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EFFECTS OF TECTONIC DEFORMATION AND LANDSLIDES IN THE EROSION OF A MOUNTAIN PLATEAU IN THE TRANSITIONAL ZONE BETWEEN THE CENTRAL AND PATAGONIAN ANDES

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ABSTRACT. Valley downcutting and tectonically-related landslides have driven the evolution of the landscape in the transitional zone between the Central and Patagonian Andes. Since the onset of the basin's development, around 300 km^3 of rock have been eroded from the plateau. Three-quarters of the erosion occurred in the area undergoing tectonic uplift. Bedrock landslides estimated between ~31 to 5 ka caused significant hillslope erosion, at a rate of 0.318 km^3/ka, and created seven dams. Despite their capacity to remove large amounts of rock from hillslopes, by creating dams, landslides have graded fluvial courses to local base levels and sediments have been trapped at timescales lasting tens of thousands of years. Around 95 percent of the total rock volume involved in large rockslides still remains in the depositional area. Only post-glacial retreat landslides are observed in the mountain area (which was glaciated during the Last Glacial Maximum, LGM), and the only landslide event contemporary to the LGM is located in the piedmont area. These facts indicate that in arid regions such as the study area, landslides do not constitute an important source of sediments to the foreland if there is a lack of coupling between them and an effective massive erosion agent, such as a glacier. Although the removal of large amounts of rock from valley slopes contributes to the degradation of the relief generated by uplift, the results presented here suggest that they might also have counteracted the effects of tectonic uplift by interrupting the sediment flux cycle, trapping sediments and creating positive sediment balances.

INTRODUCTION

Over the past ~30 years numerous studies have examined the feedback between mountain building and surface processes (Molnar and England, 1990; Burbank and others, 1996; Willett, 1999; Montgomery and others, 2001, Montgomery and Brandon, 2002; Willett and Brandon, 2002; Spotila and others, 2004; Molnar and others, 2007; Strecker and others, 2007; Koppes and Montgomery, 2009; Korup and others, 2010; Clarke and Burbank, 2010; Larsen and Montgomery, 2012). In active orogens, uplift influences the erosive power of streams through changing gradients, causing incision (Schumm and Ethridge, 1994; Bull, 2008), which in turn drives isostatic compensations with adjustments depending on lithospheric conditions (Montgomery, 1994; Champagnac and others, 2007). Most of the studies proposed glacial and fluvial processes as main actors in relief degradation. However, it has recently been recognized that bedrock landslides can have a key role in landscape evolution, depending on their dimensions and on environmental conditions. Hovius and others (1997), Montgomery and Brandon (2002), and Hovius and Stark (2006) have discussed the role of landslides in drainage basin development in young orogens and their importance as sources of sediment for fluvial courses.

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Large landslides certainly play a major role in landscape denudation, but in certain regions it can take tens of thousands of years after impoundment before their detritus become a part of the sedimentary budget of rivers. Recent studies have shown that large landslides causing river blockages can delay overall erosion in an orogen. On the Tibetan Plateau, Ouimet and others (2007) observed that landslides sometimes controlled the longitudinal profile of rivers, interrupting their adjustments to factors driving disequilibrium such as tectonic uplift, climatic conditions, or lithological contrasts. In the Himalayas, Hewitt (1998), Korup and others (2010), and Hewitt and others (2011) noted that by fragmenting rivers and constituting transitory base levels, large landslides can cause millennia to pass without incision in the sector upstream from the dam.

The above studies analyzed the link between mountain building and surface processes in the steepest orogens on Earth, where uplift and incision drive slopes to threshold values that lead to landsliding. In the plateau area of the transitional zone between the Central and Patagonian Andes, valleys are carved into a thick sequence of sub-horizontal volcanic layers (plateau), and local relief reaches maximums of 1,000 m. However, the frequency and sizes of landslides are comparable to the Himalayas (Korup and others, 2010; Penna and others, 2011). In recent years, studies have focused on the neotectonic activity that folded and faulted the plateau (Folguera and others, 2004) and have explored the role of tectonic structures in controlling the location and size of landslides (Penna and others, 2011). The present paper integrates approaches using hillslope and fluvial geomorphology to explore the landscape's responses to tectonic uplift and to address the implications of large bedrock landslides on the long and short-term development of landscapes (fig. 1).

REGIONAL SETTING

Geology

Since the late Miocene, the study area has experienced multiple phases of compressive deformation. The first phase comprised the inversion of the Oligo-Miocene Cura Mallín Basin (Jordan and others, 2001), which resulted in the deposition of synorogenic volcaniclastic sequences from the Mitrauquén Formation (9–8 Ma using the K-Ar dating method; Suárez and Emparán, 1995). Outcrops of the Cura Mallín and Mitrauquén formations are recognizable in the middle sectors of the Reñileuvú and Guañacos valleys (Penna and others, 2011). After the deposition of sediments from the Mitrauquén Formation, an erosive event produced a well-exposed horizontal surface in the middle section of the Reñileuvú valley. During the Plio-Pleistocene, volcanic sequences from the Cola de Zorro Formation covered the landscape and formed a wide volcanic plateau. The bottom of this formation dates from 5 Ma (whole rock K-Ar dating method; Vergara and Muñoz, 1982), and the top dates from 1.7 $\pm$ 0.2 Ma (whole rock K-Ar dating method from a sample taken in the Guañacos valley; Folguera and others, 2004). A second compressive event deformed the layers from the Cola de Zorro Formation, through N-S trending faults and folds (Folguera and others, 2004). Based on stratigraphic and morphologic analyses, Folguera and others (2004) proposed that there was ongoing tectonic activity in this area.

A vertical offset of 400 m in the volcanic sequences from the Cola de Zorro Formation, along the Chacayco fault (fig. 2A), allows the uplift rate to be estimated at around 0.23 mm/y. East of the Chacayco fault, the Guañacos fault has also dislocated the volcanic layers, creating a scarp around 50 m high and 43 km long (fig. 2B). On top of the structural plains, the Guañacos scarp is very well preserved, with its slope dipping to the east at around 7° and blocks of volcanic rocks forming a scree slope. The scarp is a continuous linear step with several aligned ponds that have developed at its toe. The

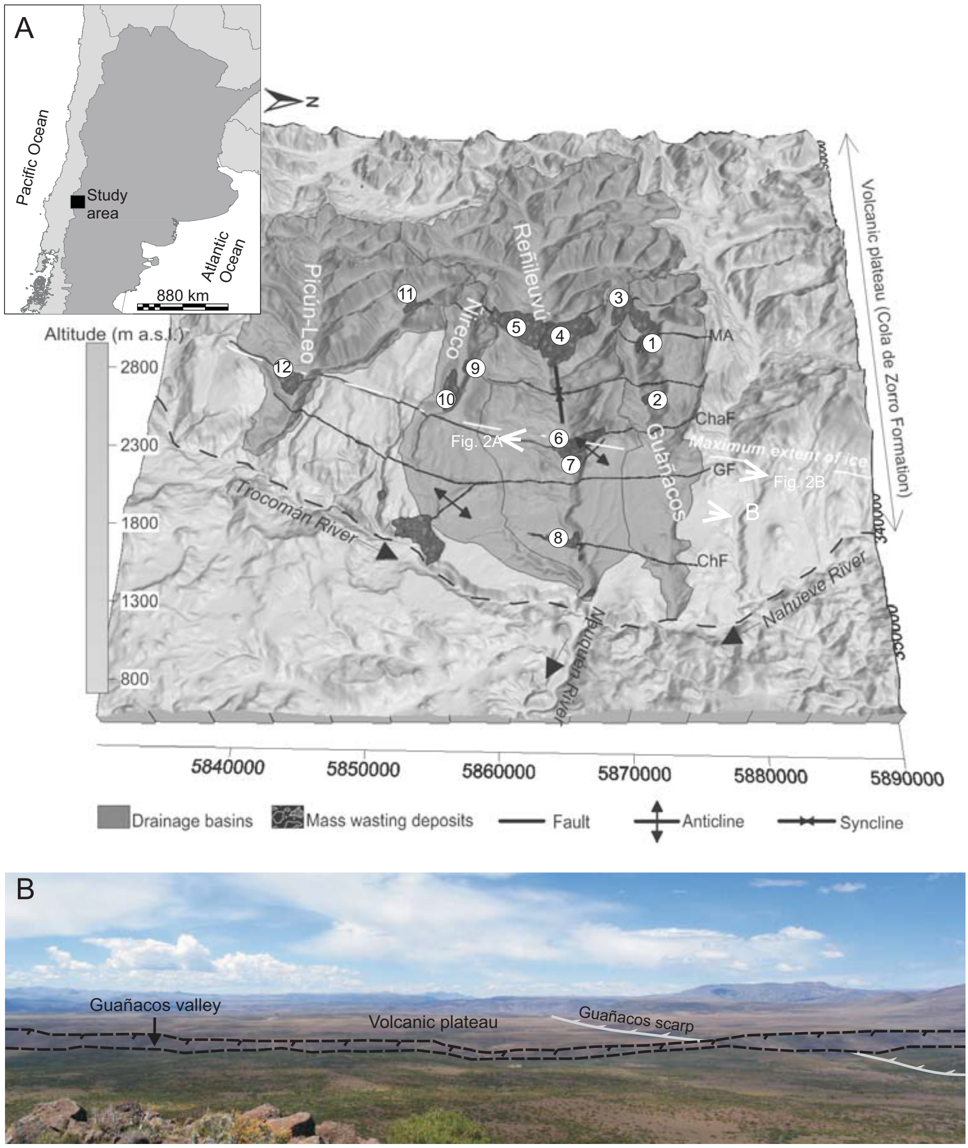


Fig. 1. (A) 3D view of the study area location from SRTM topography, drainage basins limits, and main morphological and tectonic features. UTM coordinates (UTM zone 19S). (B) View to the south of the volcanic plateau. Main tectonic structures are referred to in the figure as: MA, Moncol anticline; ChaF, Chacayco fault; GF, Guañacos fault; and ChF, Chochoy Mallín fault. Numbers relate to rockslide names: 1, Guañacos rotational slide I; 2, Guañacos rotational slide II; 3, Cerro Guañacos rock avalanche; 4, Piche Moncol rock avalanche; 5, Cerro Moncol rock avalanche; 6, Chacayco rock avalanche; 7, Chacayco rotational slide; 8, Chochoy Mallín rock avalanche; 9, Ñireco topple; 10, Lauquén Mallín rotational slide; 11, La Negra rock avalanche; and 12, Picún Leo rock avalanche.

Guañacos scarp is dissected by the main valleys, which also expose a dislocation of the Cola de Zorro lava flows (fig. 2C). To the east of the Guañacos structure, displacement along the Chochoy Mallín fault resulted in a ~15 m scarp, with some aligned ponds that have developed in the structural plain between the Guañacos and Reñileuvú valley (Penna and others, 2011).

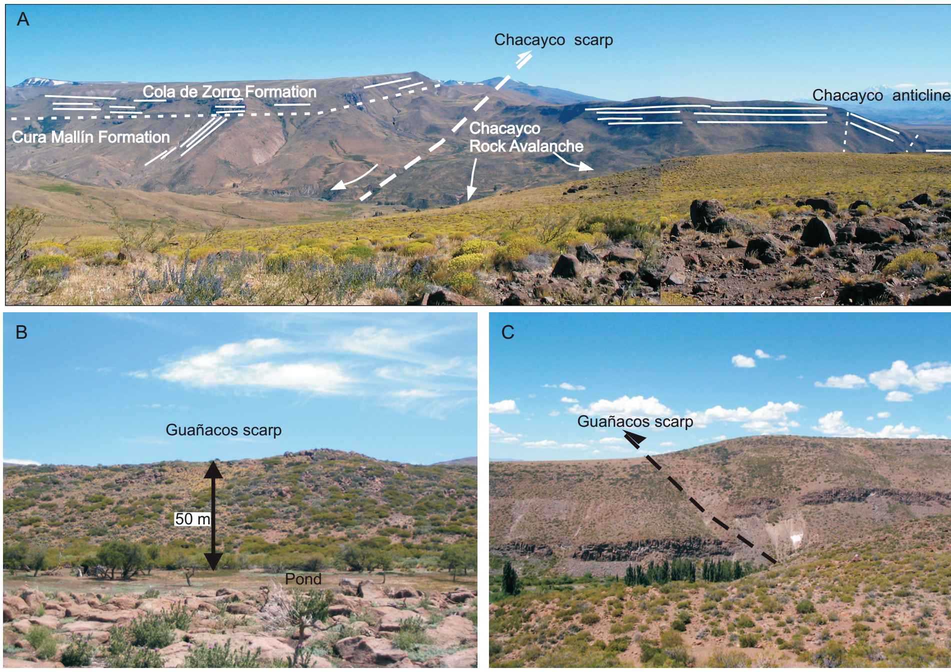


Fig. 2. (A) View to the north of the Chacayco fault, geologic units, and location of the Chacayco rock avalanche (see location in fig. 1, modified from Penna and others, 2011). (B) View to the south of the Guañacos fault (see location in fig. 1). (C) View to the west of the Guañacos scarp.

Landscape Evolution

The study area is located in an arid region of the Andes. Annual precipitation ranges between 620 to 720 mm, according to records from the meteorological stations at Chacayco (37,35S-71,07W; ~1270 m a.s.l.), and Chochoy Mallín (37,40 S-70,87 W; 1300 m a.s.l.). Most of the precipitation occurs between May and July (http://www.mineria.gov.ar/estudios/irn/neuquen/tablametypluvio.asp). The landscape is characterized by E-W valleys separated by structural plains. The Guañacos, Reñileuvú, Ñireco and Picún-Leo creeks run into deeply incised valleys and are tributaries of the Nahueve-Neuquén and Trocomán rivers, flowing N-S and S-N, respectively (fig. 1).

The landscape exhibits morphologies related to glacial, fluvial, and landsliding events. Lateral moraines are recognizable in the upper parts of the structural plains. Based on morphological analyses, Penna and others (2011) proposed that alpine glaciers filled the upper and middle sections of the valleys during the Last Glacial Maximum (LGM), while the lower sections were shaped only by fluvial processes. Radiocarbon dating of organic material from glaciofluvial deposits in the Reñileuvú valley indicates a possible glacial retreat at ~27 ka (Penna and others, 2011). From a literature review and their own observations, Rabassa and Clapperton (1990) proposed that the Patagonian Andes experienced a piedmont glaciation 2 Ma ago, with glaciers that did not incise deeply into the plateau. This was followed by younger ice-events characterized by glaciers confined to incised valleys. Based on the large altitude difference between the morphologies resulting from these two glacial periods, Rabassa and Clapperton (1990) proposed that they had been separated by a period of strong incision induced by tectonic uplift (canyon cutting event, ~0.7 Ma–125 ka).

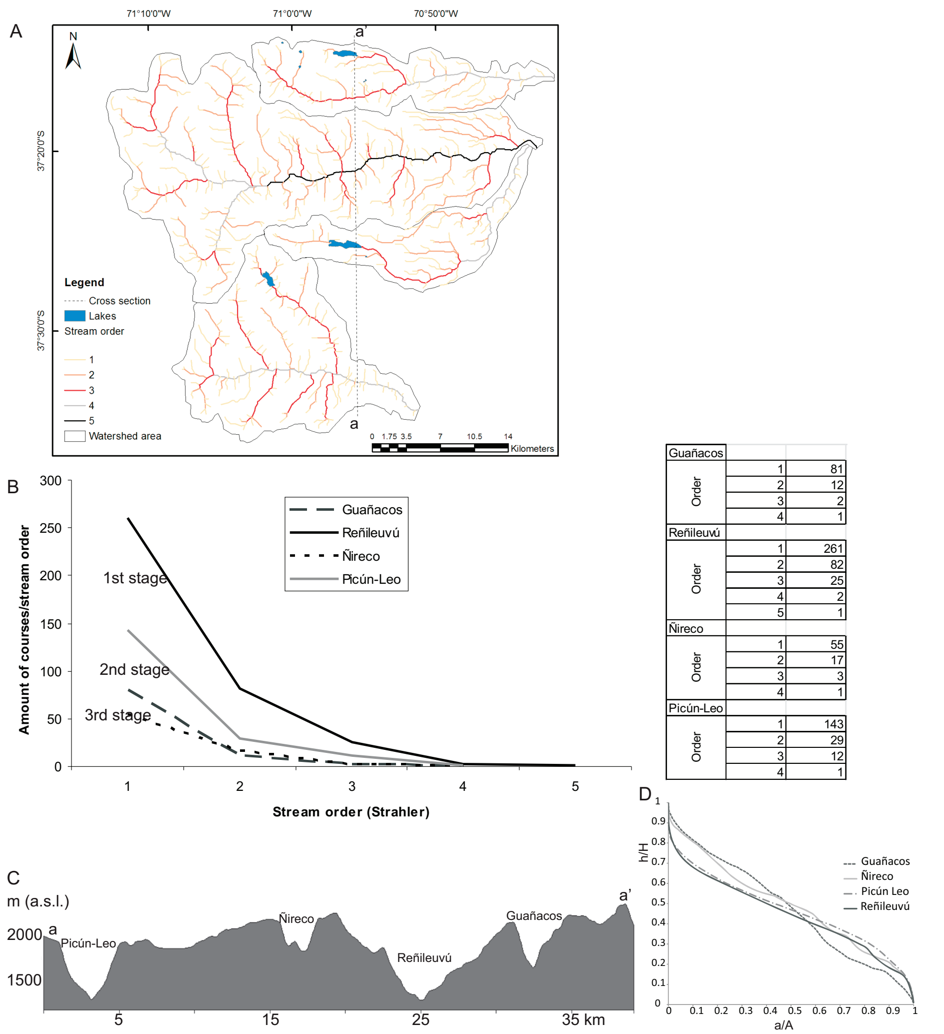
Deep scars in the valley hillslopes remain as evidence that large scale slope collapses have taken place. Several rockslides have not detached randomly, but rather at the intersection of valley slope–neotectonic structures (Penna and others, 2011). Penna and others (2011) carried out ^{3}He and ^{21}Ne surface-exposure dating of large boulders (1 m in diameter) from landslide deposits located far from trunk streams and showing no evidence of reworking after deposition. Sampling involved the extraction of 3 to 5 cm of flat-lying surfaces on boulders, shielding measurements, and further concentration of olivines and pyroxenes in the laboratory. Exposure dating, stratigraphic relations, and morphological assessments indicated that landslides occurred between pre-glacial to mid-Holocene times (further details on age determinations can be found in Penna and others, 2011).

METHODOLOGY

Aerial photos (scale = 1:50,000), satellite imagery, digital topography from the Shuttle Radar Topographic Mission (SRTM), field surveys, and a literature review were used to analyze the geomorphology and assess the evolution of the landscape. The fluvial network was determined using the SRTM data and the Flow Direction and Flow Accumulation tools from ArcGIS. Strahler's stream orders were established using ArcGIS; its Stream Order tool assigns a numerical order to segments of a raster representing the branches of a fluvial network (fig. 3). Hypsometric curves represent the distribution of elevations across a drainage basin and are often used as indicators of a drainage basin's stage of erosion in relation to geological or climatic conditions, as well as time (for example Strahler, 1952; Masek and others, 1994; Keller and Pinter, 2002; Cheng and others, 2012). Hypsometric curves were determined by using the public domain Hypsometric Toolbox for ArcGIS developed by J. Davis (2010) (fig. 3). In order to identify variations in channel gradients resulting from neotectonics or landslide dams development a steepness index was calculated (Kirkby and Whipple, 2001; Whipple and others, 2007). This index (K_s) is the relationship between the local channel gradient (S) and the contributing drainage area (A). $S = K_s A^{-\text{Ø}}$ where Ø is the concavity index, here considered to be 0.45. The steepness index calculation was made using the procedure and tools available at www.geomorphtools.org (Whipple and others, 2007). Input data came from the SRTM digital topography, a Flow Accumulation raster calculated using ArcGIS and clipped to watershed boundaries, and the starting point of each stream to be analyzed.

A topographic reconstruction of the volcanic plateau was made in order to quantify valley erosion. Input data came from the SRTM's digital topography (SRTM, 90 m horizontal resolution and 10 m vertical accuracy) and the top of the Cola de Zorro Formation's lava flows was used as a stratigraphic marker (table 1). Topographic reconstructions to calculate rates of landscape evolution have proven fruitful in a variety of different settings, but especially in plateau areas (Pederson and others, 2002; Gani and others, 2007; Pérez-Peña and others, 2009). The methodology used was a variation of that developed by Penna and others (2011) to reconstruct the topography of the slopes in rockslide headscarps. An iterative linear interpolation process is executed inside a defined region of interest (ROI) resulting in new values of Z of each pixel of the DEM contained in the ROI. Each iteration step is carried out as follows: for each point inside the ROI, the average height of its four neighbors is calculated; if the result is higher than the current height of that point, then the result becomes its new height; iteration continues until the heights converge. In this way, the borders of the ROI, together with the highest points inside it, constitute the guide levels for the reconstruction.

Once the reconstruction had been obtained, incision patterns were determined as the difference in altitude between the current SRTM topography and the paleotopography for pixels with the same coordinates (fig. 4). Eroded volumes were then measured as the sum of the incision values multiplied by the area of one pixel. Erosion rates by landslides were determined with reference to the volumes and ages from



Basin	Order	Count
Guañacos	1	81
	2	12
	3	2
	4	1
Reñileuvú	1	261
	2	82
	3	25
	4	2
	5	1
Ñireco	1	55
	2	17
	3	3
	4	1
Picún-Leo	1	143
	2	29
	3	12
	4	1

Fig. 3. (A) Map of Strahler's stream orders for each drainage basin. (B) Distribution of stream orders. (C) N-S topographic cross section showing the different positions of the valley floors. (D) Hypsometric curves of the drainage basins.

Penna and others (2011; table 2). The volume eroded from the landslides was measured in the breach zone, with regard to the equation of a trapezoid prism (table 2). In order to determine the backwater aggradation, the pre-dam profiles of the fluvial courses were reconstructed for those dams which exhibited the most marked knick-points. Pre-dam profiles were built by interpolating the upper end of the lake and the foot of the landslide dam using a best fit line. The lake's average depth was estimated (average difference in altitude between the current profile and the interpolated line representing the pre-dam profile) and multiplied by the area filled up with sediments in order to give an estimated volume of trapped sediments.

DRAINAGE BASIN DEVELOPMENT

Incision into the sub-horizontal volcanic sequences of the Cola de Zorro Formation have resulted in four drainage basins named, from north to south, Guañacos,

TABLE 1

Drainage basin features and erosion between the Guañacos and Picún-Leo valleys

Drainage basin		Guañacos	Reñileuvú	Ñireco	Picún-Leo
Area (km^2)		173	526	67	270
Total volume eroded (km^3)		23.67	186	11.64	97.10
Volume eroded in the mountain (km^3)		21.97	175.60	10.06	90.45
Volume eroded in the piedmont (km^3)		1.70	10.40	1.58	6.65
Average incision (m)	Mountain	538	862	416	753
	Piedmont	112	299	96	442

Reñileuvú, Ñireco and Picún-Leo. These basins differ in size, location of their headwaters, position of their valley floors, the degree of drainage network development, and in relief (fig. 3; table 1). The Reñileuvú extends over 526 km^2, with its headwaters in the westernmost part of the region. The Picún-Leo's catchments are located 7 km east of the Reñileuvú, and extend over 270 km^2. The Guañacos and Ñireco present almost aligned headwaters some 15 km east of the headwaters of Reñileuvú creek, covering areas of 173 km^2 and 67 km^2, respectively (fig. 3; table 1). A N-S topographic cross section reveals a relationship between drainage basin dimensions and altitudes of the valley bottoms (fig. 3C). The Ñireco, the smallest basin, has the valley bottom located at the highest altitude; the Reñileuvú has the lowest valley bottom.

Strahler's stream order analysis showed that the Reñileuvú basin was the only one exhibiting five orders—the other basins only had four (fig. 3A). Hypsometric curves for the basins were calculated, to be used as indicators of their erosive stages (fig. 3D). On comparison, the profiles of Reñileuvú and Picún-Leo present similarly S-shaped curves, whereas the curves for the Ñireco and Guañacos basins are both convex and steeper. For the latter two basins, the total basin height was greater, especially in their upper portions. The difference in their hypsometric curves relates to their stage of maturity. Considering that the four basins developed under similar lithological and climatic conditions, then the degree of development of the drainage networks, their hypsometric curves, and the position of their valley floors could indicate that the basins are not contemporaries, and that the Reñileuvú basin was the first to form, followed by Picún-Leo.

VALLEY DOWNCUTTING

The paleo-topography of the volcanic plateau was subsequently reconstructed in order to establish the spatial distribution of valley downcutting and its correlation with tectonic activity. This paleo-topography, which represents the state of the landscape prior to development of the basins, has a plateau-like relief (fig. 4A). The map of incision patterns and incision profiles (figs. 4B and 4C) shows that most of the erosion occurred upstream the Chacayco fault. The study area's denudation rates (fig. 4C; table 1) were determined with regard to the age of the top of the lava flows determined by Folguera and others (2004). An estimated 318.41 km^3 of rock was eroded from the plateau. Around 300 km^3 of this volume were eroded upstream of the mountain front by glacial and fluvial action that led to a maximum incision of ~960 m (Reñileuvú basin). In the piedmont area, fluvial courses carved between 200 to 600 m and eroded a volume ten times smaller than in the mountain area (~20 km^3; table 1). The

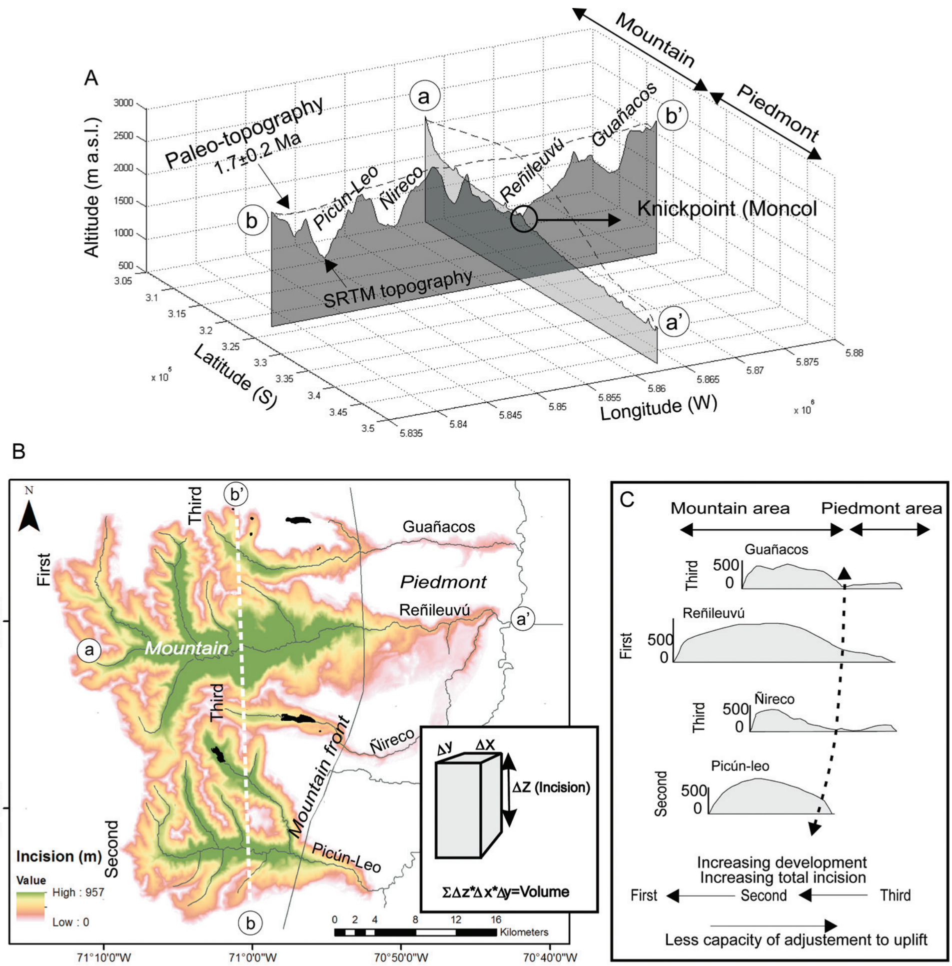


Fig. 4. (A) Block diagram showing a N-S cross section with the envelope of the reconstructed topography (note the plateau-like surface obtained), the SRTM topography, and a cross section along the Reñileuvú valley built using with the reconstructed topography and the creek profile. (B) Map with the incision patterns calculated as the difference in altitude between the SRTM topography and the reconstructed topography of the volcanic plateau by interpolation of the top of the lava flows, and conceptual diagram for the determination of incision and volumes eroded. (C) Incision profiles along the four creeks and hypothesis of drainage basins development and capacity of adjustment.

Reñileuvú and Picún-Leo are the basins where the most material has been eroded (table 1); the former accounted for 60 percent (186 km^3) of the total, and the latter accounted for 30 percent (97.10 km^3), respectively.

Incision profiles were built for all the main fluvial courses (fig. 4B). All the profiles show their highest incision upstream of the Chacayco fault. Incision decreases towards the mouth of the creek. Whereas in the Guañacos, Reñileuvú, and Ñireco creeks there is a sharp break coincident with the transition between the mountain-piedmont areas, this is not the case for the Picún-Leo creek. In this basin, incision decreases near the mouth but without a clear break. This is because the basin developed mostly in the area undergoing most of the uplift (fig. 4). Based on the age of onset of the canyon cutting event as estimated by Rabassa and Clapperton (1990; 700 ka), the incision rate was

Table 2

Characteristics of large landslides and their effects on drainage between the Guañacos and Picún-Leo valleys

Valley	Rockslide name	Volume (km^3)*	Age (ka)*	Total volume eroded/drainage basin (km^3)	Effects on drainage	Dam Height (m)**	Volume eroded from breach (km^3)	Sediments trapped (km^3)
Guañacos	Guañacos I rotational slide	0.079	>15–10, <27 (PG)	0.205	--	--	--	--
	Guañacos II rotational slide	0.126	<27 (PG)		--	--	--	--
Reñileuvú	Cerro Guañacos rock avalanche***	1.26	<15–10 (PG)	7.28	Past dam/Swamp	n/d	0.033	0.047
	Piche Moncol rock avalanche	1.34	>15–10, <27 (PG)		Past dam/Swamp	65	$0.101^{£}$	0.145
	Cerro Moncol rock avalanche	4	5.88 ± 0.50 (PG)					
	Chacayco rock avalanche	0.5	6.80 ± 0.61 (PG)		Past dam	30	0.163	
	Chacayco rotational slide	0.03	<27 (PG)		--	--	--	--
	Chochoy Mallín rock avalanche	0.15	>31 (G)		Past dam	36	0.004	
Ñireco	Ñireco Topple	0.068	6.67 ± 0.51 (PG)	0.238	--	--	--	--
	Lauquén mallín rotational slide	0.17	6.44 ± 0.38 (PG)		Lake	67	0.005	0.057
Picún-Leo	La Negra rock avalanche	0.06	<27 (PG)	0.560	Lake	47	0.003	--
	Picún-Leo rock avalanche	0.5	<27 (PG)		Past dam	75	0.085	--

Landslide erosion rate = 0.318 km^3/ka, equivalent to 0.307 mm/yr at basin-averaged rate.
* Volumes and $^{3}He/^{21}Ne$ ages, and ages based on morphological analyses (from Penna and others, 2011). PG= post-glacial times, G= glacial times.
** From Hermanns and others (2011). n/d= no data.
*** Landslide occurred in a tributary of the Reñileuvú creek but part of the rock mass dammed the Guañacos creek.
£ One value because deposits are interfingered.

calculated as being between 1.23 to 0.59 mm/yr upstream of the mountain front and up to 0.63 mm/yr downstream (table 1).

Hillslope Denudation

Large bedrock landslides have carved deep scarps in the plateau and deposited the materials in the valley bottoms (fig. 1; González Díaz, and Folguera, 2005; Hermanns and others, 2011). A previous study by Penna and others (2011) showed that neotectonic structures played a primary role in controlling the size and location of the largest bedrock landslides. Landslides with headscarps involving the deformation zone of tectonic structures measured up to 4 km^3 (average 0.73 km^3), with volumes decreasing as the extent of the exposed deformation zone diminished. Landslides with headscarps not lying on regional tectonic structures were smaller than 0.17 km^3 (average 0.04 km^3). Between the Guañacos and Picún-Leo valleys, 12 rockslides detached a total of ~8.3 km^3 of rock from the slopes, five with volumes equal or greater than 0.5 km^3 (table 2). Approximately 98 percent of rockslides occurred upstream the mountain front. The highest number occurred in the Reñileuvú basin and involved a total of ~7.3 km^3. Rockslides in the Guañacos, Ñireco, and Picún-Leo valleys only account for 1 km^3 of the total volume involved in slope collapses (table 2).

Based on these volumes and on the ages of landslides, which range between >31 and ~5 ka (Penna and others, 2011; table 2), the overall hillslope erosion rate was estimated at 0.318 km^3/ka, equivalent to 0.307 mm/yr as a basin-averaged erosion rate. Since the deposition of these rockslides, overall erosion in the deposits has been low. The drainage systems carving into the deposits are only poorly integrated, and only 0.394 km^3 of rock were removed after breaching of the dams (around 5% of the total volume involved in landslides). The volume of material eroded from rockslides by fluvial action is negligible in comparison to the volume that still lies in the valley floor.

Evidence of Fluvial Disequilibrium

Several anomalies in the dynamics of stream courses were noted as being coincident with both landslide dams and tectonic structures (figs. 5 and 6). Upstream of landslide dams, wide, flat flood plains are visible where water flow is restricted and sediments are trapped, forming swamps, permanent lakes, and aggradational terraces. The sinuosity of the creeks change due to river blockages. Creek sinuosity is higher upstream of the Guañacos, Moncol, and Lauquén Mallín dams (1.39–1.63) and average channel slopes are lower (1.4–2.99) than downstream of them, where sinuosity ranges between 1.17 and 1.28 and average channel slopes are 3.44 to 3.95.

Landslide dams currently constitute a local base level for the upper sector of the Ñireco and a tributary of the Picún-Leo creeks by retaining permanent bodies of water, the Lauquén Mallín and La Negra lakes, respectively. Upstream the Guañacos and Moncol dams, flow is delayed and large swamps have developed, especially during the peak discharge (spring), although no permanent lakes are present. At the Lauquén Mallín and La Negra dams, longevity is especially controlled by reduced contributing areas (dams are relatively close to headwaters), but in the case of Lauquén Mallín, the internal dam structure also plays an important role. This is a rotational slide dam where the deposited materials suffered less internal deformation than would occur in a rock avalanche, resulting in a greater resistance to erosion.

When analyzing creek profiles, several high-energy reaches of current were detected coincident with landslide dams and tectonic structures. At the intersection between the Guañacos creek and the Chacayco fault, a small hydropower installation (now no longer functioning) had been set-up to take advantage of the increase in energy in the current coincident with that knickpoint. By calculating the variation of the steepness index along the longitudinal profile of the creeks, several peaks coincident with knickpoints were detected (fig. 6). Along the Guañacos creek, the

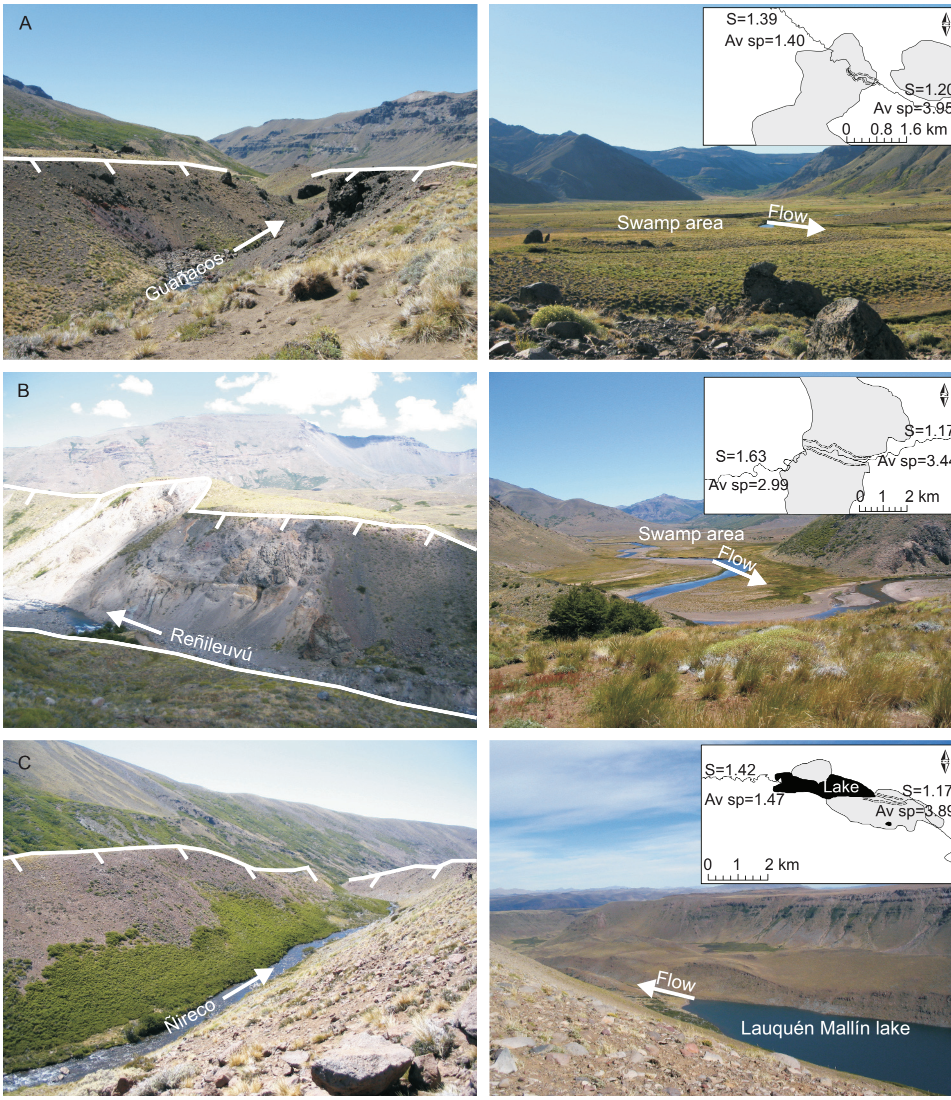


Fig. 5. (A) Breach carved into the Guañacos rock avalanche deposit in the Guañacos valley and view of the swamp upstream. (B) Breach carved in the Cerro-Piche Moncol rock avalanches and view of the swamp upstream in the Reñileuvú valley. (C) Breach carved into the Lauquén Mallín rockslide deposit and related lake in the Ñireco valley. Note: Small maps in the three pictures show river sinuosity (S) and average channel slope (Av sp) upstream and downstream from the natural dams.

clearest knickpoint coincides with the landslide deposit that created a flat reach upstream and a steeper one downstream. There are three breaks in the longitudinal profile along the Reñileuvú creek which correlate with landslide dams that occurred between ~31 to 5 ka by the deposition of the Cerro Moncol-Piche Moncol, Chacayco, and Chochoy Mallín rock avalanches (fig. 6; table 2). Knickpoint widths decrease to the east due to decreases in the dimensions of the landslide dams (fig. 6). The clearest and most well preserved knickpoints can be observed in the Ñireco profile, where they generate a step like profile (fig. 6). At the landslide-related knickpoints, the anomaly in

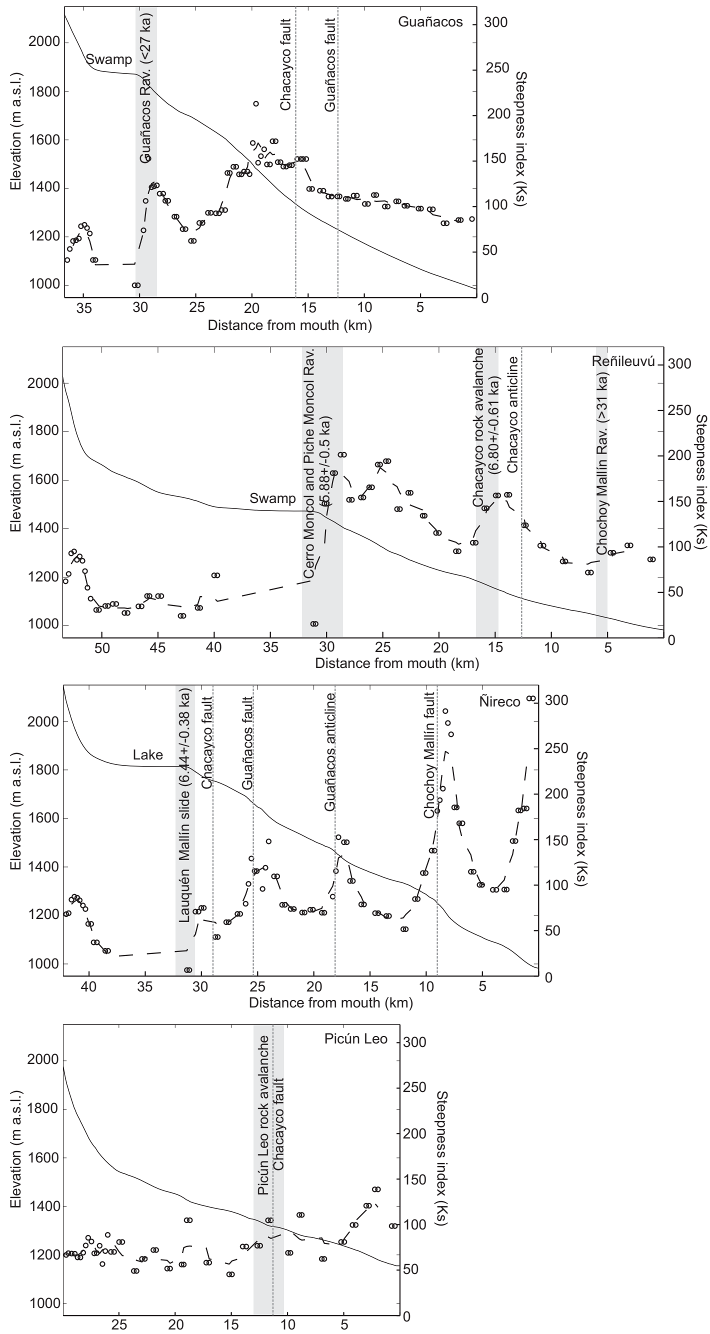


Fig. 6. Longitudinal profiles, normalized steepness index (Ks; white circles) and mean normalized steepness index determined for intervals of 3 points (dashed line) along the Guañacos, Reñileuvú, Ñireco, and Picún-Leo creeks. Note both the tectonic and landslide nature of knickpoints.

the creek's longitudinal profile consists of the landslide deposit and the related aggradation that created new valley floor conditions. It is noticeable that while landslide-related knickpoints can be identified as wide convex sections in the longitudinal profiles, those related to faults extend over smaller sections (fig. 6).

DISCUSSION

Below, we discuss the links between tectonic activity and landscape denudation caused by the development of the drainage basin and hillslope processes. Together with the occurrence of landslide dams, we examine how all these factors control the equilibrium of stream courses and, therefore, long and short-term sediment transport dynamics (fig. 7).

Influence of Tectonic Uplift on Long-Term Erosion

Incision patterns in a drainage basin generally provide insights into the tectonic uplift, changes in fluvial equilibrium, or lithologic variations that are driving its evolution (Bull and McFadden, 1977; Schumm and Ethridge, 1994; Seong and others, 2008; Koppes and Montgomery, 2009). In the present study area, incision patterns do not relate to lithologic or climatic conditions but rather to a major break in the landscape produced by displacements along the Chacayco fault. Upstream of this fault, erosion rates are 1.23 to 0.59 mm/yr, and the total volume that has been eroded is ~300 km^3. In contrast, downstream, in the piedmont, around 20 km^3 have been eroded at a rate of 0.63 mm/yr. In the mountain area subjected to tectonic uplift, a major part of the erosion relates to alpine glaciers during the LGM. Thomson and others (2010) showed the major impact of glaciers on the amount of erosion in the Patagonian Andes, with rates increasing during glacial times.

In spite of the influence of tectonic uplift on valley downcutting, incision rates (1.23–0.59 mm/yr) are higher than the uplift rate (*ca.* 0.23 mm/yr). Therefore, part of the overall incision is a response to adjustments of the fluvial systems to regional base-level changes. During the early stages of drainage basin development, most of the incision would have been concentrated in the area undergoing most uplift, with sediments deposited on top of the plateau in the piedmont area. However, as incision progressed, streams carved below the top of the plateau.

Considering that all the basins developed under similar geological and climatic conditions, we propose that they are of three different ages and thus at different stages of development, with the Reñileuvú basin being the first to have developed in the plateau. Basins of different ages, higher incision in the mountain area, and knickpoints coincident with neotectonic faults, together highlight the effects of uplift inducing fluvial adjustments and denudation. However, some of the anomalies along the creek profiles are not directly linked to fault displacements but are instead related to large rockslides. As we discuss in the following section, the removal of large amounts of rock from valley slopes contributes to the degradation of the relief generated by uplift, yet the results presented here suggest that they might also have counteracted the effects of tectonic uplift by interrupting the sediment flux cycle over more than 10^4 years.

The Role of Rockslides in Net Orogenic Denudation

Burbank and others (1996) highlighted the important role that landslides play in adjusting to rapid river incision in the north-western Himalayas. More recently, Montgomery and Brandon (2002) and Burbank (2002) identified a "limiting relief", defined as the relief above which landslides are inferred to be the primary agent of landscape denudation. Larsen and Montgomery (2012) showed that rapid exhumation and river downcutting can be balanced by an increase in landslide occurrence. The authors showed that once hillslopes attain an angle of 30°, small increases in gradient result in large numbers of landslides. Although valley downcutting into the

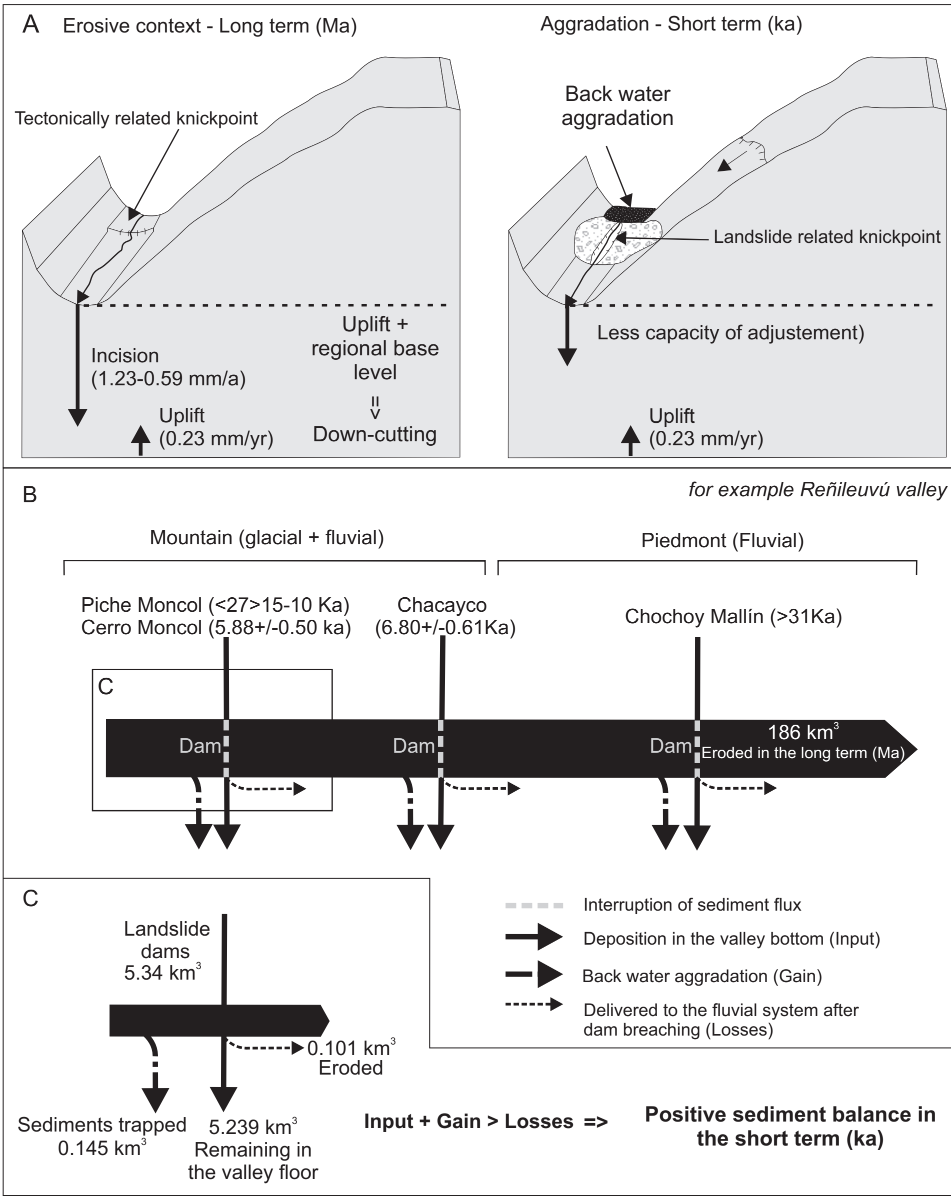


Fig. 7. (A) Diagram showing factors driving the erosive and aggradation contexts in the basins. Conceptual diagram showing main drivers of erosion (uplift and base level changes). Average incision rate since 700 Ka. Uplift rate assuming the plateau age as 1.7 Ma (age from Folguera and others, 2004) and a vertical displacement of 400 m. (B) Diagram showing processes involved in the sediment budget (input and outputs). (C) Detail of sediment budget in the Reñileuvú basin (C). Landslide dam ages were taken from Penna and others (2011).

plateau and uplift rates are low, frequencies and dimensions of rockslides are comparable to those in more active, steeper mountain regions. Penna and others (2011) showed that even if relief had a minor role in the occurrence of rockslides, the width of the deformation zone of tectonic structures was the main determinant for their size and location. This means that hillslope denudation depends on the competition between the incision and uplift creating local relief, but more importantly on rock mass strength in the source area.

Around 8.3 km^3 of rock have detached from valley slopes between ~31 to 5 ka, representing an erosion rate of 0.318 km^3/ka, equivalent to 0.307 mm/yr as a basin-averaged rate. Interestingly, this landslide erosion rate is similar to the maximum erosion rate obtained in studies carried out in areas with much higher dynamics (Korup and others, 2007). Large landslides are important suppliers of rock to glaciers and play a major role in sediment delivery to fluvial courses under humid conditions and during high precipitation events or earthquakes (Pearce and Watson, 1986; Hovius and others, 1997; Eaton and others, 2003; Hovius and others, 2011). However, the present results show that in certain settings, landslide erosion rates represent volumes of materials detached from slopes, but those materials do not constitute part of the sediment supply for creeks, at least over the short-term. In the area of the present study, rockslide materials were not delivered to the foreland: around 95 percent of their total volume still remains in the depositional area (fig. 7). The absence of rockslide deposits contemporaneous to the LGM in the mountain area and the presence of a contemporaneous one in the fluvial section of the Reñileuvú valley (Chochoy Mallín rock avalanche) reflect the inability of current fluvial dynamics to rework materials derived from these landslides. Moreover, this indicates that in the absence of an effective agent of mass transport, like glaciers that can carry tens to hundreds 10^6 m^3/yr (Hallet and others, 1996), rockslide deposits will remain in valley bottoms for longer than 10^4 years. Therefore, when considering the overall impact of landslides in landscape denudation, investigations should not neglect the residence time of rockslide materials, and the backwater aggradation period driven by dam formation, which continues even after dams are breached.

Rivers generally owe deviations in their equilibrium to lithological, sediment flux, climatic, or tectonic conditions (Bull, 1990). Terraces and knickpoints are commonly used to infer and quantify those changes. However, even in areas undergoing tectonic uplift, this assumption might not be always valid if landslides are an important factor of hillslope denudation. As Korup and others (2010) and Hewitt and others (2011) discussed, landslides can have a strong impact in limiting erosion by forming transitory river blockages. Dam-driven fluvial fragmentation decreases the stream power of courses in the contributing area upstream of the dams, leading to an aggradation stage (a no erosion period described by Hewitt and others, 2011 in the Himalayas). The flat sections along the Guañacos, Reñileuvú and Ñireco topographic profiles reflect this aggradation phase upstream from the dams. After dam breaching, incision leads to the generation of terraces on those deposits trapped during the creek blockage. Where bedrock landslides are the main agents of denudation, fill-cut terraces and knickpoints could reflect a temporary rise in the base level and disequilibrium in the stream power of rivers caused by landslide deposition (Korup, 2006; Ouimet and others, 2007). The time span of the perturbation of sediment flux and the migration rate of knickpoints caused by landslide dams will depend on climatic conditions, the contributing area and slope of the drainage basin upstream from a dam, relationships between landslide volume and valley width, and the internal structure of the deposits (Ermini and Casagli, 2003; Korup, 2004; Evans and others, 2011). Landslide-related knickpoints and morphological features indicated that these creeks have not yet reached a pre-landslide profile, and that they still exhibit disturbed fluvial dynamics, even at the Chochoy Mallín dam, which is the oldest (>31 ka).

CONCLUSIONS

In the study area, tectonic deformation has conditioned landscape denudation, driving fluvial disequilibrium. This in turn has controlled the development of drainage basins, the glacial extent, and the valley downcutting that has also exposed the deformation zone of tectonic structures where most of the landslides have occurred. Despite the fact that large bedrock landslides caused significant hillslope erosion, around 95 percent of those materials still remain in the valley bottoms, acting as sediment traps thousands of years later. Therefore, far from leading to a net erosion of the orogen, these landslides have led to a period of positive sediment balance in the area upstream from the blockages (fig. 7). The "natural" dynamics of stream courses—which would be to incise in order to keep pace with the ongoing tectonic uplift—have been altered. The facts that only post-glacial retreat landslides are observed in the mountain area (glaciated during the LGM), and the only landslide deposit contemporary to the LGM is located in the piedmont area, indicate that in arid regions such as the present study area, landslides do not constitute an important source of sediment to the foreland if they are not coupled with an effective massive erosion agent, such as a glacier. Furthermore, due to their relative long longevity, landslide dams have a counteracting effect on net orogen denudation in the short term by trapping sediments and creating positive sediment balances.

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