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Anna Plotzki

University of Bern, plotzki@giub.unibe.ch

Jan-Hendrik May

University of Wollongong, hmay@uow.edu.au

Frank Preusser

University of Bern, frank.preusser@natgeo.su.se

B Roesti

University of Bern

Sebastian Denier

University of Bern

See next page for additional authors

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Abstract

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Geomorphology and evolution of the late Pleistocene to Holocene fluvial system in the south-eastern Llanos de Moxos, Bolivian Amazon

A. Plotzki^{a*}, J.-H. May^b, F. Preusser^c, B. Roesti^a, S. Denier^a, U. Lombardo^a, H. Veit^a

^aInstitute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland (Bedaroesti@gmail.com, Sebastianidenier@gmail.com, Lombardo@giub.unibe.ch, Veit@giub.unibe.ch)

^bGeoQuEST Research Centre, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW, 2522, Australia (hmay@uow.edu.au)

^cDepartment of Physical Geography and Quaternary Geology, Stockholm University, 10961 Stockholm, Sweden (Frank.Preusser@natgeo.su.se)

*corresponding author (email: Plotzki@giub.unibe.ch, phone: 0041 31 631 8890, fax: 0041 31 631 85 11)

Abstract

In the Bolivian Amazon several paleochannel generations are preserved. Their wide spectrum of morphologies clearly provides crucial information on the type and magnitude of geomorphic and hydrological changes within the drainage network of the Andean foreland. Therefore, in this study we mapped geomorphological characteristics of paleochannels, and applied radiocarbon and optically stimulated luminescence dating. Seven paleochannel generations are identified. Significant changes in sinuosity, channel widths and river pattern are observed for the successive paleochannel generations. Our results clearly reflect at least three different geomorphic and hydrological periods in the evolution of the fluvial system since the late Pleistocene. Changes in discharge and sediment load may be controlled by combinations of two interrelated mechanisms: (i) spatial changes and re-organizations of the drainage network in the upper catchment, and/or (ii) climate changes with their associated local to catchment-scale modifications in vegetation cover, and changes in discharge, inundation frequencies and magnitudes, which have likely affected the evolution of the fluvial

system in the Llanos de Moxos. In summary, our study has revealed the enormous potential which geomorphic mapping and analysis combined with luminescence based chronologies hold for the reconstruction of the late Pleistocene to recent fluvial system in a large portion of Amazonia.

Keywords: paleochannels; paleohydrology; fluvial geomorphology; stratigraphy

1. Introduction

Paleohydrological studies are of major importance for understanding present day and future responses of rivers to environmental changes (Starkel, 1993). As the largest river system on Earth, the Amazon River with its tributaries should therefore contribute essential information to our understanding of global to regional-scale variability of fluvial systems over late Quaternary timescales. Little is known with regard to the longer-term evolution of rivers in the Amazon basin (Sinha et al., 2012), despite the extensive evidence for past geomorphological and hydrological variability documented in aerial photography and satellite imagery, such as underfit rivers, numerous paleorivers, meander scars and oxbow lakes. So far, most studies have focused on the Amazon River and its main tributaries in Brazil and Peru (summarized in Latrubesse, 2003). Even less information from marginal regions such as south-western Amazonia and the Llanos de Moxos (LM) lowlands of Bolivia is known, although several studies have reported large-scale river migrations of the Beni, Mamoré and Grande Rivers (Allenby, 1988; Dumont, 1996; Hanagarth and Sarmiento, 1990; Hanagarth, 1993; Lombardo et al., 2012; Plafker, 1964; Plotzki et al., 2011). Avulsive shifts along the Mamoré and Grande Rivers must have occurred in the mid to late Holocene (Lombardo et al., 2012; Plotzki et al., 2013), but no comprehensive geomorphological or chronological dataset is available for the older, Pleistocene fluvial system in the region. In the southern Llanos de Moxos, remnants of the fluvial lobe of the Grande River as well as other traces of former

rivers were grouped in two generations of paleochannels (Lombardo et al., 2012). Partly, this may express a bias towards younger fluvial events, as older landforms and features have often been buried by younger ones, or appear less pronounced due to erosion and fragmentation (e.g. Hanagarth, 1993). In the Llanos de Moxos the abundance and diversity of former river traces, however, suggests that more channel generations are preserved than previously reported, likely covering longer timescales. Their wide spectrum of morphologies has not yet been documented but clearly provides crucial information on the type and magnitude of geomorphic and hydrological changes within the extensive drainage network of the Andean foreland in Bolivia. Therefore, in this study we (i) map geomorphological characteristics of paleochannels, (ii) apply radiocarbon and optically stimulated luminescence (OSL) dating to establish a first chronology for paleochannel activity, and (iii) analyze geochemical composition of fluvial sediments to assess a preliminary framework for changes in provenance of sediments in these paleorivers.

2. Regional setting

The study area is situated in the Llanos de Moxos in north-eastern Bolivia (Fig. 1). The region investigated comprises an area of around 130 km x 130 km. The Mamoré and the Grande River form the western and southern margins of the study area, respectively. The LM are a large, seasonal inundated savannah (150,000 km²) within the Amazon Basin. To the east the plains are confined by the Brazilian Shield and in the south-west by the Andes Mountains. Whereas the Andes and Subandean ranges are primarily composed of Paleozoic sediments (shales and evaporitic sediments; Elbaz-Poulichet et al., 1999; Stallard and Edmond, 1983), the Brazilian Shield consists of crystalline rocks (granite and gneiss; e.g. Litherland et al., 1989). Elevation above sea level is around 150 m. The plains, which are drained by the Mamoré River flowing in a northerly direction, show a gradient of less than 10 cm km⁻¹ (Dumont and Fournier, 1994). The Mamoré River originates in the Eastern Cordillera. As a

white water river it carries a significant load of sediment ($64 \times 10^6 \text{ t y}^{-1}$ at the confluence with the Beni River; Guyot et al. 1999). Mean annual discharge of the Mamoré River at Trinidad (Fig. 1) is $2,850 \text{ m}^3 \text{ s}^{-1}$, although interannual variability is high, with discharge ranging from $<500 \text{ m}^3 \text{ s}^{-1}$ in the dry season to $7,600 \text{ m}^3 \text{ s}^{-1}$ in the rainy season (data from the HYBAM-Observatory, IRD-SENAMHI joint research project in Bolivia, 1986-2008, gauging station Puerto Varador; Ronchail et al., 2005). The Grande River, which discharges into the Mamoré River around 100 km upstream of Trinidad, also originates in the Eastern Cordillera. It drains parts of the Subandean Ranges and the Chaco lowlands of eastern Bolivia, and carries a suspended sediment yield of approximately $136 \times 10^6 \text{ t y}^{-1}$ at Abapo (Guyot et al. 1994). More than 30% of transported sediments in rivers draining the Eastern Cordillera are deposited directly after emergence of the piedmont in megafans (Guyot et al., 1994; Horton and DeCelles, 2001). In the mid-Holocene the Grande River discharged in a northerly direction and formed a sedimentary lobe which covers an area of approximately $2,600 \text{ km}^2$ and which shows an elevated, convex topography (Lombardo et al., 2012). In contrast to the rivers with Andean headwaters, the clear water rivers originating in the plain (e.g. the Ibaré, Mocoví, and Cochamarca Rivers, Fig. 1) and the black water rivers originating in the Brazilian Shield (e.g. Iténez River) carry only minor amounts of sediment (Sioli, 1984). All of them discharge in a northerly or north-western direction.

Belonging to the south-western Amazon Basin, the LM are climatically dominated by the South American Summer Monsoon (SASM), resulting in heavy convective rainfall during austral summer and markedly dry conditions in winter (Garreaud et al., 2009; Zhou and Lau, 1998). In the rainy season, inundations cover an area between $2,000$ and $78,000 \text{ km}^2$, occasionally reaching $150,000 \text{ km}^2$ (Hamilton et al., 2004; Hanagarth and Sarmiento, 1990; Hanagarth, 1993). Forest in the LM is generally restricted to slightly elevated areas such as river levees and forest islands which are not affected by the seasonal inundations. Large forest areas are found in the eastern part of the study area (San Pablo channel belt forest) and in the

south-west (Grande and San Andrés channel belt forest, Fig. 1), which are located on river levees, created by overbank sedimentation of paleorivers.

3. Methods

3.1 Remote sensing and mapping

Comprehensive mapping of paleochannel segments and meander scars in the study region was performed using satellite images (Landsat TM 2001, Google Earth 2002, 2011). In some cases, linear forest segments without visible channel were mapped, as these indicate gallery forest on elevated levees along former channels. In order to characterize and classify the mapped paleoriver generations morphological parameters were measured. Mean channel width was measured manually for each mapped meander scar at 3-7 sections across the channel near the inflection points, thereby minimizing effects of increased variability in widths at bend apices. Radius of curvature (RoC) was determined by measuring the radius of a superimposed arc with best fit (determined visually) to the interpreted paleochannel center line. Sinuosity was determined, given as the ratio of thalweg length to valley length. Length of the channel segments was measured. Forest cover was determined on Landsat imagery. Land cover was classified using the Maximum Likelihood Supervised classification (Richards and Jia, 1999) into 3 classes (water, forest and savannah) using bands 7, 5, 4 and 3. Color RGB (5, 4, 3) composites were displayed as background and used as reference to identify training areas. Percentage of forest cover along the channels, representing levees, was calculated from length of the channel segments and forest cover. All image processing, mapping and analysis was done with Google Earth and ArcGIS10.

3.2 Field work

Paleochannel infill and bedload sediments were sampled from paleochannel segments and/or meander scars at La Chacra (Ch), Loreto (Lo), Santa Fe (SF) and Limones (Li) in the years

2009 to 2011, using percussion drilling equipment (Wacker vibracorer) (Fig. 1, Fig. 2). Additionally, the levees of Ibiato (Ib) and Estancia (Es) were sampled in 2011 for geochemical analysis. At La Chacra (Fig. 2a) a transect of 10 boreholes was cored across the channel and its levee and one pit was excavated on the paleorivers levee (Ch-1 to Ch-11). At Loreto, a transect of 10 boreholes was cored across the whole widths of the meander channel (Fig. 2b, Lo-1 to Lo-10). One additional core (Lo-157) was taken at the other side of the meander for dating purposes the year after. Due to flooding by the Tico River no coring was possible in that year at the previous site. At Santa Fe two cores and at Limones one core were collected respectively (Fig. 2c, d). Overall maximum coring depth was 8.5 m. Description and sampling of the fluvial sands, infill sediments and levee sediments on all sites for laboratory analysis were performed on the open cores. Closed and lightproof plastic tubes were used for collecting samples for luminescence dating.

One outcrop each at the river banks along the Mamoré and the Grande River was sampled 3.3 and 7 km, respectively, upstream of their confluence for geochemical analysis.

3.3 Luminescence dating

A total of eleven samples for Optically Stimulated Luminescence (OSL) dating was taken by drilling cores using opaque liners. Approximately 3 cm of sample was removed from the two ends of the sample tube, which may have been exposed to daylight during sampling, was used for determination of dose-relevant elements, and equivalent dose (D_e) was measured on material extracted from the inner part of the tubes. The sand fraction (see Table 1 for sieved grain size) was used with carbonates and organic matter being dissolved using 10% and then 32% hydrochloric (HCl) acid, and 10% and then 50% hydrogen peroxide (H_2O_2) solution, respectively (Wintle, 1997). Quartz grains were isolated using sodium polytungstate solutions with specific gravities of 2.70 to remove heavy minerals and 2.62 to remove feldspars, and subsequently etched with 40% HF for 60 min, followed by HCl treatment.

The single-aliquot regeneration (SAR) protocol of Murray and Wintle (2000) was applied for D_e determination, using a Risø TL/OSL DA-20 reader equipped with blue diodes and Hoya U-340 detection filters. The purity of samples (i.e. the presence of feldspars) of 2 mm aliquots (ca. 100-150 grains) was checked by measuring infrared stimulated luminescence (IRSL). Preheating at 230 °C for 10 s was used prior to all OSL measurement, for which we found good reproducibility in dose recovery tests and negligible thermal transfers (supplementary Table 1).

Palaeodose calculation is based on circa 50 individual D_e measurements. Due to the small number of grains on the discs, we expect that the OSL signal is dominated by emissions from very few or even a single grain. For most of the samples we observe complex D_e distributions (supplementary Fig. 1), indicating both the effect of incomplete bleaching prior to deposition as well as post-sedimentary mixing. The D_e distributions were investigated in detail using three different age models (Central, Minimum, and Finite Mixture Models: CAM, MAM, FMM) originally suggested by Galbraith et al. (1999). The CAM includes all analysed aliquots, but leads to incorrect estimates of the sediment deposition age in the presence of incompletely bleached grains (age overestimation), post-sedimentary mixing (age underestimation), or both. The MAM will account for the effect of incomplete bleaching but is very sensitive to post-sedimentary mixing. We therefore favor the application of the FMM that allows discriminating individual D_e populations, i.e. aliquots representing incomplete bleaching, sediment mixing and the deposition event. The FMM was dynamically modeled by changing the number of expected components and the expected overdispersion. The latter had very little effect on the results and we used an overdispersion of 0.20, as observed for well-bleached and undisturbed samples from the region (unpubl. data). The number of components in the FMM was chosen by monitoring the Bayesian information criteria (Table 1). Differences between the different age models are mainly moderate and the results of the

FMM, being most consistent stratigraphically, are used in the discussion of the age of fluvial deposition (supplementary Fig. 2).

The concentration of dose-rate relevant elements (K, Th, U) was determined using high-resolution low-level gamma spectrometry (cf. Preusser and Kasper, 2001). We did not observe any indication for radioactive disequilibrium in the U decay chain using the approach described by Preusser and Degering (2007) and Zander et al. (2007). Dose rates and OSL ages have been calculated using ADELE software (Kulig, 2005), with cosmic dose rate being calculated using present day depth and correcting for geographical position (latitude, altitude) following Prescott and Hutton (1994). Average water content during sediment burial was estimated based on present day water content and hydrological context.

3.4 Radiocarbon dating

AMS ^{14}C analysis on nine samples was conducted at the Poznan Radiocarbon Laboratory. In order to assess possible contamination of the samples with younger or older carbon, humins and humic acids were dated separately (Table 2). For sample Lo-1-6 only bulk soil (humin fraction) was dated. In general the humin fraction is considered to be more reliable, whereas the humic acid fraction gives crucial information about degree of contamination and thus the reliability (Pessenda et al., 2001; Grootes et al., 2004). Humic acids are more soluble and may be transferred within the soil, giving younger ages with depth. Radiocarbon ages were calibrated using Calib 6.0 online (latest version of Calib program by Stuiver and Reimer, 1993; <http://calib.qub.ac.uk/calib/>) with the southern hemisphere calibration data set (McCormac et al., 2004) and are indicated as cal ka BP.

3.5 Provenance analysis

Elemental composition of the sediments was determined by x-ray fluorescence spectroscopy (Phillips 2400 XRF) at the Department of Geosciences of the University of Fribourg. The

UniQuant program was used for semi-quantitative measurements. Four g of dried and milled (vibration disk mill) sample material was mixed with 0.9 g of wax (Licowax C Micropowder PM) and then pressed into pellet form at 10-15 tons.

Additionally to grain size determination in the field on the open cores (AG Boden, 2005), grain size for selected samples was measured in the laboratory. Prior to grain size measurement sesquioxides were removed from the samples by adding 0.3 M sodium citrate-solution, 1 M sodium carbonate-solution and sodium dithionite. Organic matter was removed by oxidation with 30% H₂O₂. A solution of sodium hexametaphosphate with sodium carbonate was added as a dispersant agent. Grain size measurement was conducted with the Malvern Mastersizer 2000 (Hydro S) with a stirring speed of 2000 rpm and a measurement time of 50 s. Fraunhofer theory was used for calculating the particle size distributions. In order to compensate for the underestimation of clay content by the laser particle measurement with respect to the pipette method (i. e. the international standard method) (Di Stefano et al., 2010; Loizeau et al., 1994), results were recalculated to “pipette clay content” with the equation by Konert and Vandenberghe (1997).

The geochemical data were used for provenance analysis of the paleoriver generations and the Grande and Mamoré River. Only sandy samples were used (n = 11; Table 3), as hydraulic sorting during transport results in compositional differences between the grain-size classes (D’Haen et al., 2012). Cs was excluded from the subsequent statistical analyses, as contents are very high (up to 50 times and more than continental crust concentrations), probably due to peak overlapping with neighboring elements, such as Ba. To reduce the effects of grain-size variations such as dilution of the material by quartz, element contents are normalized to Al (e.g. Horowitz, 1991; Taylor and McLennan, 1985). Agglomerative hierarchical cluster analysis (AHC) was conducted to test if the samples from the different rivers could be differentiated, followed by principal component analysis (PCA) for data reduction. A subsequent linear discriminant analysis (LDA), using the principal components from the PCA

as new variables, was calculated in order to discriminate the rivers from each other. The Excel-add-in XLSTAT was used for statistical analyses.

4. Results and Interpretation

4.1 Remote sensing and mapping

The mapped paleochannel segments comprise meander scars, and short to long paleochannels with varying sinuosity and segments of gallery forest without visible channels. They were differentiated into seven groups (i.e. P0 - P6, Fig. 1 and Fig. 3) based on sinuosity, channel width, lengths of river segments, percentage of gallery forest, appearance and recognisability, and spatial relation to each other (Table 4). First, based on the quantitative width and sinuosity parameters, four groups were differentiated: narrow and low sinuosity channels (P3, P4, P5), narrow and high sinuosity channels (P0, P6), wide and high sinuosity channels (P1), and intermediate wide and high sinuosity channels (P2) (Fig. 4). Further differentiation between the channels is based on percentage gallery forest, fluvial pattern style, and chronological constraints (based on position and recognisability of the channels), as discussed below.

P0 channels are sinuous (2.1) and narrow (mean channel width 38 m) and appear smoothed out due to subsequent erosion, with only short channel segments are preserved (mean length of river segment 4.3 km) and little gallery forest exists (12%) (Fig. 3a, Table 4). P1 channels are sinuous (1.8), have a radius of curvature of 317 m, are wide (199 m), and only short segments preserved (4.5 km) (Fig. 3b, Table 4). P1 channels often appear washed out due to subsequent erosion and only 4% associated with gallery forest. The meander scars of Loreto, Santa Fe and Limones belong to the P1 generation. P2 channels are clearly identified as long (31 km), sinuous (1.8) channel segments, confined by gallery forest (20%) (Fig. 3c, Table 4). Radius of curvature is smaller than for P1, at 190 m. In the southeast the P2 channels are occasionally flanked by meander scars which are wider than the P2 channels (~120 m),

indicating an underfit pattern. The La Chacra and Estancia channels belong to the P2 generation (Fig. 1). The La Chacra segment has a length of 43 km and in the upstream sector is superimposed by P3 channels (Fig. 1). The Estancia segment has a length of 107 km. Most of the P2 fragments may have been formed by one river. P3 channels are narrow (20 m) and have a low sinuosity (1.2) (Fig. 3d, Table 4). Most of the channels are bordered by gallery forest (21%). Half of the P3 network is recognizable due to the existence of linear gallery forests, even though no channels could be detected (Fig. 1). The channels/gallery forest show a parallel or distributive pattern and form a sedimentary lobe (Lombardo et al., 2012) which overlies the P1 and P2 channels (Fig. 1). P4 channels occur in the San Pablo and Grande forests and emerge from the latter (Fig. 1 and Fig. 3e, Table 4). In the San Andrés forest no channels could be recognized, but gallery forests that are interpreted to represent former channels of the P4 generation. Sinuosity is low (1.3), the channels are narrow (28 m) and show a parallel pattern. Identification of paleorivers in the forests is difficult and probably many more channels than have been identified are present. Assignment of channels to either the P3 or the P4 generations is not always straightforward, as they display similar channel widths and sinuosity, and are found in close proximity. P3 and P4 channels however may be differentiated because (i) they show different patterns (distributive versus parallel); and (ii) it does not seem likely that the Grande lobe (P3) and the P4 channels were all active contemporaneously. In comparison with P0 - P4, P5 and P6 channels are narrow (20 m) and cross P1, P2 and P4 channels or use P1 channels as underfit rivers (Fig. 3b, f, Table 4). These two generations differ from each other in sinuosity and percentage gallery forest. A sinuosity of 1.5 was used to divide straight and low sinuosity rivers (P5) from sinuous to high sinuosity rivers (P6). Percentage gallery forest is double for the P6 compared to the P5 channels.

Modern rivers are all sinuous but show a wide range from 1.6 to 2.7 (Fig. 4, Table 4). The rivers in the San Pablo forest (San Pablo River and its tributary, and the Negro River) show the lowest sinuosity. Modern rivers are narrow and gallery forest percentage is highly

variable. Rivers with sinuosity >2 show cut-off meanders, whereas they are absent in rivers with sinuosity <2 .

Summarizing the characteristics of the paleochannel generations, P1 channels are widest, followed by P2 channels (Fig. 4a). The channels are grouped according to sinuosity (Fig. 4b), those with sinuosities of 1.8 or higher (P0, P1, P2, P6, modern) and those with sinuosities of around 1.2 and 1.3 (P3, P4, P5). P4 channels constitute almost half of the entire paleochannel network ($>40\%$) and build up the forested areas of San Pablo, San Andrés and Grande.

4.2 Stratigraphy

Cores were taken from meander scars at Loreto, Santa Fe and Limones, and from the paleochannel at La Chacra. Their stratigraphy is taken to mark the base of an OSL-derived estimation of their latest period of activity, and provides information on type and duration of their infilling history. The bottom sands are generally interpreted as bedload, and should thus reflect deposition during the phase of channel activity, i.e. prior to meander cut-off or abandonment of the channel. In contrast, clayey silts should be indicative of deposition in lacustrine environments of oxbow lakes. Termination of lacustrine conditions due to silting-up of the oxbow lakes led to the onset of organic matter accumulation.

At Loreto, Santa Fe and Limones, ochre to yellowish and blue-greyish sands were found at the lowest levels, namely 2.5 m (Li-211), 3.2 m (SF-145), 3.8 m (SF-146), 4.0 m (Lo-157) and 4.2 m (Lo-2) (Fig. 5), representing fluvial sands of the active meander. The sands are overlain by clayey-silty to loamy sediments, which are mainly ochre colored with varying degrees of grey and red mottling and ochre and red concretions. This indicates gleyic activity with alternating oxidizing and reducing conditions. These fine grained sediments have been deposited after meander cut-off. In core Lo-157 a lens of loamy texture was found between 4.80 and 4.95 m, which may indicate post-depositional mixing. An organic soil horizon is developed in the uppermost sediments in all cores ranging in thickness from around 0.5 to 1.0

m. These suggest the end of lacustrine conditions, and the beginning of plant colonization and accumulation of organic matter.

At La Chacra the fluvial sand in the channel cores (Ch-2, Ch-3, Ch-4, Ch-6, Fig. 1; Fig. 5, only Ch-4 and Ch-6 shown) occurs at a depth of 1 to 4 m. The sands are overlain by ochre colored clayey-silty to loamy sediments. An organic soil horizon is developed at the surface of those cores, ranging in thickness from 0.4 to 0.75 cm. The levee (Ch-1 and Ch-7 to Ch-11, Fig. 1; Fig. 5, only Ch-9 shown) is built up of clayey-silty to loamy sediments. All levee cores show alternating clayey and silty layers. Sediments of the Estancia levee consist mainly of silt. The levee sediments of Ibiato are loamy.

4.3 Chronological framework

Sands at Loreto have an age of 14.9 ± 1.4 ka at their upper boundary (Fig. 5, and Table 1), with samples from beneath dating to 18.5 ± 1.3 and 16.9 ± 1.2 ka. We interpret the youngest age to give the maximum age for fluvial activity of the Loreto meander, suggesting the channel was abandoned after 15 ka. At Santa Fe the sands date to 13.1 ± 1.1 , 17.0 ± 1.5 , 15.6 ± 1.3 and 14.4 ± 1.7 from top to bottom. From these ages, we interpret the channel to have been abandoned after ca. 14 ka. At Limones, sands date to 11.5 ± 1.8 and to 19.1 ± 1.3 . Samples at Limones likely show two distinct depositional ages, suggesting the presence of a stratigraphic unconformity, and reactivation of the channel. Sands of the La Chacra channel date consistently to 14.7 ± 1.2 and 14.6 ± 1.3 ka, respectively (Table 1). Taken together, all samples date to the late glacial (Fig. 6).

Radiocarbon ages from the lower boundaries of the organic soil horizons should roughly indicate the onset of soil formation (i.e. the exposure to seasonal changes between sub-aquatic and sub-aerial conditions). Radiocarbon dating in Loreto at Lo-1 yielded ages from 8.2 - 8.3 cal ka BP (humins, Table 2, Fig. 5 and Fig. 6) at the lower boundary of the soil horizon (1.3 m) to 1.3 - 1.4 cal ka BP and 1.1 - 1.3 cal ka BP, respectively (humins/humic acids) at 0.6 m.

In Lo-157 the ages are 4.7 - 4.9 cal ka BP and 4.2 - 4.4 cal ka BP in 1 m and 2.9 - 3.0 cal ka BP and 2.2 - 2.4 cal ka BP at 0.5 m depth. For Santa Fe the radiocarbon results are 5.8 - 6.0 and 4.8 - 5.0 cal ka BP at 0.8 m, and 3.3 - 3.4 cal ka BP and 2.76 - 2.84 cal ka BP at 0.45 m depth. In Limones the soil dates to 6.3 - 6.5 cal ka BP and 3.0 - 3.1 cal ka BP at 0.55 m depth. For La Chacra results are 8.0 - 8.2 cal ka BP, and 3.6 - 3.8 cal ka BP at 0.7 m depth. Humic acids consistently yield younger ages than the humin fraction. The differences between the two dated fractions are small, indicating reliable ages. This does not apply however for Limones and La Chacra where the differences account for more than 50%. Here contamination with younger or older material must have occurred.

4.4 Provenance analysis

Cluster analysis clearly shows that the samples from La Chacra and Limones differ from all other samples (Fig. 7a). Thus, Limones which has been assigned to the P1 river generation resembles La Chacra from the P2 generation and there seems to be no resemblance between Limones and the two other P1 samples (Lo, SF). Furthermore, Limones was subsequently used by a P2 channel as shown by mapping evidence (Fig. 2d), and OSL data also indicate a reactivation of the channel (Fig. 6). Therefore it appears that the P2 generation occupied the abandoned P1 meander of Limones, and that the sample Li, although taken from the P1 paleochannel generation, was probably deposited by a P2 paleoriver. Therefore, for principal component analysis (PCA) and linear discriminant analysis (LDA), Li has been assigned to the P2 generation. The first three principal components of the PCA, which explain 61% of the variability, were used in the LDA as new variables (supplementary Table 2). The first component of the LDA explains 97% of the variability (Fig. 7b, supplementary Table 2). The LDA result shows that P1, P3, Grande and Mamoré plot together and that P2 is isolated, indicating a similar chemical composition of P1, P3, Grande and Mamoré. By multiplying the factor loadings of the three variables used in LDA for the first component (which explains

almost all variability) with the factor loadings of each element for the first three components of the PCA, an explanatory value for each element is retrieved (supplementary Table 2). Those elements with high values (positive and negative) best differentiate between the rivers, namely Si, K, Rb, Te, Ba, Pb, Mg, Ti and Zn (see values ≥ 0.7 in supplementary Table 2). The last three (Mg, Ti, Zn) are represented in smaller quantities in P2 sediments compared to the other generations, whereas the other elements (Si, K, Rb, Te, Ba, Pb) show higher contents in P2 sediments (Al normalized contents). Clearly the P2 generation differs geochemically from all other generations and the modern rivers.

In order to identify the elements which may differentiate between Brazilian Shield and Andean provenance, their composition was compared to samples from the headwaters of the Grande and Mamoré Rivers in the Subandean ranges (Guyot, 1993), and to samples from the western Brazilian Shield (Matos et al., 2009) by calculating ratios of Al normalized element contents. These ratios were calculated only for elements which differentiate the P2 generation from the other rivers, and for which information was available (i.e. for K, Rb, Ba, Pb, Mg, and Ti; Fig. 8).

For K, Ba, Mg, and Ti the ratio of our samples compared with the Subandean ranges differs from those of the Brazilian Shield (Fig. 8), and therefore may differentiate sediments of the Andes from those of the Shield. For Rb and Pb, Subandean ranges and the western Brazilian Shield provenances are similar and no differentiation between them is thus possible. It would be expected that Grande (G) and Mamoré (M) sediments display contents similar in K, Mg, Ba and Ti to the Subandean ranges, as they originate in the Andes. This is true for K and Mg (giving ratios around 1, Fig. 8). But Grande and Mamoré sediments however show Ba and Ti contents similar to Brazilian Shield samples, and much more Ba and less Ti compared to the Andes. Therefore, K and Mg may best differentiate between Andean and Brazilian Shield origins.

Sediments from the paleoriver generations P1 and P3 mostly show the same pattern as Grande and Mamoré sediments (concerning K, Mg, Ba, Ti, Rb and Pb), indicating their Andean origin. P2 differs significantly from this pattern. K contents are much higher compared to the Andes and only slightly lower than the Brazilian Shield, thus showing a higher resemblance to Brazilian Shield sediments. Mg contents are lower than in P1, P3, Grande and Mamoré compared with the Brazilian Shield. Ba and Pb contents in P2 are very high compared to Brazilian Shield and Andes and compared to the other channels. Ti is lower than for the Brazilian Shield, whereas P1, P3 and Grande have higher contents. Rb values are slightly higher than for the other generations and resemble more the sediments from the Andes.

In summary, sediments from the P1 and P3 channels show good resemblance with Grande and Mamoré sediments, most likely indicating their dominantly Andean origin. In contrast, particularly the high K contents observed in P2 sediments, may indicate differences in provenance, possibly from the Brazilian Shield. However, high contents of Rb, Ba, Pb cannot be explained by Brazilian Shield input, and suggest that the chemical composition of P2 reflects a mixing of sediment from both highland (Andes) and lowland (Brazilian Shield) sources.

5. Discussion

Geomorphological and dating evidence suggests that generation P0 or P1 constitute the oldest paleoriver generation, and generations P5 and P6 the youngest. In the following discussion of their overall significance for the evolution of the fluvial system in the south-eastern Llanos de Moxos, all mapped generations are subdivided into three groups according to their similarity and chronological constraints.

5.1. P0, P1, and P2 channels: Late Pleistocene and transition to Holocene

P0 and P1 channels show a similar less pronounced appearance due to subsequent erosion and only short river segments are preserved. This contrasts with P2 channels which are well distinguished and display long preserved river segments (Fig. 1 and Fig. 3, Table 4). It is therefore argued that P0 and P1 channels are older than P2 channels, although no direct dating for P0 is available, and due to the low precision of ages for P1 and P2 no chronology of river activity can be conclusively determined. OSL dating indicates fluvial activity of P1 and P2 in the late Pleistocene between circa 20 to 10 ka (Fig. 6). The minimum age for fluvial activity is constrained by soil formation in the infilled channel and meander scars which started at around 8 ka BP in Loreto and La Chacra (Fig. 5 and Fig. 6). This implies that fluvial activity must have ceased earlier to allow sedimentation of the fine grained material in which subsequent soil formation took place. Thus, P1 and P2 were probably active until the late Pleistocene or early Holocene.

The P2 generation differs geomorphically from the P1 generation and geochemically from the P1 and P3 generations and also from the Grande and Mamoré Rivers. Although the P1 and P2 generations show the same mean sinuosity (Table 4, Fig. 4b), P2 channels show a smaller radius of curvature, are narrower, and are flanked by a few bigger meander scars, indicating an underfit relationship. The absence of other oxbow lakes and meander scars along P2 channels also indicates a low-energy, passive meandering system (Brice, 1982; 1983; Thorne, 1997). This is a stable system compared to the P1 generation. A low-energy system not only indicates a decrease in discharge, but also denotes a change in the sedimentary load compared to P1, e.g. decrease in bed- and/or increase in suspended load (Brice, 1982; Bridge, 2003). Furthermore, this suggests that river flow was relatively continuous with a reduced flood peak compared to the previous generation, which would have otherwise led to a more active system with meander cut-offs and meander migration (Stølum, 1998; Schumm, 2005).

Clearly, the P2 generation differs geochemically from all other generations and the modern rivers (Fig. 7b). These geochemical differences could be explained by (i) differences in source material and provenance, or (ii) by different fluvial regimes and thus different transport and erosion mechanisms. (i) The chemical composition of P2 neither indicates a clear Andean nor Brazilian Shield provenance. Elevated K contents may point to input from the Brazilian Shield via tributaries. The modern San Pablo River flows along the border of the Brazilian Shield, a pathway which may have been formerly used by the P2 generation. This would have facilitated a measurable contribution from the Brazilian Shield. The fact that P2 transported and deposited sediments (levee building) supports the idea of an Andean origin, as rivers from the Brazilian Shield are so poor in sediment load (Sioli, 1984). (ii) The differences in geochemical composition may reflect in part also the effect of hydrodynamic processes during transport and deposition (due to different densities and shapes of minerals, Garzanti et al., 2010; Mongelli et al., 2006). Thus, different fluvial behavior may generally cause selective enrichment or depletion of minerals and consequently elements in suspended and bedload (Garzanti et al., 2010; 2011). The P2 generation shows a completely different morphology and points to a low-energy meandering river, which transports more suspended than bedload. Even though it is unlikely that sorting processes alone account for the observed differences they may have contributed to the differences in geochemical composition.

5.2. P3 and P4 channels: Holocene

River generations P3 and P4 show low sinuosity (1.2 - 1.4), a parallel to divergent river pattern and overlie the P0 - P2 generations. Probably the channels of each generation were not all active simultaneously but formed subsequently due to avulsions. P3 channels are younger than P2 channels, as P3 channels cross and overlie P2 channels (Fig. 1). Additionally, Bt horizon development was found in levees of P2 channels (Estancia, La Chacra), whereas such development is absent in the levee of Ibiato (P3), indicating weaker soil development and

more recent deposition (Denier, 2013). No P3 channels overlie P4 channels, whereas in the south of the San Pablo forest it seems that P4 channels overlie P3 channels (provided that they are not P3 channels which have been classified wrongly as P4 channels). Therefore, P4 channels are tentatively interpreted to be younger than P3 channels.

The LDA result (Fig. 7b) shows that P3 and modern Grande River sediments display similar chemical composition. This corroborates the idea that the P3 channels are built up by the Grande River as a sedimentary lobe (Lombardo et al., 2012).

With the formation of the P3 channels, a completely different fluvial regime evolved compared to generations P0 - P2. Due to the similarity of P4 to P3 channels – i.e. low sinuosity, high percentage of gallery forests (Table 4) – it is assumed, that P4 channels were built up under comparable conditions to those represented by the P3 channels. P3 activity has been associated with the formation of a large-scale depositional lobe composed from multiple P3 paleochannels organized in a distributary pattern (Lombardo et al., 2012). Comparatively rapid deposition of this lobe around 4.5 - 5.0 cal ka BP, and its subsequent abandonment, has been inferred from the interpretation of radiocarbon ages from an underlying regional paleosol (Lombardo et al., 2012) and from the presence of buried archaeological material dated to 4.2 cal ka BP (Lombardo et al., 2013). Whereas older dates from this paleosol of 5.8 - 7.0 cal ka BP were attributed to contamination due to bio- and pedoturbation (Lombardo et al., 2012), the spatial and temporal range evident in this dataset may also be interpreted as the result of less instantaneous deposition of the sedimentary lobe. This interpretation generally agrees with the successive construction of levees along the numerous P3 channels and their subsequent avulsion (a process already described by e.g. North and Warwick, 2007), leading to the overall mid-Holocene construction of the lobe. This change in the fluvial regime with formation of P3 channels has been attributed to increased transport capacities of the river system, coinciding with the formation of a delta-like terminal fluvial system prograding into a region with high water-tables and seasonal inundations (Lombardo et al., 2012; Nichols and

Fisher, 2007). However, the deposition of sediments in the LM may also have been the result of a progressive downstream decrease in discharge and transport capacity (Cain and Mountney, 2009) of the Grande River, which may have been unable to transport its sediment load beyond the Beni Basin towards the Amazon River.

The successive evolution of P3 and P4 channels contradicts the assumption of counter clockwise shifting of the Grande River and the associated proposed tectonic control suggested earlier by Dumont (1996) and Hanagarth (1993). A shift in westerly direction was proposed to have resulted from uplift along the margin of the Brazilian Shield (Dumont 1996; Hanagarth, 1993). P4 channels, however, are found to the east and west of P3 channels, rather indicating avulsive and more random course shifting of the upstream fluvial system at some nodal point.

5.3. P5 and P6 channels: the late Holocene and modern river network

P5 and P6 channels clearly constitute the youngest paleoriver generations, as they cross P1, P2 and P4 channels and occupy P1 river beds as underfit rivers (Fig. 2c, d and Fig. 3b). Probably they were active contemporaneously, as they are distinguished only by sinuosity which is an arbitrary measure. Nevertheless, P6 channels, which are more sinuous, show a much higher percentage of gallery forest (Fig. 4b, Table 4). Some of the P5 channels seem to be now inactive tributaries to the modern rivers, which would indicate that they were active contemporaneously with the latter. P5 channels were short and originated in the savannah plains. P6 channels, in contrast, might well be precursors of the modern rivers. This is indicated by their longer preserved river segments and their orientation parallel to the Ibaré and Tico Rivers. This may explain the differences in sinuosity and percentage of associated gallery forest between P5 and P6 channels.

P5 channels acted as short tributaries to the active rivers, originating in the savannah plain and therefore likely carrying little sediment. The P6 channels also reflect a completely different

fluvial regime compared with the P3 and P4 channels. Sinuosity is much higher (Fig. 4b) and sediment transport is interpreted to have been much lower, although levees have been built up (now occupied by gallery forest) indicating at least some sediment transport. The change in fluvial behavior from the P3/P4 system to the P6 channels may be explained by the fact that P6 channels probably originate in the lowland plains rather than the Andes as in the case of the generations P0 - P4. Therefore, predominantly fine grained suspended load was available and transport capacity was low due to the low gradient of the savannah plains.

Modern rivers in the study area are narrow, sinuous and have a gallery forest (Fig. 4, Table 4). They originate in the plain and probably developed from the P5/P6 system. The different sinuosities of the modern rivers are likely caused by the existence of dense forest, which restricts meander formation in the Negro River and San Pablo River and its tributary, located in the San Pablo forest (Fig. 1).

The modern Grande and Mamoré Rivers which border the study area in the south and west are wide and sinuous white water rivers, originating in the Andes. They are probably the successors of the P3/P4 system which also originated in the Andes. The Mamoré and Grande Rivers, in contrast to P3/P4 generations, show a higher sinuosity and greater discharge, indicating a change in the fluvial/sedimentary regime. The observed active meandering system likely points to a late Holocene fluvial system characterized by comparatively high discharge and suspended load as well as frequent floods.

5.4. The late Quaternary fluvial system in the Llanos de Moxos and its paleoclimatic implications

The channel form changes from the P1 to the P2 generation, pointing to changes in discharge and/or sediment load, may be related to a decrease in discharge and/or seasonality in the upper catchment, or to high channel mobility and avulsions on megafans along the Andean piedmont in the upper catchment (Piray, Grande and Parapeti Rivers; Horton and DeCelles,

2001); or they may be climatically driven. The Grande and Parapeti Rivers generated megafans with maximum extension during the Pleistocene (circa 60 to 28 ka), related to high seasonal discharge variability (Latrubesse et al., 2012). These Andean megafans reached as far downstream as the border of the Brazilian Shield and thus possibly received additional sediment input from the Brazilian Shield, as is proposed for the P2 generation. In fact, other fluvial systems in tropical South America indicate overall humid conditions in the late Pleistocene and transition to the Holocene, e.g. the Madre de Dios River in Peru, where aggradation has been interpreted as the result of increased sediment transport and discharge from around 12 cal ka BP on (Rigsby et al., 2009). Rivers of the Chaco-Pampa plain in Argentina and Paraguay (Pilcomayo, Bermejo, Salado) deposited extensive flood loams from ~13 to 8 cal ka BP and several displacements of river courses occurred (Barboza et al., 2000; Kruck et al., 2011). Climatically wet environmental conditions prevailed from ~18 ka on the Altiplano (Argollo and Mourguiart, 2000; Baker et al., 2001b; Placzek et al., 2006), leading to the high lake levels of the Tauca phase (Baker et al., 2001a). High lake levels from 17.4 - 12.4 cal ka BP (Argollo and Mourguiart, 2000), 18 - 11 ka (Placzek et al., 2006) or 13 - 11.5 cal ka BP (Baker et al., 2001b) on the Altiplano, and from 12.8 cal ka BP in the Pantanal (Whitney et al., 2011) indicate increased humidity due to strengthening of the SASM (Baker et al., 2001b). At the transition to the Holocene seasonality may have decreased and winter precipitation increased as interpreted from wetland formation in the Andes and its foreland (May et al., 2008; Servant and Servant-Vildary, 2003).

With the formation of the P3 channels a markedly different fluvial regime evolved. This change in the fluvial regime has been held responsible for the rapid deposition of a sedimentary lobe in the Llanos de Moxos, and was attributed to increasingly humid conditions in mid to late Holocene times (Lombardo et al., 2012). However, in the absence of further age constraints for P3, the interpretation of a successive construction of levees along the numerous P3 channels could also point to a longer, mid-Holocene depositional history of this

lobate distributary fluvial system, with only its subsequent avulsive abandonment resulting from a late Holocene climate change towards more humid conditions. In fact, dry fluvial basins adjacent to an upland area characterized by higher precipitation are typical settings for the formation of such fluvial distributary systems (Nichols and Fisher, 2007). Nevertheless, according to North and Davidson (2012), alluvial fans may evolve in all climates, the controlling factors rather being sediment supply and flow regime. Interestingly, particularly the megafans along the Subandean ranges in the Bolivian Chaco seem to have been active during the early and mid-Holocene (May, 2006; 2008), which would in turn have highly influenced fluvial responses in the LM. Rapid sedimentation and channel shifting, for example was characteristic on the Andean piedmont and on the megafans of the Piray, Grande and Parapetí Rivers during the mid-Holocene (~8 - 3 ka) and was attributed to geomorphic instability in relation to increased aridity and/or seasonality, with increasing importance of high-magnitude and low-frequency run-off events (May, 2006; 2008). Kruck et al. (2011) interpreted channel sands and dunes in the Chaco-Pampa plain in Argentina and Paraguay as markers for an intensification of aridity between 8.5 and 3.5 ka with occasional high magnitude floods. Parabolic dune formation between ~10 and 3.5 ka on the Bolivian Chaco megafans also indicates aridity (Latrubesse et al., 2012). Dry climatic conditions during the mid-Holocene in the Bolivian lowlands and the Altiplano are evidenced by numerous archives (Abbott et al., 1997; Baker et al., 2001b; Burbidge et al., 2004; Cross et al., 2000; Mayle et al., 2000; Tapia et al., 2003). In the Brazilian Pantanal pollen assemblages indicate a drier and/or more seasonal climate in the early to mid-Holocene (Whitney et al., 2011). In turn, the transition to wetter and less seasonal conditions from the mid-Holocene onward, led to overall geomorphic stability. Pollen assemblages and lake levels in the Bolivian lowlands and the Altiplano also indicate a return to wetter conditions in the late Holocene (Abbott et al., 2003; Argollo and Mourguiart, 2000; Baker et al., 2001a; Burbidge et al., 2004; Mayle et al., 2000; Tapia et al., 2003; Taylor et al., 2010). The time from 3.5 ka BP to the present is described as

a dominantly humid phase with arid spells in the Chaco-Pampa Plain (Kruck et al., 2011). Incision on the megafans of the Piray, Grande, and Parapetí Rivers and meandering of the rivers likely indicate smoothed discharge regimes under overall more humid conditions (May, 2006). A large scale shift of the Mamoré River after ~3 ka BP was attributed to more humid conditions and possibly a connection of the Grande River system to the paleo-Mamoré River via build-up of the P3 sedimentary lobe (Plotzki et al. 2013).

Recognition of climate changes in fluvial systems is not straightforward because reactions of river systems to climate changes are complex and non-climatic factors may also be responsible for fluvial changes (Macklin et al., 2012). Likely, the observed changes in the fluvial regime in the LM are substantially influenced by climatic changes, which are also evident in the regional paleoclimatic archives, but also affected by changes in the drainage network in the upper catchment.

6. Conclusions

Based on new geomorphological, stratigraphic and chronological evidence, seven paleochannel generations are identified in the southern Llanos de Moxos of SW Amazonia, for the first time providing insights into the evolution of the regional fluvial system since at least the late Pleistocene. The successive paleochannel generations are characterized by changes in sinuosity, channel width and river pattern, thus indicating substantial changes in the fluvial regime, most likely resulting from changes in discharge and sediment supply. Particularly, the transformation from an active meandering system (P1) to a passive meandering system (P2) at the Pleistocene to Holocene transition may be related to a climatically induced decrease in humidity and seasonality associated with changes in sediment load. In contrast, the subsequent Holocene fluvial system in the southern Llanos de Moxos (P3 and P4) seems to have been characterized by a phase of pronounced levee building, frequent local avulsions and overall low sinuosity channels. These dynamics

generally point to increasing sediment transfer from the upstream catchment, probably corresponding to the frequent channel shifts observed on the large upstream megafans of the Rio Grande and Parapeti along the proximal Andean foreland. Finally, the late Holocene is characterized by a highly active meandering system (P5, P6 and modern rivers).

While our results clearly reflect at least three significantly different geomorphic and hydrological periods in the evolution of the fluvial system since the late Pleistocene, the interpretation of these changes is ambiguous. In this context, changes in discharge and sediment load in the southern Llanos de Moxos during this timeframe may be controlled by combinations of two interrelated mechanisms: (i) spatial changes and re-organizations of the drainage network in the upper catchment, which are expressed by the observed differences in geochemical signatures between P2 and P1/P3, and are especially relevant when considering the high channel mobility and frequent avulsions inherent to river behavior on the megafans along the Andean piedmont (Piray, Grande and Parapeti Rivers); and/or (ii) climate changes with their associated local to catchment-scale modifications in vegetation cover, and changes in discharge, inundation frequencies and magnitudes, which have all likely affected the evolution of the fluvial system in the Llanos de Moxos, such controls are also evident in the available regional paleoclimate archives from the Andean catchments to the Amazonian lowlands. While a more detailed stratigraphical and chronological study in the Llanos de Moxos will further refine our results, additional data from upstream portions of these large catchments would substantially facilitate a more complete assessment of the temporal and spatial scales of changes. In summary, however, our study has revealed the enormous potential which geomorphic mapping and analysis combined with luminescence based chronologies hold for the reconstruction of the late Pleistocene to recent fluvial system in a large portion of Amazonia.

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Remote sensing data

- Google Earth 2002 and 2011. Source: <http://www.google.com/earth/index.html>.
- Landsat ETM 2001-08-11 (path 231, row 70 and 71). Source: <http://earthexplorer.usgs.gov/>.
- Landsat ETM 2001-09-19 (path 232, row 70 and 71). Source: <http://earthexplorer.usgs.gov/>.

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Table 1.

Summary data of OSL dating with site, sample name and Lab no., depth below present surface (used for cosmic dose rate calculation), grain size of quartz separates, the number of repeated D_e measurements (n), observed overdispersion (od), the concentration of dose rate relevant elements (K, Th, U), sediment water content used for calculations, dose rate (D), mean paleodose determined using the Central Age Model (CAM), the Minimum Age Model (MAM), and the Finite Mixture Model (FMM) as well as the resulting OSL ages. FMM parameters indicate which component was used (e.g., C1 = first (lowest) component), the number of components in the model (in parentheses), and the percentage of individual measurements included in the chosen component.

Location	Sample	Lab no.	Depth (cm)	Grain size (μm)	n	od	K(%)	Th(ppm)	U(ppm)	W (%)	D_{cos} (mGy a^{-1})	D (Gy ka^{-1})	D_e CAM (Gy)	D_e MAM(Gy)	D_e FMM (Gy)	FMM parameters	Age CAM (ka)	Age MAM (ka)	Age FMM (ka)
Loreto	Lo-157-3	AP16-1	420	100–150	52	0.25	1.52 ± 0.08	10.30 ± 0.40	2.92 ± 0.16	16 ± 2	118 ± 19	2.62 ± 0.17	42.95 ± 1.53	35.69 ± 2.65	38.97 ± 2.58	C1(2)/72	16.4 ± 1.3	13.6 ± 1.4	14.9 ± 1.4
Loreto	Lo-157-4	AP16-3	455	100–150	53	0.31	1.39 ± 0.04	8.46 ± 0.28	2.81 ± 0.16	14 ± 2	113 ± 11	2.42 ± 0.15	46.59 ± 2.05	43.29 ± 1.74	44.73 ± 1.38	C1(2)/96	19.3 ± 1.4	17.9 ± 1.3	18.5 ± 1.3
Loreto	Lo-157-5	AP16-5	490	100–150	51	0.33	1.53 ± 0.08	8.66 ± 0.28	2.47 ± 0.11	14 ± 2	108 ± 11	2.47 ± 0.16	39.58 ± 1.84	30.27 ± 2.54	41.67 ± 1.26	C2(2)/96	16.0 ± 1.3	12.2 ± 1.3	16.9 ± 1.2
Santa Fe	SF-145-1	AP17-1	310	150–200	50	0.32	1.13 ± 0.04	14.40 ± 0.40	4.05 ± 0.14	14 ± 2	135 ± 14	2.80 ± 0.15	36.96 ± 1.73	26.94 ± 2.06	36.58 ± 2.40	C2(3)/67	13.2 ± 1.0	9.7 ± 0.9	13.1 ± 1.1
Santa Fe	SF-145-2	AP17-3	350	150–200	51	0.35	0.88 ± 0.05	10.67 ± 0.27	3.09 ± 0.14	14 ± 2	128 ± 13	2.15 ± 0.15	39.12 ± 1.98	28.65 ± 3.67	36.61 ± 2.03	C2(3)/ 75	18.2 ± 1.5	13.3 ± 1.9	17.0 ± 1.5
Santa Fe	SF-145-3	AP17-5	390	150–200	47	0.44	1.14 ± 0.04	3.63 ± 0.12	1.09 ± 0.10	14 ± 2	122 ± 12	1.51 ± 0.10	30.56 ± 2.00	26.83 ± 1.03	23.54 ± 1.26	C2(3)/83	20.2 ± 1.8	17.7 ± 1.3	15.6 ± 1.3
Santa Fe	SF-145-4	AP18-1	485	150–200	44	0.27	1.21 ± 0.04	7.68 ± 0.27	2.14 ± 0.21	14 ± 2	109 ± 11	2.03 ± 0.14	36.56 ± 1.43	29.69 ± 2.68	29.20 ± 2.84	C1(2)/40	18.1 ± 1.3	14.7 ± 1.6	14.4 ± 1.7
Chacra	Ch-6-1	AP20-2	200	100–150	49	0.28	1.46 ± 0.05	8.23 ± 0.29	2.34 ± 0.18	14 ± 4	156 ± 16	2.40 ± 0.18	37.31 ± 1.51	34.50 ± 1.38	35.34 ± 1.17	C1(2) / 92	15.5 ± 1.3	14.3 ± 1.2	14.7 ± 1.2
Chacra	Ch-6-2	AP20-4	250	150–200	53	0.27	1.18 ± 0.04	4.85 ± 0.18	1.74 ± 0.24	14 ± 4	146 ± 15	1.78 ± 0.15	28.03 ± 1.08	25.58 ± 0.98	25.99 ± 0.90	C1(2)/88	15.7 ± 1.4	14.4 ± 1.3	14.6 ± 1.3
Limones	Li-211-2	AP21-1	280	200–250	53	0.42	1.86 ± 0.06	10.60 ± 0.50	2.52 ± 0.25	23 ± 2	140 ± 14	2.59 ± 0.39	35.50 ± 2.10	28.74 ± 1.30	29.74 ± 1.07	C1(2) / 80	13.7 ± 2.3	11.1 ± 1.8	11.5 ± 1.8
Limones	Li-211-3	AP21-2	540	150–200	48	0.38	1.00 ± 0.02	3.71 ± 0.16	1.14 ± 0.13	23 ± 2	102 ± 10	1.28 ± 0.08	26.75 ± 1.51	23.10 ± 1.03	24.53 ± 0.83	C1(2)/91	20.8 ± 1.7	18.0 ± 1.3	19.1 ± 1.3

Table 2.

^{14}C ages and calibrated ^{14}C ages BP (1 σ age range) from Loreto (Lo), Santa Fe (SF), Limones (Li) and La Chacra (Ch).

Location	Latitude	Longitude	Site	Sample	Lab no.	Material	Depth (cm)	^{14}C (a) BP	1 σ age range cal ^{14}C (a) BP
Loreto	– 15°12'06	– 64°45'38	Lo-1	Lo-1-4	Poz-34294	Soil (humin fraction)	60	1545 $\pm$ 30	1403–1342
					Poz-39539	Soil (humic acids)		1300 $\pm$ 35	1096–1262
			Lo-1	Lo-1-33	Poz-34295	Soil (humin fraction)	117	6970 $\pm$ 50	7681–7794
					Poz-39540	Soil (humic acids)		6650 $\pm$ 40	7440–7556
Loreto	– 15°12'09	– 64°46'12	Lo-1	Lo-1-6	Poz-36164	Soil (humin fraction)	135	7,440 $\pm$ 40	8168–8311
			Lo-157	Lo-157-1	Poz-39600	Soil (humin fraction)	50–53	2880 $\pm$ 40	2865–2991
					Poz-39636	Soil (humic acids)		2370 $\pm$ 60	2,160–2452
Santa Fe	– 15°08'26	– 64°43'07	Lo-157	Lo-157-2	Poz-39601	Soil (humin fraction)	100–105	4280 $\pm$ 40	4654–4851
					Poz-39637	Soil (humic acids)		3890 $\pm$ 50	4151–4385
			SF-146	SF-146-1	Poz-39602	Soil (humin fraction)	43–45	3175 $\pm$ 35	3268–3389
					Poz-39638	Soil (humic acids)		2745 $\pm$ 35	2756–2844
Limones	– 15°25'59	– 64°19'20	SF-146	SF-146-2	Poz-39603	Soil (humin fraction)	78–80	5200 $\pm$ 40	5,764–5984
					Poz-39639	Soil (humic acids)		4340 $\pm$ 40	4824–4958
La Chacra	– 14°51'06	– 64°43'38	Li-211	Li-211-1	Poz-46213	Soil (humin fraction)	55	5710 $\pm$ 50	6,325–6497
					Poz-46230	Soil (humic acids)		2925 $\pm$ 35	2929–3069
La Chacra	– 14°51'06	– 64°43'38	Ch-4	Ch-4-2	Poz-46219	Soil (humin fraction)	70–75	7380 $\pm$ 70	8027–8192
					Poz-46238	Soil (humic acids)		3490 $\pm$ 50	

Table 3.

Chemical composition of selected samples (sands and sandy) from paleochannel generations P1–P3 and the Grande and Mamoré Rivers.

Generation	P1	P1	P2	P2	P3	P3	modern	modern	modern	modern	modern
Site	Lo-157	SF-145	Li-211	Ch-2	Ib	Ib	Grande	Grande	Mamoré	Mamoré	Mamoré
Depth (cm)	460–480	455–480	260	440	140	220	255	380	0–15	340–355	380
<i>wt. %</i>											
SiO ₂	80.71	68.38	90.13	84.64	67.60	69.03	73.67	71.37	82.80	87.01	80.42
TiO ₂	0.18	0.29	0.06	0.11	0.28	0.26	0.24	0.27	0.17	0.10	0.14
Al ₂ O ₃	9.99	18.24	5.05	7.79	17.20	16.20	13.47	14.90	8.86	6.71	10.30
Fe ₂ O ₃	2.69	2.71	1.36	2.39	5.49	5.24	4.08	3.99	2.60	2.07	3.05
MnO	0.02	0.03	0.01	0.04	0.04	0.03	0.03	0.04	0.02	0.01	0.01
MgO	0.65	1.12	0.26	0.45	1.31	1.39	1.02	1.13	0.71	0.55	0.83
CaO	0.14	0.29	0.07	0.07	0.34	0.33	0.31	0.31	0.12	0.10	0.12
Na ₂ O	0.73	0.46	0.33	0.44	0.60	0.71	0.66	0.75	0.48	0.38	0.53
K ₂ O	2.15	2.89	1.42	2.12	2.82	2.79	2.61	2.67	1.72	1.40	1.90
Px	0.05	0.04	0.03	0.07	0.06	0.11	0.09	0.08	0.05	0.04	0.05
<i>ppm</i>											
S	127	95	26	95	139	128	199	213	108	66	92
V	42	105	6.2	35	71	83	78	85	46	29	47
Cr	9.6	57	9.6	24	963	935.1	32	53	27		20
Cl	84	73	26	61	95	52	77	47	62	22	57
Co	35	12		27	59	50	35	47	39	25	37
Ni	8.6				31	31		22	11		
Cu	14	10			141		8	19	9.6		
Zn	36	57	14	18	59	62	59	64	37	38	43

Generation Site Depth (cm)	P1 Lo-157 460–480	P1 SF-145 455–480	P2 Li-211 260	P2 Ch-2 440	P3 Ib 140	P3 Ib 220	modern Grande 255	modern Grande 380	modern Mamoré 0–15	modern Mamoré 340–355	modern Mamoré 380
Ga	12	19			16	12	16	18		9.7	
Ge		9									
As					10		10				
Rb	91	149	56	72	134	128	120	122	73	59	81
Sr	80	123	50	63	109	124	106	108	55	50	58
Y	32	33	12	17	46	38	35	41	32	13	20
Zr	500	481	133	331	568	484	480	497	1080	204	204
Nb	12	15		8.4	19	17	15	17	9.8		
Mo					17			14	17	11	17
Cd				11					21		
Te			10	40					10	10	
Cs	123	125	169	250	130	148	133	92	137	119	108
Ba	664	763	582	786	898	862	723	772	578	511	578
Ce				28	11	17		107			
Nd								31		27	
Hf	15	36		19	51		21	30	28	25	16
W				138							
Au				12							
Hg		18		21	28						
Pb	18	45	31	34	45	32	41	25	28	19	32
Bi	22	18	13	16	42	17	24	16	14	30	22

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Fig. 1. Geographical setting. Study area within Bolivia (inset) and the north-eastern Bolivian lowlands, the Llanos de Moxos. B = Beni River, M = Mamoré River, G = Grande River, I = Iténez River (parallel to Brazilian border). Study sites are indicated with white circles. Ch = La Chacra, Ib = Ibiato, SF = Santa Fe, Lo = Loreto, Es = Estancia, Li = Limones. Tr = Trinidad. P0 - P6 = paleoriver generations, dotted lines indicate paleochannels indicated by linear gallery forest, no channels could be detected there. Flow direction of rivers in north, north-western direction. Green = forests (San Pablo, San Andrés, Grande), grey colours = savannah. The sedimentary lobe of the former Grande River is represented by the P3 paleoriver generation.

Fig. 2. Illustration of meander scars and paleo channels (grey) with coring locations (white circles), temporal water filling (dark grey), forest (light grey) and underfit rivers (black dashed lines in c and d). a) La Chacra with corings Ch-1 to Ch-11. b) Loreto with corings Lo-1 to Lo-10 and Lo-157. c) Santa Fe with corings SF-145 and SF-146, and P6 channel. d) Limones with coring Li-211 and P2, P5 and P6 channels in vicinity.

Fig. 3. Satellite images of paleoriver generations (north is up). a) P0 channel at northern border of San Andrés forest. b) P1 channel, used subsequently by narrower P5 channel. c) P2 channel and meander scars. d) P3 channels and coring location of Ibiato (Ib). e) P4 channels in Grande forest. f) P6 channels.

Fig. 4. Box-and-Whisker plot diagrams of morphological parameters for paleochannel generations P0 - P6 and modern rivers. Center line displays the median, lower box the first quartile, upper box the third quartile and the vertical line the minimum and maximum of the data. a) Channel widths, b) sinuosity.

Fig. 5. Stratigraphy of cores taken at Loreto, Santa Fe, Limones and La Chacra with luminescence (lka; white boxes) and radiocarbon ages from humins and humic acids (cal kaBP; grey boxes). Soil horizon in black.

Fig. 6. Chronology of river generations P1 (Limones, Santa Fe, Loreto), P2 (La Chacra) and P3 (various, data from Lombardo et al., 2012). Black = OSL data (FMM), dark grey = ¹⁴C cal humins, light grey = ¹⁴C cal humic acids. OSL data give time of deposition of fluvial sands in the active channel; radiocarbon data give the subsequent organic matter accumulation in the infilled paleochannel.

Fig. 7. Results of statistical analyses. a) Dendrogram of agglomerative hierarchical cluster analysis. Horizontal dashed line discriminates three clusters: cluster 1 = Santa Fe (SF), Mamoré (M), Ibiato (Ib), Loreto (Lo), Grande (G); cluster 2 = Limones (Li); cluster 3 = La Chacra (Ch). b) Observations of linear discriminant analysis (LDA), the first component (F1) explains 97.10% of the variability, the second component (F2) explains 2.79% of the variability. Small symbols represent samples from the paleoriver generations P1, P2, P3, and from the Grande (G) and Mamoré (M) River. Big symbols represent the centroid of each group.

X¹ = Eastern Brazilian Shield, Granite, Subandean ranges, and PAAS, respectively

Fig. 8. Ratios of element content for selected elements (Al normalized) of P1, P2, P3, Grande (G) and Mamoré (M) to samples from the western Brazilian Shield (Matos et al., 2009) and samples from the headwaters of the Grande and Mamoré Rivers in the subandean ranges (Guyot, 1993). Samples with ratios close to 1 have similar element content as samples from the western Brazilian Shield or from the subandean ranges, respectively. Values > 1 indicate that our samples have higher contents in comparison to the others, whereas values < 1 indicate that our samples have lower contents.

A. Supplementary material

Supplementary Table 1. Results of dose recovery and thermal transfer tests.

sample	Lab no.	n	Given dose (Gy)	Recovered dose (Gy)	RSD (%)	Recovery ratio	Thermal transfer (Gy)	Thermal transfer (%)
Lo-157-5	AP16-5c	15/3	39.32	40.01 ± 2.68	6.7	1.02	0.01 ± 0.12	0.0
SF-145-4	AP18-1c	15/3	39.32	41.46 ± 4.23	10.2	1.05	-0.37 ± 0.72	-1.0
Ch-6-2	AP20-4c	14/3	29.49	30.67 ± 2.90	9.5	1.04	-1.59 ± 0.67	-5.7
Li-211-3	AP21-2c	15/3	29.49	30.68 ± 2.68	8.7	1.04	-0.54 ± 0.21	-2.0

Supplementary Fig. 1. Radial plot of paleodose values obtained by OSL in function of their statistical error. The distribution shows that the paleodoses values are distributed around the mean value represented by the gray band (2 sigma).

Supplementary Fig. 2. OSL ages for Loreto, Santa Fe, La Chacra and Limones with three different age models: Finite Mixture Age Model (FFM), Central Age Model (CAM) and Minimum Age Model.

Supplementary Table 2. Results of PCA and LDA and explaining values obtained for the elements (≥ 0.7 in bold).

PCA	PC1	PC2	PC3	LDA	F1	Calculation ^a	c
Na	0.555	0.235	0.536	PC1	-0.974	Na	-0.41
Mg	-0.733	0.257	0.446	PC2	0.063	Mg	0.83
Si	0.825	-0.157	0.494	PC3	0.218	Si	-0.71
P	0.474	0.621	0.187			P	-0.38
S	-0.147	0.750	0.197			S	0.23
Cl	0.427	0.536	-0.146			Cl	-0.41
K	0.969	0.082	0.122			K	-0.91
Ca	-0.685	-0.066	-0.110			Ca	0.64
Ti	-0.694	0.442	-0.021			Ti	0.70
V	-0.690	0.362	-0.230			V	0.64
Cr	-0.406	0.043	-0.285			Cr	0.34
Mn	0.578	0.654	-0.366			Mn	-0.60
Fe	0.074	0.527	0.455			Fe	0.06
Co	-0.317	0.784	0.395			Co	0.44
Ni	-0.567	0.365	-0.119			Ni	0.55
Cu	-0.389	0.157	-0.205			Cu	0.34
Zn	-0.539	-0.004	0.782			Zn	0.70
Ga	-0.584	-0.177	0.090			Ga	0.58
Ge	-0.193	-0.508	-0.549			Ge	0.04
As	-0.312	0.100	-0.154			As	0.28
Rb	0.825	-0.261	0.114			Rb	-0.80
Sr	0.666	-0.234	-0.036			Sr	-0.67
Y	-0.177	0.607	0.111			Y	0.23
Zr	-0.045	0.639	0.158			Zr	0.12
Nb	-0.363	0.631	-0.563			Nb	0.27
Mo	-0.301	0.228	0.673			Mo	0.45
Cd	0.259	0.706	0.000			Cd	-0.21
Te	0.845	0.357	-0.073			Te	-0.82
Ba	0.952	0.015	0.191			Ba	-0.88
Ce	-0.020	0.376	-0.196			Ce	0.00
Nd	-0.125	-0.083	0.662			Nd	0.26
Hf	-0.203	0.425	0.296			Hf	0.29
W	0.642	0.502	-0.359			W	-0.67
Au	0.642	0.502	-0.359			Au	-0.67
Hg	0.348	0.322	-0.603			Hg	-0.45
Pb	0.855	-0.202	0.040			Pb	-0.84
Bi	0.318	-0.134	0.714			Bi	-0.16

^acalculation for Na as example: $c(\text{Na}) = (-0.974 \times 0.555) + (0.063 \times 0.235) + (0.218 \times 0.536)$