ENSO-orchestrated sediment accumulation on Amazonian floodplains

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Application of a new geochronological method¹ quantifies century-scale floodplain sedimentation rates across a pristine 720,000 km² basin covering the principal sediment and water sources for the Madeira River^{2,3}, the largest sediment source for the Amazon⁴. Unlike previously studied floodplains, characterized by chronic sedimentation processes, accumulation is dominated by episodic crevasse splays emplaced hundreds to thousands of meters from the channel as 20-80-cm thick lenses, with system-wide and local recurrence intervals of ~8 years and multiple decades, respectively. Ocean temperature and stream flow records link these episodic events to cold-phase ENSO (El Niño-Southern Oscillation) *rapid rise* floods that debouch extraordinary volumes of sediment from the Andes. Transient, ENSO-driven processes control the formation of floodplains and modulate the efflux, transport, floodplain storage, and downstream delivery of sediment and associated nutrients to the Amazon main-stem. Consequently, resolving the role of large, infrequent events is essential for studies of particulate fluxes within tropical fluvial dispersal systems. Large, continental-scale, sand-bedded rivers sequester a significant proportion of their sediment load in floodplains, but the conditions under which storage occurs are undocumented and unpredicted. Previous studies of floodplain accumulation have described the spatial extent and depth of deposits⁵, estimated floodplain deposition using numerical models and surveys of grain size⁶⁻⁸, or used a variety of mapping, field sampling, and computations of the diffuse and channelized over-bank advection of turbid water⁴. Recent studies have measured floodplain accumulation using geochronology sufficient to resolve these rates on decadal timescales⁹⁻¹². No study has resolved the spatial and temporal distribution of individual floodplain accumulation events for large, dynamic fluvial dispersal systems. It is now possible to identify discrete events and measure the accumulation from such processes with near-annual resolution^{1,13}. Our measurements along two rivers at a variety of distances from the channel reveal previously undocumented spatial and temporal patterns that reflect the hydraulics of sedimentation and the occurrence of flooding and sediment delivery forced by global atmospheric processes.

The Beni and Mamore Rivers (Fig. 1) transport sediment from the rapidly eroding Bolivian Andes¹⁴ across the floodplains of a large foreland basin^{15,16}. Floodplains and channels are essentially pristine, without artificial levees, dams, dredging, roads, significant deforestation or cultivation, or other anthropogenic complications. The Beni drains 70,000 km² of the northern Bolivian Andes into the lowland Amazon Basin and then through 50,000 km² of forested floodplain, depositing ~100 Mt y⁻¹ of sediment as it traverses the foreland basin^{2,13}. The adjacent Mamore drains a 600,000-km² basin, much of which is floodplain. These basins are representative of the vast expanse of Andean-Amazonian foreland basins to the north.

Sampling was conducted at locations representing a variety of channel-floodplain geometries, during August and September of 1999 and 2000¹³. Sediment cores 65- to 160-cm deep were extracted (153 Beni and 123 Mamore) from surveyed transects at distances of 50-1200 m from the channel, predominately from the higher, mature floodplain on the cut-bank side of the river. Such spatial coverage allows: 1) resolution of discrete deposition events across transects traversing hundreds of meters of floodplain,

with cores typically spaced every 50 m, and 2) measurement of sedimentation along thousands of kilometers of river.

Cores were X-rayed to evaluate sedimentary structures and potential postdeposition disturbance. After imaging, some of the cores (80 Beni and 35 Mamore) were cut, processed, and clay-normalized ²¹⁰Pb activity profiles were measured with methods described and calibrated elsewhere¹, which allow the identification of individual sediment packages and their dating with annual resolution. The CIRCAUS (constant initial reach clay activity, unknown sedimentation) procedure for floodplain geochronology accounts for the basin-wide variation in the ²¹⁰Pb activity of riverborne sediment and relies upon only a few assumptions, each of which is testable.

More than 95% of Beni and Mamore cores depict episodic sediment accumulation best described by the CIRCAUS model¹. In most floodplain locations, sediment arrives as discrete packages of uniform age across an observed depth range (Fig. 2). Core granulometry and X-radiographs indicate that this sediment is silt-sized and is deposited as coherent packages in a low-energy environment. Fine horizontal laminations and other sub-millimeter scale structures show that the floodplain sediment has not been significantly disturbed since deposition and that bioturbation is negligible at most locations. Cross-bedding and other evidence for higher-energy deposition environments are rare on the cut-bank side of the floodplain, and is found mainly in point bar deposits close to the edge of the vegetation. Sediment packages are typically 20-80 cm thick, and vertical profiles from 6-m-high cut-bank outcrops indicate that the layers do not exceed 2 m in thickness. Hiatuses of decades occur between layers in cores with several events. Furthermore, the sediment at the floodplain surface (after accounting for the meteoric cap) is often decades old, and in such cases is not blanketed by fresh sediment with higher ²¹⁰Pb activity from recent sedimentation events. Although Beni and Mamore floodplain sediment arrives as discrete pulses, any particular floodplain location receives sediment infrequently. Hence, episodic sedimentation is the predominant mechanism for floodplain accumulation.

Averaged over these events, the accumulation rate varies with floodplain distance from the active river channel (Fig. 3). High, variable rates proximal (<300 m) to the channel represent *local* processes that construct natural levees through frequent decanting

of sediment over bank during annual floods – the few cores exhibiting constant sedimentation were located within this zone. Farther from the channel, lower, spatially uniform, temporally episodic rates represent the *extensive* processes that convey most sediment onto the floodplain through crevasse failures that produce broad splay deposits.

When accumulation dates from all cores are compiled (Fig. 4A), a basin-wide pattern emerges: distinct sedimentation pulses are separated by years to decades. This century-long geochronological record spans the entire foreland, suggesting that floods needed to facilitate widespread accumulation occur approximately every 8 years (11 events in 90 y). This is a separate phenomenon from the prior observation that many decades may pass between sedimentation events at a specific floodplain location. Because younger events bury older ones and most of the cores are \sim 1 m deep, our record is biased toward recent events and densely sampled river reaches. Therefore, only the dates of the peak centers should be considered, not the relative heights.

To interpret this temporal pattern, we investigated climatic variability. Eastern Bolivia experiences high rainfall in the Andes during cold-phase ENSO events (La Niña)¹⁷, causing the Beni River to flood¹⁸. We devised a sea temperature index (STI) appropriate for the Beni River (Fig. 4A). Over the last century, the nine La Niña years match the sediment accumulation record²⁷. Two exceptions, 1983 and 1998, are minor cold-phase ENSO years that follow intense warm-phase ENSO years. Sediment accumulation correlates well with such transitional cold-phase years (1975 is nontransitional La Niña, and 1977 the only exception).

The Mamore floodplain spans a transitional region of climate response to ENSO¹⁹, which appears to have migrated in the early 1970s: prior to 1970, rainfall was high during La Niña; after 1970, rainfall was lower during La Niña, and higher or unaffected during El Niño²⁰. However, the rainfall response in the Andean tributaries remained the same: elevated La Niña rainfall. After 1970, Mamore floodplain runoff was no longer synchronous with Andean sources, affecting flooding hydrology. For locations spanning the Mamore foredeep, no sediment has accumulated since 1974. This suggests a hiatus in significant flooding following a change in rainfall response to ENSO.

To explore the mechanisms governing floodplain accumulation and verify the last third of our century-scale geochronology, we examined water discharge at Rurrenabaque (Fig. 4B). Sediment accumulation consistently occurs whenever discharge rises more than 8,000 cms over a period of two days²⁷. These *rapid rise* years also correspond to peak discharges >12,000 cms. However, there are four *slow rise* years with maximum discharges above that threshold; these events are not recorded in our cores. As a result, the record of maximum flooding does not correlate to La Niña as well as does our floodplain accumulation record.

Beni floodplain topographic surveys indicate that floodplain inundation begins when discharges exceed 6,000 cms²⁷, a value exceeded annually. However, distal floodplains do not exhibit chronic accumulation. Sedimentation is episodic in several ways: 1) events correspond only to large, rapid rise floods; 2) neighboring cores (within 1 km) typically record the same event, but there is little synchrony between locations tens of kilometers apart; and 3) at any specific location, sediment accumulates only during some floods, with a hiatus of decades typically separating sediment pulses 20-80 cm in thickness. The environment of deposition is low energy and silt rich. Beni suspended sediment is dominated by fine silts, while the bed is composed of sand^{13,21}, so source material for floodplain sedimentation is derived from high in the water column. Inundation of the *entire* floodplain by sediment-laden water slowly decanted over levees during annual floods, the *local* mechanism that constructs the levees, would result in chronic, thin, synchronous sediment accumulation.

Instead, the thick episodic deposits are probably crevasse splays, delta-shaped deposits formed during levee failure. The banks are composed of loamy deposits susceptible to incision of crevasse channels during rapid overtopping¹³. Floodwater, decanted from high in the water column, would diverge into the densely vegetated floodplain, depositing an extensive lens of fine sediment within this low-energy environment. Such deposits are similar to crevasse splays described in the literature, including ancestral foredeep deposits preserved in the Andes²². Crevasse failure is more likely when the surrounding floodplain is relatively low, because of the higher hydraulic head. Conversely, a high floodplain is typically inundated by sediment-free water²³ from: 1) local rainfall; 2) river water that enters the floodplain through distant crevasses but deposits its sediment as it traverses the inundated forest; and 3) water that slowly decants over bank, depositing its sediment as it crosses the vegetated levees. The prevalence of

such 'black' water inhibits crevasse formation by reducing head. Hence, only a rapid rise flood can engender the critical elevation differential between water in the channel and in the floodplain required to form crevasses.

Sedimentation across the Bolivian Llanos, and therefore critical flooding, is closely correlated with ENSO. Crevasse splays, triggered by large, rapid-rise floods, account for the preponderance of floodplain accumulation – a fundamental and poorly understood process that appears central for pristine fluvial dispersal systems. Such transient floods also convey an extraordinary volume of sediment into and across the foreland – bank-full floods account for most of the sediment discharged and exceptional floods far surpass the mean annual flux (Fig. 4B). However, annual water discharge is relatively constant. Sediment transport, storage, and efflux within these major Amazonian tributaries are therefore dominated by extreme climate and flooding, fundamental processes that regulate fluxes of particles and associated carbon and nutrients within the Earth's largest river basin. Prior studies have construed Amazonian fluxes and fluvial processes as chronic and regular^{4,24,25}. We conclude that, on the contrary, the contributions of sporadic, extreme events merit special attention.

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- 27. Supplementary material.

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Figure 1. The Beni and Mamore River floodplains within the Llanos (lowland plains), northern Bolivia. Elevations > 300 m depicted as gray shaded relief, lower as a rainbow equal-area stretch. Floodplain transects are denoted with squares, in-channel samples with crosses. Approximate location of the foredeep and forebulge are determined with GPS surveys of longitudinal river gradient. One degree latitude is ~ 110 km.



Figure 2. Unsupported ²¹⁰Pb activity profiles from representative floodplain cores (dots) and clay abundance (×). Accumulation events (denoted with arrows) are dated with CIRCAUS geochronology^{1,13}. Increases within the top 10 cm represent meteoric fallout. **(A)** Beni River site located 2,000 m and 2,900 m from the channel when the sediment was deposited in 1974 (+/- 1.8 y) and 1951 (+/- 1.9 y). Meteoric cap is incomplete. X-ray depicts fine laminations throughout upper core, with minor cross-bedding below 80 cm depth. **(B)** Mamore River site located 175 m from the river when sediment was deposited in 1944 (+/- 2.0 y). Cap date is 1945. X-ray depicts fine laminations throughout core. These examples portray typical episodic accumulation events, without chronic sedimentation. Nearby sites along floodplain transects record similar events, a characteristic result that suggests such sediment packages blanket regions hundreds to thousands of meters in width and length.



Figure 3. Mean floodplain accumulation rates as a function of distance from the channel, Beni River, with best exponential fit ($r^2 = 0.82$). Because many floodplain cores do not resolve the lower bound of accumulation events, rates are conservative. Due to rapid channel migration across the floodplain, many of the core sites lay farther from the river during the most recent recorded deposition – concurrent river distances were measured from images (Landsat or aerial) bracketing the recorded date of each accumulation event. Projected across the floodplains of the Beni foreland basin¹³, this relationship provides for an estimated average net sediment loss of ~100 Mtonnes y⁻¹.



Figure 4. (A) Temporal distribution of floodplain accumulation events. STI is the average sea-surface temperature anomaly in the eastern equatorial Pacific (150W-80W, 4N-4S) from Nov to Feb (the early rainy season months, temperatures derived from (26). Marked years exhibit either STI <-1° (La Niña, threshold marked) or the floodplain accumulation of sediment (CIRCAUS geochronology cannot discriminate events 1 year apart). ENSO, sediment, and water years run from Oct to Sep. (B) Maximum (solid curve) and mean annual (dotted) water discharge, and 2-day rise to flood peak (dashed) discharged from the Andes (Beni River at Rurrenabaque). Lower threshold shows both the minimum rapid flood rise (~8,000 cms) associated with floodplain accumulation and the mean annual sediment flux (~250 Mtonnes). Upper threshold represents the minimum discharge associated with floodplain accumulation (~12,000 cms). Also plotted is total sediment discharge (bars) conveyed by transitory bank-full floods (>6,000 cms)²⁷, which comprise >60% of the average efflux.