Fluvial transport of sediment across a pristine tropical foreland basin: channel–flood plain interaction and episodic flood plain deposition

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Abstract We present the results of study of the Beni River, a large, sand-bedded river which drains 68 000 km^2 of the northern Bolivian Andes into the Amazon River basin. The fieldwork included surveys of channel, bank, and flood plain topography, granulometry, stratigraphy, and system-wide flood plain accumulation rates measured with ^{210}Pb geochronology. These results were evaluated within the spatial and temporal framework of a GIS analysis of four decades of channel migration, derived from Landsat and aerial imagery. The resulting flux model of sediment interchange between the channel and flood plain agrees with a net foreland accumulation of ~100 Mt year^{-1}, as independently determined using three decades of stream sampling and gauging records. The majority of this sediment is distributed throughout the distal flood plain, while channel-proximal and bed accumulation, lateral migration, and the formation and filling of oxbow lakes all play a relatively minor role. This predominantly distal flood plain accumulation occurs in remarkable episodic pulses of decadal recurrence interval, linked to major floods associated with cold phase ENSO events.

**Key words** flood plain accumulation; ^{210}Pb geochronology; ENSO; Bolivia; river migration; sediment budget

INTRODUCTION

Decadal-scale mechanics of sediment transport and accumulation, lateral channel migration, flood plain deposition, and flood plain–channel interaction within large, sand-bedded rivers are topics of considerable global relevance to scientists, engineers, and land-use planners. However, most such rivers throughout the world have been profoundly altered by dams, levees, dredging, and flood plain deforestation, making it difficult to

study such rivers in a natural state. Our objective was to develop a means to quantify the sediment budget of large, sand-bedded river systems, including an accounting of the annual interchange of sediment between the channel and the flood plain. This approach was then applied to the Beni River, which drains 68 000 km^2 of the northern Bolivian Andes into the lower Amazon basin, depositing ~100 Mt of sediment annually as it traverses 800 km (river distance) across a large foreland basin. The Beni offers a unique opportunity to study a pristine river which interacts dynamically with its forested flood plain, so that we can quantify these processes for a natural fluvial system.

STUDY AREA

The Beni River is the principal sediment source for the Madeira River (Guyot, 1993), in turn one of the most important tributaries of the Amazon River and its principal sediment source (Dunne *et al.*, 1998). During the Cenozoic, crustal thickening and eastward propagation of the central Andean Cordillera provided a topographic load on the cratonal lithosphere, forming a large retroarc foreland basin, with an active foredeep at the Andean piedmont (Horton & DeCelles, 1997). Andean tributaries of this river drain both semiarid areas of high altitude and areas of tropical humid forest of the sub-Andes. Elevations range from 6400 m along the Cordilleran peaks to 200 m at the piedmont town of Rurrenabaque, located at the upper limit of the extensive flood plains of the Beni foredeep, to 115 m at its confluence with the Mamore River at the
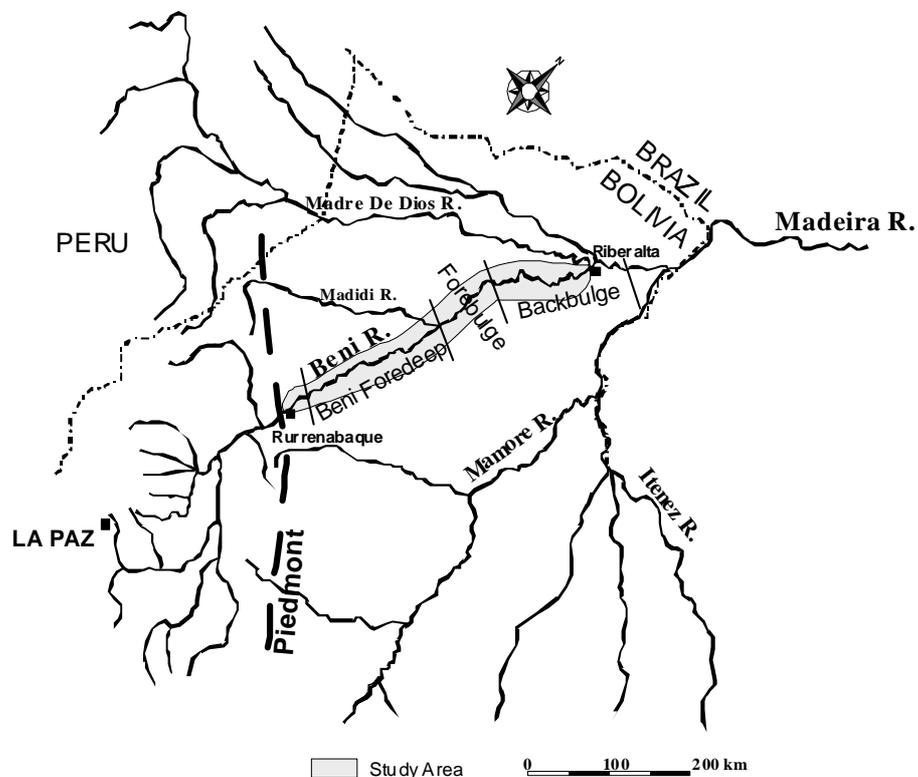
Fig. 1 The Beni River and study area for flood plain sampling, and principal long-term river gauging stations at Rurrenabaque and Riberalta are noted. Approximate location of the foredeep, forebulge, and backbulge secondary basin are depicted, as determined by differential GPS surveys of river gradient (Aalto, 2002).

Brazilian border to form the Madeira. The study area comprises an extensive forested flood plain in near pristine condition without levees, upstream dams, bridges, or roads; it is effectively uninhabited, with minimal logging and agricultural clearing of the dense primeval tropical rainforest (Fig. 1). While portions of the Andean tributary basin above Rurrenabaque have been disturbed by mining, road construction, and agriculture, the overwhelming majority of the land remains in a natural state. Sediment supply to Rurrenabaque and the Beni foredeep has been measured (Guyot, 1993) and modelled (Aalto *et al.*, in review) on daily-to-decadal temporal scales over the past 35 years, and the bed and suspended sediment granulometry have been measured throughout the system (Guyot *et al.*, 1999; Aalto, 2002). Along with the hydraulic geometry, these data provide insight into the mechanics of sediment transport along the Beni River.

METHODS

To investigate the sources, transport and storage mechanics, and chronology of flood plain sedimentation for this important tributary to the Amazon, we surveyed channel, bank, and flood plain topography, channel slope, granulometry, and stratigraphy (Aalto, 2002). The flood plain was cored at 139 locations, and system-wide flood plain accumulation rates across the foreland basin were measured with ^{210}Pb geochronology, using the recently-developed CIRCAUS (Constant Initial Reach Clay Activity, Unknown Sedimentation) model (Aalto, 2002; Aalto & Nittrouer, unpublished manuscript). Core sampling was primarily along transects into the forested flood plain on the cutbank side of the river, both at meander bends and straight reaches of the river. Locations were chosen randomly, subject to logistical constraints. These field data are buttressed spatially and temporally with a geographical information system (GIS) analysis of four decades of channel migration, derived from overlays of Landsat and aerial imagery. Water and sediment discharge have been measured at Rurrenabaque and Riberalta over the past several decades (Guyot, 1993), indicating a net sediment loss to the foreland of approximately 100 Mt year^{-1}.

SEDIMENT INTERCHANGE BETWEEN THE CHANNEL AND FLOOD PLAIN

The GIS analysis of channel location over four decades provides a measurement of eroded and deposited channel bank area for each time interval. Converting these areas to migration rates (area/channel length) and then averaging for each 10 km UTM latitude increment of Beni River valley length, we have produced a number of decadal-scale measurements, including lateral migration rate, sinuosity, oxbow lake infilling rate, and bar and channel area (Aalto, 2002). For these same intervals, we surveyed the heights of the channel banks, including the height of the eroded cut banks (the outer banks of a river meander) and the deposited point bar (50–100 m past the edge of the vegetation). Therefore, by multiplying the eroded or deposited bank area by the respective heights (including the channel depth to the thalweg) and sediment density, we estimated that the channel migration of the Beni erodes 220 Mt of cutbank sediment every year, redepositing 212 Mt of sediment back onto the point bars (Aalto, 2002). This exchange is larger than the total annual sediment discharge at

Rurrenabaque, gauged at approximately 200 Mt year[-1] (Guyot, 1993). Because the cut banks are on average higher than the vegetated point bars, channel migration results in a net transfer of 8 Mt year[-1] of sediment from the flood plain to the channel, as depicted in Fig. 2. Also shown are the accumulation fluxes derived from measured deposition rates for the proximal and distal flood plain and the channel bed, determined using ^{210}Pb geochronology (Aalto & Nittrouer, unpublished manuscript). To produce these estimates, the average flood plain and channel areas are measured for each 10 km UTM interval and then each area is multiplied by the measured accumulation rate, an empirically-determined function of lateral distance from the active channel (Aalto, 2002).

An accumulation of 98 Mt year[-1] of sediment with the Beni foreland is estimated as the integrated result of the processes of flood plain accumulation and sediment interchange between the channel and flood plain. This total sediment loss agrees with the difference between the fluxes at Rurrenabaque and Riberalta observed in the long-term gauging records. The annual sediment transfer from the cut banks to the point bars is larger than the annual sediment input at Rurrenabaque, but the net change in

Calculated Beni River Sediment Fluxes


Total Net Annual Flux to FP: 98 Mt/a.
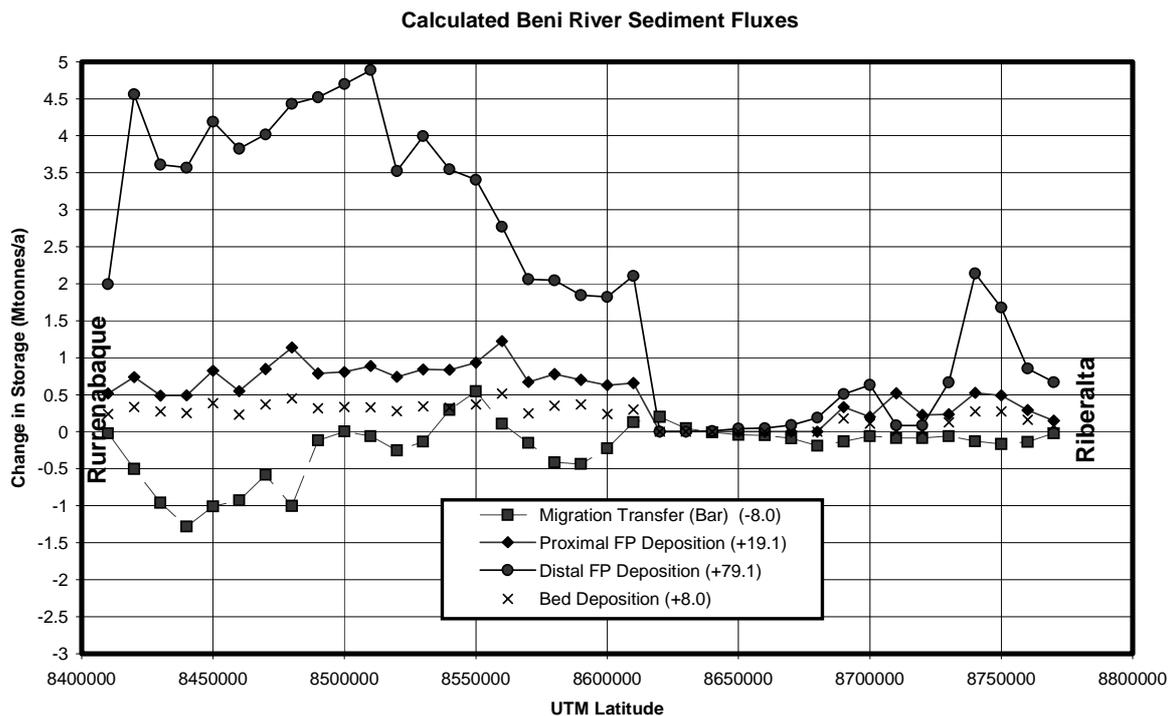
Fig. 2 Summary of results from the sediment transfer calculations for the Beni river–flood plain system spanning the retroarc foreland basin. Sediment interchange is plotted for each 10 km UTM latitude interval along the Beni River valley, from Rurrenabaque to Riberalta. (Because the Beni River flows approximately from south to north across its foreland basin, this is a convenient way to present results from the GIS analysis; to account for deviations from a due north direction, all results have also been corrected for true valley and channel length.) Totals for each sediment transfer process summed across the Beni foreland are reported in parentheses, with positive numbers representing an increase in flood plain storage. Bar migration transfer flux is net (bar deposition – bank erosion). Proximal flood plain deposition represents the higher accumulation rates observed within 300 m of the channel, while distal flood plain deposition occurs primarily as massive crevasse splay deposits hundreds of metres wide and extending up to 10 km distance from the channel. Modified from Aalto (2002).

storage due to such channel migration is small. The majority of the system accumulation is distributed throughout the distal flood plain, while channel-proximal and bed accumulation, lateral migration, and the formation of oxbow lakes all play a relatively minor role (Aalto, 2002).

EPISODIC FLOOD PLAIN ACCUMULATION AND ENSO

The CIRCAUS model developed for ^{210}Pb geochronology on river flood plains (Aalto & Nittrouer, unpublished manuscript) has so far been applied to more than 90 of the several hundred flood plain locations sampled by vertical coring throughout the Beni and Mamore river systems. Applying this method to date the depositional events that formed our sediment cores, we find (Aalto, 2002) that the vast majority of flood plain sites receive sediment in temporally-isolated episodic pulses, rather than as the "constant" annual sediment accumulation assumed in previous ^{210}Pb geochronological models. When all such accumulation events are plotted according to the year of deposition (Fig. 3), we observe (Aalto, 2002) episodic flood plain deposition pulses of decadal recurrence interval, most likely linked to major floods closely associated with large "La Niña" events (the cold phase of the well-known El Niño-Southern Oscillation cycle of equatorial Pacific sea surface temperatures). Field observations on the modern Beni and Mamore flood plains (Aalto, 2002) and ancestral foredeep deposits preserved as lithological remnants throughout the Andes and Altiplano (Horton & DeCelles, 2001) suggest that such deposits typically form as large crevasse
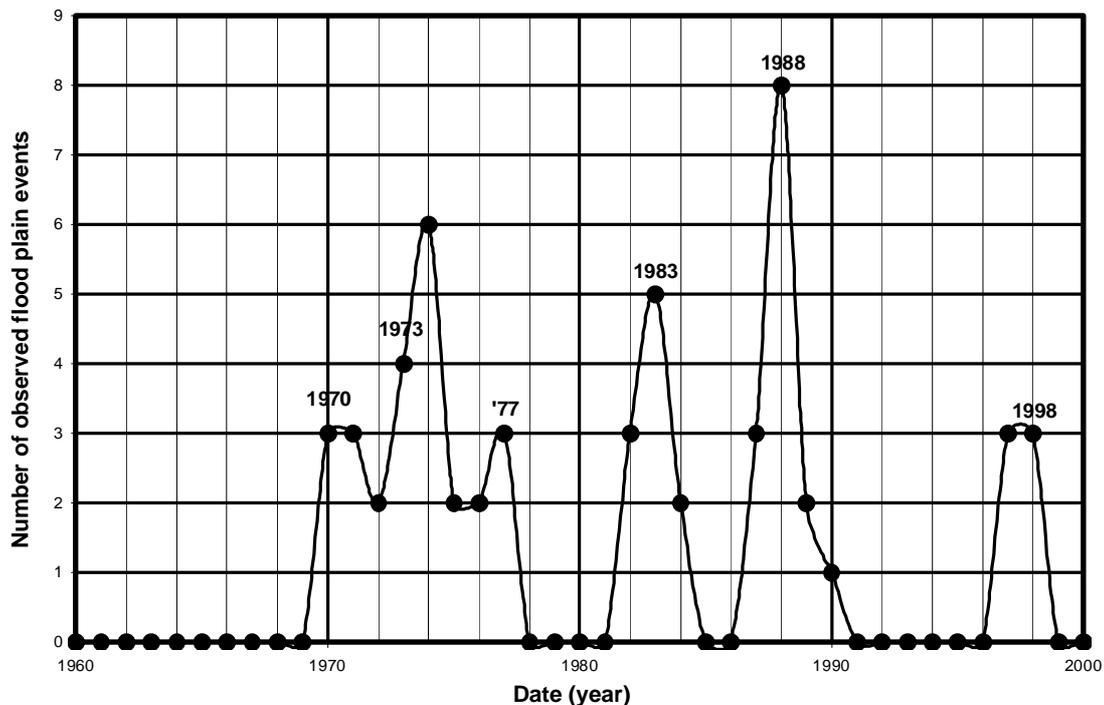
Fig. 3 Flood plain sedimentation events for the past 40 years, as dated with the CIRCAUS ^{210}Pb method. The date of each discrete depositional event was determined by dating sediment in the flood plain cores. Significant cold-phase ENSO dates are depicted in black. Modified from the 100-year flood plain deposition data set in Aalto (2002).

splays deposited during major floods. A detailed comparison (Aalto, 2002) of historical gauge records of extraordinary water and sediment discharge events at Rurrenabaque likewise show a strong correlation to equatorial Pacific sea surface temperature anomalies associated with cold-phase ENSO. Because the Beni is a principal sediment supplier to the lower Amazon River and is also analogous to other sediment-laden rivers draining Bolivia and eastern Peru, these ENSO-driven processes probably modulate sediment delivery to the mainstem Amazon, estuary, and shelf environs.

CONCLUSION

Sediment supply, interchange, and accumulation along the Beni River is dominated by channel–flood plain interaction orchestrated by channel migration and cold-phase ENSO events. This perspective, established here for a pristine fluvial dispersal system, suggests that similar flood plain processes may also be or perhaps at one time were important for other large, sinuous, actively migrating rivers endemic to lowland flood plains throughout the world. However, many of these systems have been dammed, straightened, and immobilized with rock or concrete levees, diminishing the magnitude of these natural processes of sediment exchange between the river and its flood plain. Despite such prevalent anthropogenic alterations and other significant differences in climate and fluvial geomorphology between river basins, the basic processes of flood plain deposition and sediment exchange due to channel migration can be quantified in a similar matter. Therefore, the techniques presented here can be employed to investigate the sediment budgets of other sand-bedded river–flood plain systems.

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