Río Grande (WERDING 1977a). Suspended load shows a clear peak in the clay and fine silt fraction. Downstream of the apex, strong percolation into the sandy fluvial deposits is partly responsible for very high transmission losses

(WERDING 1977b). Additionally, potential evaporation reaches $\sim 1400 \text{ mm/a}$ with a peak between September and December (AGTECA 2010). Due to the combined effect of percolation and high evaporation, the river flow usually ceases during dry season.

3 Methods

Landsat images and a SRTM derived digital elevation model (DEM) were integrated into ArcGIS 9.3 to extract drainage divides and megafan boundaries. Then, the images were visually interpreted to achieve a broader-scale geomorphic overview and map individual landforms. Visual interpretation incorporates colour, density and texture of the imagery, but also deduces information from elevation, vegetation and land-use patterns (VERSTAPPEN 1977). More detailed mapping of small-scale landforms such as dunes, channels etc. was additionally facilitated by the high-resolution imagery in Google Earth. During the dry season 2005, four sediment cores of three to five metres depth were recovered along a W-E transect across the Bañados de Izozog. Following the guidelines summarized in AG BODEN (1994), the cores were described with regard to grain size, colour, and main pedogenic fea-

tures. In addition, the total organic matter of one sediment sample (Poz-19842) was radiocarbon dated at the Radiocarbon Laboratory in Poznan (Poland); the result was calibrated using Calib 6.0 at 2σ and the calibration dataset *intcal09.14c* (REIMER et al. 2009; STUIVER & REIMER 1993).

4 Results

4.1 Río Parapetí megafan geomorphology

The Río Parapetí exits the Subandean ranges at ~600 m asl (Fig. 2a). Contrasting with the dominantly forest-covered and inactive megafan surface, four different active geomorphic reaches are distinguished along the modern Río Parapetí: (i) For ~150 km, the river is characterized by a sand-bed channel with ~2-5 km long sand bars, and channel widths >1000 m (locally >2000 m). Source-bordering transverse crescentic and parabolic dunes delineate the southern channel margin, and generally have not migrated more than a few hundred metres away from the channel. (ii) ~150 km downstream from the apex, the channel width rapidly decreases, then bifurcates into a large number of breaches (crevasses) and successively minor distributary channels, and terminates into a lobate splay of sediment extending 1-2 km into the wetland forest (Fig. 2a; i.e. «floodout», TOOTH 1999). (iii) No confined channel is developed downstream within the wetlands of the Bañados de Izozog, which receive the seasonal floodwaters. (iv) ~175 km downstream of the apex a narrow, meandering channel of variable sinuosities (~1.1-1.8) and ~15-20 m channel width routes the floodwaters further downstream (Fig. 2a). The succession of these reaches may be attributed to a gradual downstream decrease in discharge, transport capacities and grain sizes commonly observed in megafans (SHUKLA et al. 2001), and the abrupt channel breakdown and well-defined floodout clearly mark the limit between the bedload dominated proximal megafan versus the medial and distal fan with sedimentation from mainly suspended sediment.

Based on geomorphic mapping, the Parapetí megafan surface can be divided into a southern half, south of ~20°S, characterized by the Lomas de Parapetí paleodunes and the lack of clearly distinguishable paleochannels, and a northern half with more diverse geomorphic pattern of paleochannels and smaller-scale paleodunes. In detail, the megafan is further subdivided into five megafan segments (Fig. 2a), each of them radiating in different directions from the apex, and generally representing a formerly active lobe of the Río Parapetí:

- Segment A exhibits only very few paleochannels at the surface on the proximal megafan and is entirely covered by the Lomas de Parapetí dune field.

- Segment B is characterized by few paleochannels; the longest of them reaches ~240 km into Paraguay and there bifurcates and/or avulses into a number of smaller distributary channels (KRUCK 1998). This segment is sharply confined by large complexes of source-bordering dunes to the south, and by the topographically elevated Alto de Izozog to the north.
- Segment C has short paleochannels (~40 km) but extensive sand lobes in its distal part, probably reflective of former floodout zones.
- Segment D has paleochannels of ~60-80 km with frequent source-bordering paleodunes.
- Segment E has similar characteristics to segment D, but occupies the area west of the modern river, showing that the Río Parapetí is currently not located at its westernmost location.

4.2 The Bañados de Izozog wetlands

Between 1975 and 2010, the Parapetí channel has prograded ~17 km northwards into the wetlands with an average progradation rate of ~500 m/a, creating a series of nested splays as well as crevasse channels and failed local avulsions (Fig. 3a). Several sparsely vegetated splay-shaped areas are visible north of the active channel in 1975, indicating that splay deposition, progradation, channel avulsion and abandonment must have occurred in the area long before 1975, and probably represent recurring cycles of filling the available accommodation space in the wetlands.

Most of the profiles along a W-E transect across the Bañados de Izozog wetland transect (Fig. 2a) are built up by comparatively fine grained sediment only occasionally interrupted by coarse silts and sands (Fig. 3b). Clays, muds and silts are generally associated with deposition in slowly moving waters of overbank environments, with increasing grain size and decreasing sorting going along with increasing proximity of the channel (GUCCIONE 1993). In contrast, coarse silts and sands indicate deposition in near-channel environments such as levees or splays (BRIDGE 1984). While most sediments range in colour from greyish brown, beige, brown to orange, the upper sediments in the centre of the wetlands are very dark brown to reddish brown clays and mud of variable depths (Fig. 3b). These clays and muds overly a paleosol; they are ~150 cm thick in the central part of the wetlands, and thin out to the west. They are thus interpreted as representative for deposition by very slowly moving water under the currently active flooding regime of the Bañados de Izozog. At their base a radiocarbon age of total organic carbon (TOC) yielded 1192 ± 52 ¹⁴C years BP, corresponding to a calibrated age range of 980-1262 cal yr BP and providing the first and as yet only available estimate for the age of the wetlands.

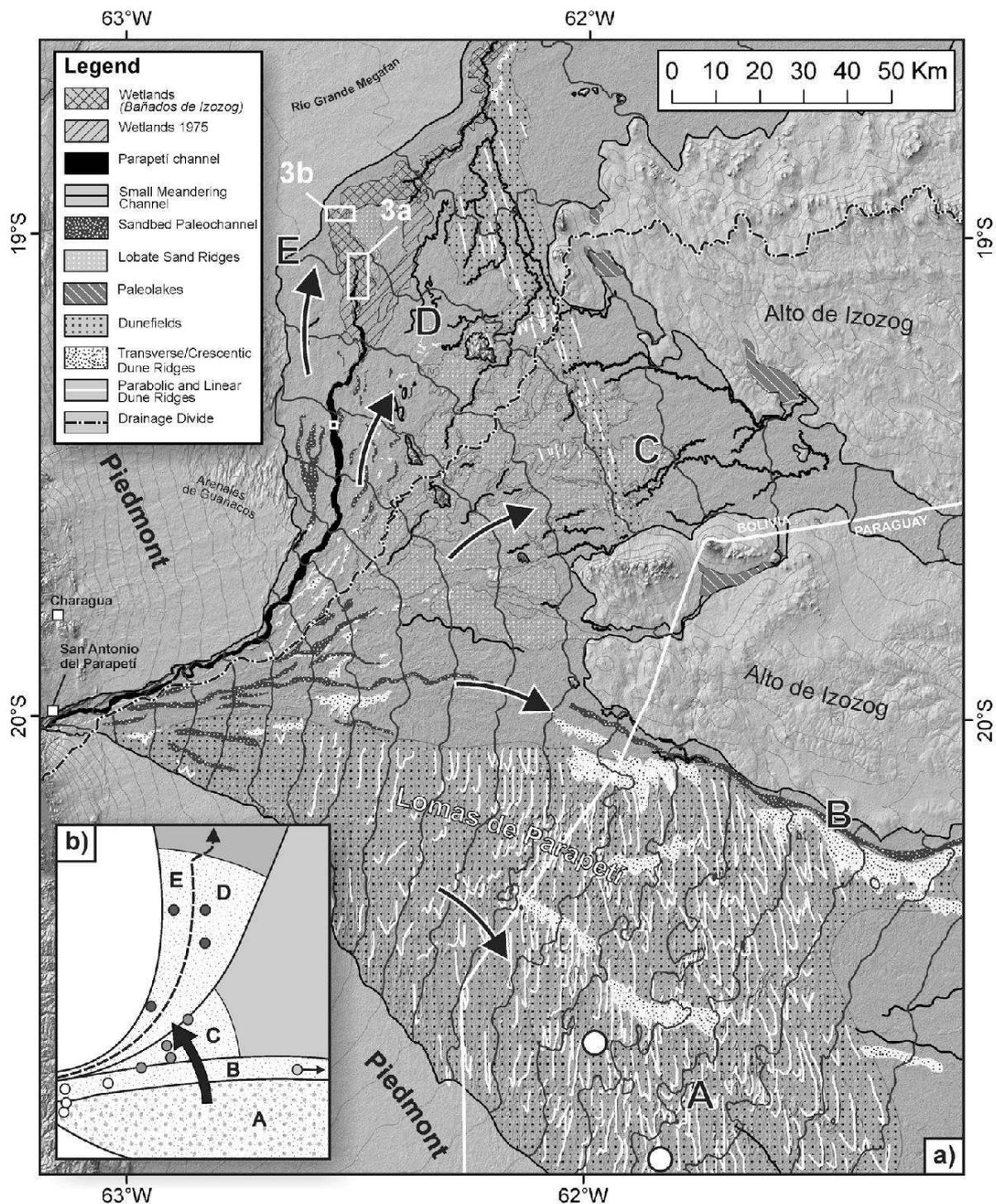


Fig. 2: Geomorphology of the Parapetí megafan: a) overview of mapped features; b) conceptual illustration of the Holocene Río Parapetí megafan evolution

A-E denote the megafan segments (see text for details), dotted areas indicate the length of paleochannels on each segment, and circles mark paleochannel divergence points (white = older, black = younger).

Geomorphologie des Parapetí-Megafans: a) Überblick über die kartierten Formen; b) konzeptuelle Illustration der holozänen Megafan-Entwicklung des Río Parapetí

Géomorphologie du mégafan de Parapetí: a) aperçu des éléments cartographiés; b) illustration conceptuelle de l'évolution holocène du mégafan du Río Parapetí

Source: SRTM digital elevation model (<http://srtm.csi.cgiar.org/>); cartography: J.-H. MAY

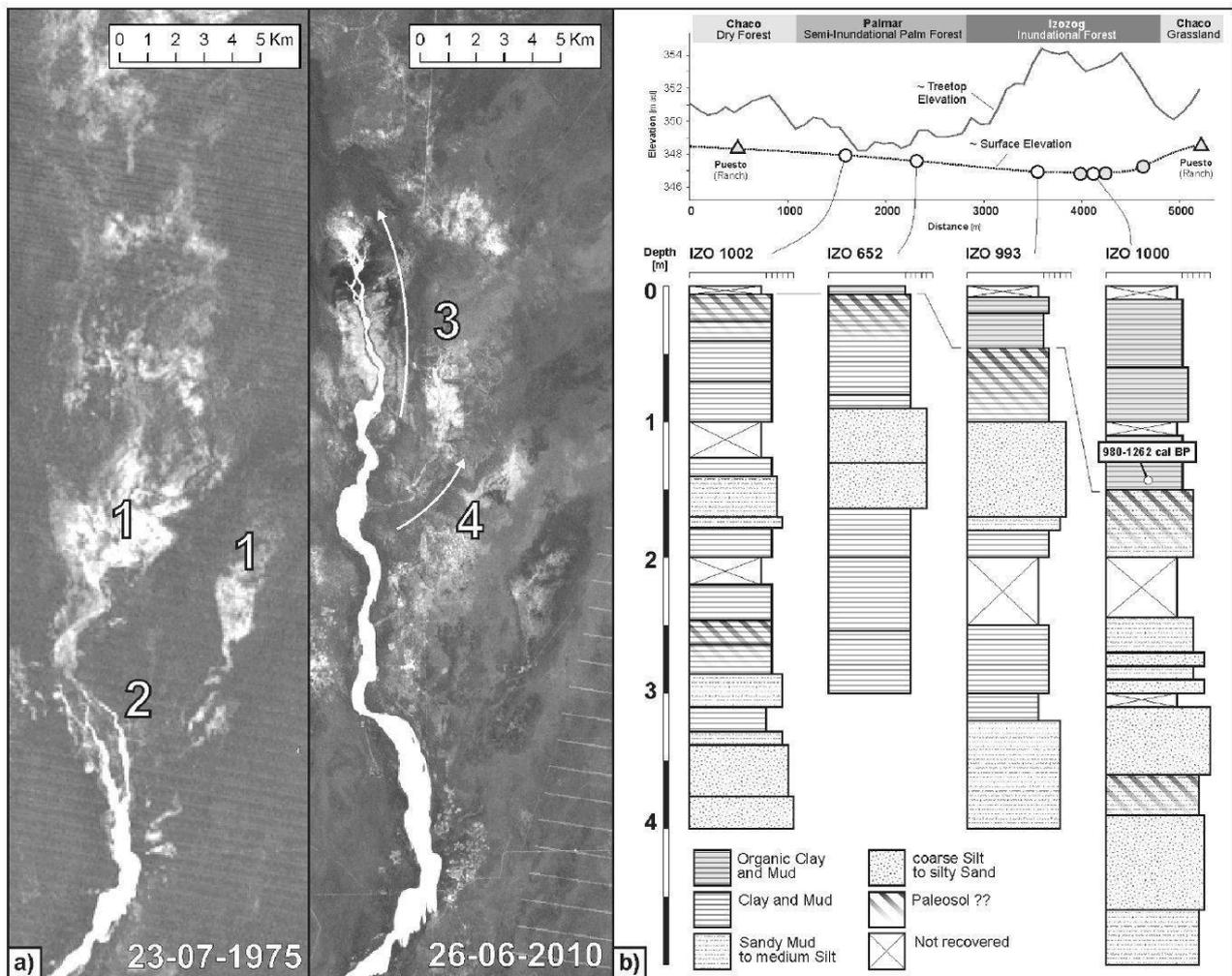


Fig. 3: Overview of recent and late Holocene evolution of the Bañados de Izozog wetlands: a) comparative satellite images of the floodout zone in 1975 and 2010 from near-infrared (band 5) Landsat images (1: older splays, 2: channel termination, 3: splay progradation, 4: crevasse channel and failed avulsion); b) stratigraphic profiles along a transect across the wetlands

Überblick über die rezente und spätholozäne Entwicklung der Bañados de Izozog-Sümpfe: a) vergleichende Satellitenbilder der «Floodout»-Zone von 1975 und 2010 auf Basis nah-infraroter (Band 5) Landsat Bilder (1: ältere Sedimentloben, 2: Ende des Flussbettes, 3: Voranschreiten der lobenartigen Sedimentation, 4: Durchbruchskanal und gescheiterte Flussumlagerung); b) stratigraphische Profile entlang eines Transektes durch die Sümpfe

Aperçu des évolutions récentes et anciennes des zones humides des Bañados de Izozog pendant l'Holocène: a) comparaison de la zone d'épandage en 1975 et 2010, images Landsat infrarouge proche (bande 5) (1: anciens deltas, 2: fin des chenaux, 3: progression des deltas, 4: crevasse sur chenal et avulsion manquée); b) profils stratigraphiques le long d'un transect de zones humides

Source: USGS (<http://edcns17.cr.usgs.gov/NewEarthExplorer/>)

5 Discussion and interpretation

Despite its significantly smaller catchment and megafan area as compared to those of the large, adjacent megafans of the Río Grande and Río Pilcomayo, the Río Parapetí megafan is characterized by a wide range of landforms variably distributed over the fan, indicat-

ing changes in geomorphic processes and/or environments over time.

Over the recent decades, crevasse, channel and splay progradation into the wetlands have been the dominant geomorphic processes on the megafan. It is likely that the spatial and temporal vari-

ability of these processes are directly controlled by the highly variable flow regime of the Río Parapetí, and thereby strongly linked to precipitation in the Subandean catchment (Fig. 1b). In this context, the seasonal to inter-annual rates of sediment supply and aggradation effectively create the topographic set-up for avulsion (JONES & SCHUMM 1999; SLINGERLAND & SMITH 2004). Contrasting with this spatially constrained short-term history of the floodout zone, shifts over much larger areas are manifest on the Río Parapetí megafan and require divergence points much closer to the apex. Here, the lengths and divergence points of the mapped paleochannels vary significantly between the five different megafan segments (A-E) and indicate significant shifts in transport capacity, sediment supply and dominant geomorphic processes on the individual megafan segments (Fig. 2b).

Along with the modern Río Parapetí, segments D and E lack signs of large-scale channel shifts and are characterized by progressive down-fan migration of the avulsion point probably linked to fan-head incision and terrace formation as observed at the apex (IRIONDO 1993). In combination, this likely reflects an overall stable position of the channel belt on the megafan with only minor adjustments in the floodout zone and some limited lateral accretion of source-bordering dune/paleochannel complexes. Based on the stratigraphic data in the Bañados de Izozog, this situation has been in place for the last ~1200 years. Similar to the Río Parapetí, laterally stable but prograding fluvial activity has been observed for most smaller piedmont streams around Charagua west of the megafan, and was dated to <1000 cal yr BP (MAY et al. 2008a). To the north, aggradation of river terraces along the Río Grande between ~1700 and <1400 cal yr BP was followed by incision (MAY et al. 2008b). Along the Andean piedmont around Santa Cruz de la Sierra wetter conditions with incision along the Río Piraf were established after ~1300 14C yr BP (SERVANT et al. 1981). This coincides well with the proposed change in fluvial activity before ~1200 cal yr BP along the Río Parapetí, and suggests that the marked shift from a W-E flow direction (segment B) during or before the activity of segment C towards a northerly direction (segments D, E and modern river) took place before ~1200 cal yr BP. Comparatively short paleochannels and extensive lobate floodout deposits on this segment (Fig. 2) may point to a period of environmental and climatic aridification.

This scenario invokes decreasing transport capacities, discharge and/or increased sediment supplies and sedimentation rates as potential causes for the observed river shifts. Thus, it clearly contradicts a hypothesis

which considers the formation of source-bordering dune complexes responsible for most river shifting (WERDING 1977a). While source-bordering dunes are not common on segments C, but best developed on segments D and E, they may have caused some of the lateral accretion and limited migration of the channel belt over the last ~1200 years. Larger-scale shifts and directional changes, however, probably owe to earlier avulsions closer to the megafan apex. Interestingly, several sandy paleochannels along the Río Pilcomayo megafan were TL dated to 7600-3400 years ago, equally indicating aggradation and laterally active fluvial systems (GEYH et al. 1996; PASIG 2005). Evidence for a mid-Holocene phase of drier conditions between ~8000 and 5500 14C yr BP (SERVANT et al. 1981) could thus potentially explain the dynamic changes associated with activity on segment C. In this context, sands from parabolic paleodunes in the Lomas de Parapetí dune field on megafan segment A (Fig. 2a) were TL and OSL dated to 5500 BP to 2900 years ago, respectively (GEYH et al. 1996; KRUCK 1996). While these authors attribute dune activity to increased aridity, the dates may equally be interpreted as reflecting successively wetter environmental conditions towards increased vegetation cover and dune stabilization such as required for the formation and preservation of parabolic dunes (CHASE 2009; LANCASTER 2002; TSOAR 2005). In fact, a change towards more stable and humid late Holocene conditions between 3800 and ~3000 cal yr BP has also been deduced from radiocarbon dating of paleosols in the Paraguayan Chaco (BARBOZA et al. 2000) and pollen evidence in NE Bolivia (BURBRIDGE et al. 2004; MAYLE et al. 2000), and was even recorded in rising Lake Titicaca levels (ABBOTT et al. 1997; BAKER et al. 2001). The mid- to late Holocene dates from paleodunes in the Lomas de Parapetí dune field represent the only available chronologic information and provide a minimum age on any older fluvial activity. In particular, the paleochannel of segment B reaches furthest to the east and thereby points to significantly increased flow and transport capacities under conditions of longer and/or intensified wet seasons compared to today. Extensive, fine-grained overbank and lacustrine sediments were dated to 12300-9800 years ago (TL and OSL) further E on the distal Río Pilcomayo megafan (GEYH et al. 1996), and to 11500-10000 cal yr BP on the Andean piedmont (MAY et al. 2008b), probably indicating widespread and intense overbank flooding during the late Pleistocene and early Holocene. In fact, a six to tenfold increase in groundwater recharge (PASIG 2005) reflects extraordinary wet conditions throughout the Bolivian Chaco at the same time, coinciding with the prominent «Tauca-Coipasa» wet phase reported from large number of records throughout the Central Andes (ARAGOLLO & MOURGUIART 2000; PLACZEK et al. 2006).

6 Conclusions

The in-depth analysis of the Río Parapetí megafan has documented a large variability of geomorphic processes involved in megafan evolution, both in time and space. Even though a detailed timeframe for fluvial activity is still absent, the rate and spatial extent of the documented large-scale lateral shifts of the Río Parapetí across its megafan appear to be linked to significant variability in transport capacities over the course of the Holocene with drier phases likely causing enhanced aggradation on the proximal fan, itself eventually causing avulsions and river shifts. In contrast, wetter conditions may help to stabilize the river course on any given segment, leading to floodout progradation, fan-head trenching and sedimentation along the downstream termination of the channel. In summary, these considerations (i) provide a readily testable hypothesis given the large number of paleochannels and source-bordering dunes on all mapped megafan segments: these features offer a promising opportunity for intensified future research on late Quaternary megafan evolution in the Chaco with a focus on the extensive application of luminescence dating of landforms and stratigraphy. Finally, our results (ii) highlight the role of climate and environmental change as a key control on megafan evolution on Holocene timescales via its influence on sediment supplies, flow regimes and transport capacities. These parameters consequently influence the spatial and temporal pattern of aggradation on the megafan, and are therefore crucial in determining the ecology and life cycles of wetlands such as the Bañados de Izozog (WILKINSON et al. 2006). Despite the importance of climate on shorter timescales, however, there is no question that tectonics (e.g. Andean uplift and/or subsidence in the foreland basin) play a crucial role for megafan evolution on longer, late Cenozoic timescales by creating, maintaining and renewing gradient and downstream accommodation space as necessary preconditions for the continued aggradation by these dynamic fluvial processes.

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Abstract: The Río Parapetí – Holocene megafan formation in the southernmost Amazon basin

Research on fluvial megafans and foreland basins so far has been mainly concerned with their evolution over geologic timescales, or focused on various aspects of their recent history. This paper documents the landforms on the Río Parapetí megafan in the southernmost Amazon basin in detail in order to unravel changes in geomorphic processes over the Holocene. In addition, new stratigraphic and chronological data from the Bañados de Izozog – an important wetland in the semi-arid Chaco region – is presented. In combination, the data allows the reconstruction of wetland history and suggests significant changes in flow regime and sediment supply of the Río Parapetí throughout the Holocene. In conclusion, these results are discussed in the context of regional environmental change in eastern Bolivia.

Keywords: megafan, Holocene, avulsion, Bolivia, Chaco

Zusammenfassung: Der Río Parapetí – Holozäne Bildung eines Megashwemmfächers im südlichsten Amazonasgebiet

Studien der grossen Megafans und Vorlandbecken haben sich bislang vorwiegend mit deren Entwicklung über geologische Zeitskalen beschäftigt oder untersuchten verschiedene Aspekte ihrer rezenten Vergangenheit. Diese Arbeit zielt auf eine detaillierte Darstellung der Formen auf dem Río Parapetí Megafan im südlichsten Amazonas-Becken ab, um Änderungen der geomorphologischen Prozesse im Laufe des Holozäns zu enträtseln. Zusätzlich werden neue Daten zur Stratigraphie und Altersstellung der Bañados de Izozog – eines wichtigen Sumpfbereiches im semi-ariden Chaco – vorgestellt. Insgesamt erlauben diese Daten die Rekonstruktion der Sumpfungwicklung und bieten Einblick in bedeutsame Änderungen des Abfluss- und Sedimentaufkommens des Río Parapetí über das Holozän. Schliesslich werden diese Ergebnisse im Kontext der regionalen Umweltveränderungen in Ostbolivien diskutiert.

Schlüsselwörter: Schwemmebene, Holozän, Flussumlagerung, Bolivien, Chaco

Résumé: Le Río Parapetí – formation holocène d'un mégafan à l'extrême sud du bassin amazonien

Les recherches sur les mégafans fluviaux et les bassins d'avant-pays ont jusqu'ici plutôt concerné leur évolution au cours des temps géologiques ou focalisé sur certains aspects de leur histoire récente. L'objectif de cet article est de documenter précisément les formes du mégafan du Río Parapetí situé à l'extrême sud du bassin amazonien, afin de comprendre les changements des processus géomorphologiques durant l'Holocène. En outre, l'article présente des données stratigraphiques et chronologiques nouvelles venant des Bañados de Izozog, une importante zone humide située dans la région semi-aride du Chaco. Ces données permettent de procéder à la reconstruction de l'histoire des zones humides et d'interpréter les changements importants des régimes fluviaux et des apports de sédiments du Río Parapetí au cours de l'Holocène. L'article discute finalement ces résultats dans le contexte du changement environnemental régional de l'est de la Bolivie.

Mots-clés: mégafan, Holocène, avulsion, Bolivie, Chaco

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