Nat Hazards
DOI 10.1007/s11069-008-9341-4

ORIGINAL PAPER

Evolution of a debris-rock slide causing a natural dam: the flash flood of Río Santa Cruz, Province of San Juan—November 12, 2005

Laura P. Perucca · M. Yanina Esper Angillieri

Received: 22 October 2008 / Accepted: 29 December 2008

Abstract Between 2001 and 2005, a large debris rock slide occurred on the western slope of the Cordillera de Santa Cruz in the southeast Andean corner of the Province of San Juan (31°40′ S–70°16′ W). The landslide material accumulated in a downstream gorge as a natural dam of the Santa Cruz river, forming a large-volume lake. In November 2005, probably as a result of the increasing pressure of the water volume, this natural dam breached off with a violent and unexpected flash flood. In addition to life-threatening instances lived by some people downstream, this flood caused great economic loss to main localities of the Department of Calingasta, as well as considerable damage to one of the most relevant projects of the Province, the Caracoles Hydropower Project dam on the San Juan river. Considering the high costs of any physical remediation for a natural dam located in this high, remote, and inaccessible mountain area with no reliable road access, the main protective measures left to be pondered are the installation of a flash-flood early-warning system connected to downstream localities, along with a program of hydrological monitoring at the dam-forming area and annual satellital monitoring to verify the evolution of accumulated mass movements.

Keywords Flash flood · Debris-rock slide · Santa Cruz river · San Juan Province · Argentina

1 Introduction

On the eastern side of Cordillera de Santa Cruz, numerous deposits caused by mass movement processes have been observed. This range is characterized by steep slopes carved by late

L. P. Perucca · M. Y. Esper Angillieri
CONICET, Buenos Aires, Argentina
e-mail: yaninaesper@gmail.com

L. P. Perucca (✉) · M. Y. Esper Angillieri
Gabinete de Neotectónica, INGEO, FCEFN, UNSJ, Av. Ignacio de La Roza y Meglioli, 5400 San Juan, Argentina
e-mail: lperucca@unsj-cuim.edu.ar; lauraperucca@gmail.com

Pleistocene glacier retreat, lack of vegetation, and intense cryoclastism. Mass wasting, such as rock avalanches, debris falls, and large-volume rock slides, takes place in certain areas above the glaciofluvial terraces built up after the retreating ice of the last Holocene glaciation.

The use of air-photography and satellite imagery (TM, ETM+ LandSat, and Spot) obtained through a number of years helped to study the formation of a natural dam on the river Santa Cruz, caused by a debris-rock slide during 2001–2005. Because of the rather loose nature of the dam, the rapid water rise, and the absence of a controlled spillway, the landslide dam failed catastrophically in November 2005 and led to violent downstream flooding.

Flash floods are one of the most common types of geological hazards in western Argentina. Traditionally, most human settlements in Andean regions have been located in valleys and alluvial fans of mountain foothills, though this has also implied that these localities and rural areas are placed within hazardous zones, at risk of flash floods and river high-flows. Flash floods are a type of landslide that consist of a spatially continuous movement of a saturated mass of earth materials, such as debris and mud, mainly controlled by gravity and whose movement mechanics resemble that of a viscous liquid (Cruden and Varnes 1996). According to IAHS-UNESCO-WMO (1974), flash floods are defined as sudden floods with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent. Flash floods occur within a few minutes or hours of excessive rainfall, a dam or levee failure, or a sudden release of water held back by an ice dam. Flash floods can roll boulders, tear out trees, destroy buildings and bridges, and scour out new channels. Occasionally, floating debris or ice can accumulate at a natural or man-made obstruction and restrict the flow of water. Water held back by the ice dam or debris dam can cause flooding upstream. Subsequent flash flooding can occur downstream if the obstruction should suddenly release (NWS 2006). They commonly pose a hazard, particularly due to their great velocity, long run-out distance (many kilometers), and their capacity to transport large and heavy items such as trees and rock blocks several meters in dimension, implying significant destructive power (Sepúlveda 2000). Numerous cases of natural dam rupture and associated flash floods have been recorded worldwide and in western Argentina. One of the most damaging landslides occurred in the northwestern Argentina was the rainfall-triggered debris flow of January 1976 that swept down the Escoipe river in Salta Province and destroyed the town of San Fernando de Escoipe, which was buried under a thick mantle of mud and rock (Igarzábal 1979; Wayne 1987; Alonso and Wayne 1992). Groeber (1916, 1933), González Díaz et al. (2001), and Hermanns et al. (2006) described in northern Patagonia, a landslide dam blocking the Barrancas river that failed in December 1914. A water volume of 1.55 km^3 was released from the lake causing a great flow, which destroyed lowlands in the Barrancas and Colorado valleys down to the Atlantic. Moreiras and Banchig (2008) pointed landslides blocking the Villavil river in Catamarca province, in repeated moments at historical times (Fig. 1).

Kimio et al. (2005) described two landslides in Japan caused by heavy rainfall from a typhoon on July 25, 1892. These landslides blocked rivers and formed natural dams. In the worst case, the landslides blocked the Naka river and formed a 71-m natural dam which breached off after a 52-h impoundment. The large-volume flood rushing down the river valley caused damage to more than 300 houses and the death of 60 persons.

2 Study area

The steeply walled Santa Cruz river is located in the SW area of the Province of San Juan, in the Department of Calingasta, on the Cordillera de los Andes and north from Cerro

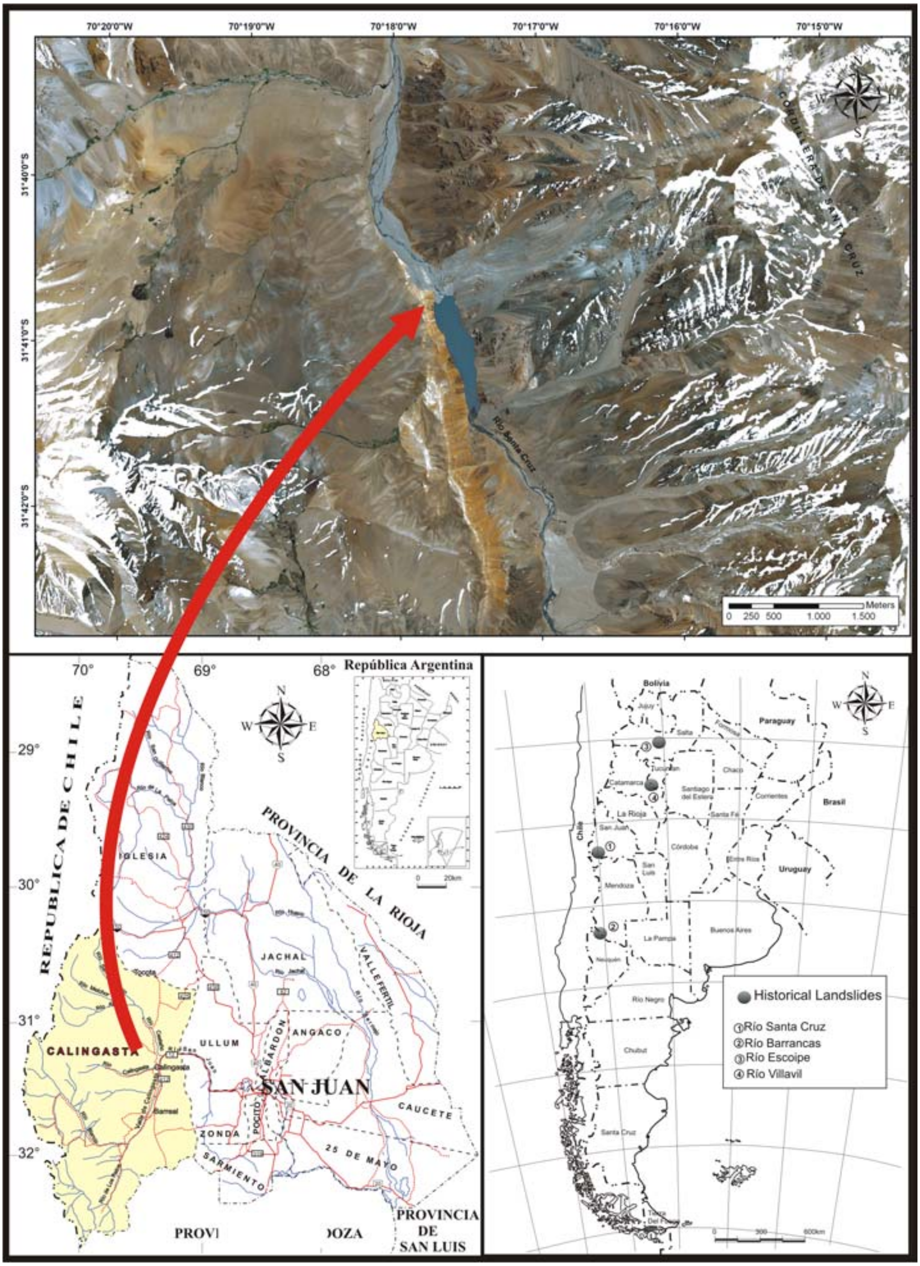

Fig. 1 Overview of the study area on approximately 31°40′ S

Mercedario (6,770 m asl). This area can be laboriously reached by Provincial Roads 400 and 402, which are actually mine trails (Fig. 1).

The Province of San Juan has a general arid and semiarid climate; the total annual rainfall average is very small: about 93.3 mm/year. Winter temperatures range between 1.0

and 18.0°C, whereas summers are hot and very dry, with temperatures between 19.0 and 35.0°C.

The climate and topography varies along the length of the Andes Mountains. For this reason, the Cordillera de los Andes is divided into the Dry Andes, covering the region from latitude 17°30′ to 35° S, and the Wet Andes, covering the region south of latitude 35° S. The Dry Andes section has been further divided into the Desert Andes from latitude 17°30′ to 31° S and the Central Andes from latitude 31° to 35° S. In the *Desert Andes,* arid conditions limit the ice-and-snow formation to small patches on the highest peaks (Lliboutry et al. 1958). Here, most of the small ice-and-snow areas are found on the main range, which is the border between Argentina and Chile and the precipitations occur during local storms. In contrast, in the Central Andes, true glaciers flowing at the head of valleys exist because of higher mountains and greater precipitation.

In the specific study area, meteorological observations have been carried out from 1981 to 1995. The climate is characterized by semi-arid conditions, short-lived summers, and rigorous winters with very low temperatures (−18 to 10°C). Data recorded at Pachón Station (31°44′ S, 70°19′ O), at 3,030 m asl, indicate a yearly mean temperature below 0°C. During 6 months a year, (May–October), the monthly mean temperature is below 0°C, whereas for the 12 months of the year the monthly mean temperature is never above 10°C. Besides, the amount of snow recorded in the winter of 2005 was 2 m, and the temperature on the first days of November was between 17 and 20°C. The precipitation level for most of the area is between 300 and 400 mm annually (Minetti et al. 1986). Table 1 shows data of precipitations, temperatures, and mean wind speed, for the period 1981–1995 (Departamento Hidráulica).

According to Köeppen's classification (1931), based on mean temperatures and monthly precipitations, the region's climate belongs in high altitude (E); the average temperature in January is below 10°C; the thermal swing is ample—both daily and yearly; the precipitations are mainly featured by heavy snowstorms on high ranges, mainly during the May–August period.

Mountain ranges show a N–S trend, with altitudes reaching 5,000 m asl. Most rivers have a steady-flow pattern fed by snowmelt from ice and snow masses accumulated in winter. The region's relief has been carved by extensive Pleistocene glaciation and by the action of landslides. The intensive detritus accumulation in the Holocene also produced important relief changes. Cordillera de Santa Cruz is a N–S elongated high range dissected by deep valleys controlled by fault structures. On its flanks, mainly the western one, there are abundant mass-removal phenomena such as creeping movements in a talus slope, solifluxion, mudflows, talus cones, and rock avalanches. With a 1.44 m^3/s mean flowrate, with a minimum volume during June of 0.28 m^3/s and a maximum one in November of 3.22 m^3/s (data recorded at the Meteorological Station "Pachon," Calingasta, San Juan, from January to November, 1970, Departamento Hidráulica), the Río Santa Cruz runs N–S as a tributary of Río Blanco, which runs NW–SE. Both rivers are controlled by megafractures. The oldest stratigraphic units outcropping in this mountain sector are represented by Permic granitoids and Permic–Triassic vulcanites (volcanic complex), conglomerates and litic sandstones, ignimbritic breccias, and Upper Triassic tuffs. There also overlie marine calcareous deposits, evaporites, and terrigenous deposits represented by conglomerates and red sandstones of the Upper Jurassic. Higher up in the sequence, andesitic breccia and volcaniclastic deposits from the lower Cretaceous are found, and, in discordance on Mesozoic deposits, there lies a series of volcanite and volcaniclastite formations from the Miocene. Finally, modern alluvial and colluvial deposits are visible (Fig. 2). The structure is complex, defined by a Cenozoic compressive deformation that masks Triassic

Table 1 Metereological elements during 1981–1995 period (from Departamento Hidráulica)

Years	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	Average
T_{max} (°C)	18.4	20.2	19.4	21	22	21.3	21.3	19	20.3	21.5	20.6	20	19.6	20.2	21.2	20.4
T_{min} (°C)	−9.3	−21.6	−26	−26.6	−23.6	−24.2	−26	−20.2	−21.5	−24	−29.7	−26	−26.6	−22.3	−23.2	−23.5
Wind (km/h)	10	9	9	10	10	10	9	10	10	10	9	10	10	9	9	10
Precipitation (mm)	136	525	249	284	160	344	472	123	248	132	429	377	247	236	534	300

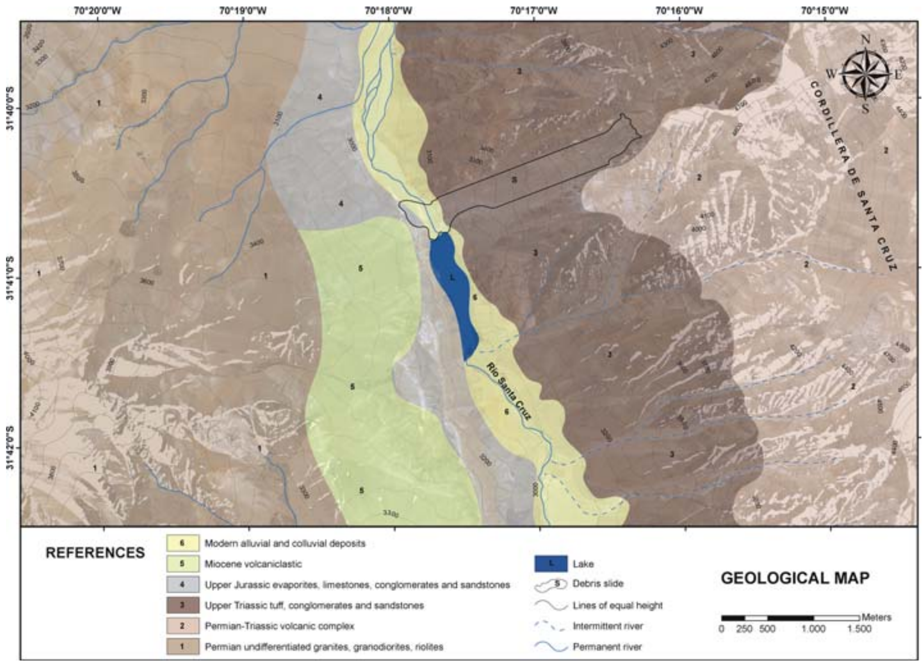

Fig. 2 Lithological map of the Santa Cruz river area

extensional features marked by faults and broken folds affecting the Jurassic and Cretaceous rocks, onto which the Andean tectonics play an important role (Pérez 1995). The Santa Cruz fault (Lencinas 1982) is a reverse fault with western dip affecting the western slope of Cordillera Santa Cruz and a main cause for block-lifting this range. On the western margin of Santa Cruz river, numerous gravitational mass movements took place, mainly rock avalanches, detritic cones, and debris-rock slides. Upstream, in the head waters of the basin, numerous rock glaciers, mainly talus-derived rock glaciers, are found.

3 Methodology

The methodology applied for this research work is based on the compilation of local newspaper reports, the interpretation, and digital analysis of air-photographs obtained in a regional flight during the fall seasons of the 60 s, scale 1:50,000 and LandSat 7 ETM+ and Spot satellite images, 15–30 m resolution for a period starting in 1990 until April 2008.

Once the debris rock slide was correctly identified in air photograms and imagery, the area's evolution was analyzed for the period mentioned above, in addition to a geometry study based on calculations of areas and lengths. The slope analysis was performed in a GIS environment. The slope functions calculate the maximum change in elevation over the distance between the cell and its nearest neighbor. The output slope dataset was calculated as degree of slope. The elevations were obtained by digitalizing the contour maps from the Military Geographic Institute, scale 1:100,000, and with topographical information obtained from the Radar Shuttle Topographical Mission (USGS 2000). For the geometric interpretation of the debris rock slide, the following parameters were used (modified data from Dikau et al. 1996; Table 2):

Table 2 Morphological parameters of the debris-rock slide

Parameters	Value
Altitude (H)	
Maximum ($H_{máx}$)	4,481 m asl
Minimum (H_{min})	2,950 m asl
Mean (H_m)	3,716 m asl
Slope (S)	
Max ($S_{máx}$)	42°
Min (S_{min})	5°
Mean (S_m)	23°
Central-point coordinates	
Latitude	31°40′27″
Longitude	70°16′51″
Surface of rupture	Plana
Total length (L)	2,633.95 m
Displaced material length (L_d)	812.01 m
Length of the rupture surface (L_r)	2,304 m
Depth of displaced material depth (D_d)	50 m
Width of the surface of rupture (W_r)	283.35 m
Width of the displaced material (W_d)	355.3 m
Perimeter length of the displaced material (P)	2,711.09 m
Area (A)	
Total (A_t)	0.84 km^2
Displaced material (A_d)	0.24 km^2
Estimated volume (V)	12×10^6 m^3

– Altitude (H): maximum ($H_{máx}$), minimum (H_{min}), and mean (H_m) altitude contour level.
– Slope (S): Maximum ($S_{máx}$) and mean (S_m) gradient.
– Central-point coordinates: represented by latitude and longitude values.
– Surface of rupture: scarp type (plane, curve, etc.).
– Total length (L): minimum distance comprised between the tip and the top of the landslide.
– Length of the rupture surface (L_r): the minimum distance between the bottom of the rupture surface and its crown.
– Depth of the displaced material (D_d): the maximum depth of the slided deposit, measured on the direction perpendicular to the plane formed by W_d and L_d.
– Width of the surface of rupture (W_r): maximum width of the displaced rockmass, measured perpendicularly to the L_r direction.
– Width of the displaced material (W_d): maximum width of the displaced rock mass measured perpendicularly to the L_d direction.
– Height of the surface of rupture (H_r): vertical distance between the crown and the foot of the rupture surface.
– Perimeter length of the displaced material (P): total contour length of the displaced material accumulation.
– Area (A): total area, including the surface of rupture (A_t) and the area of the displaced material (A_d)

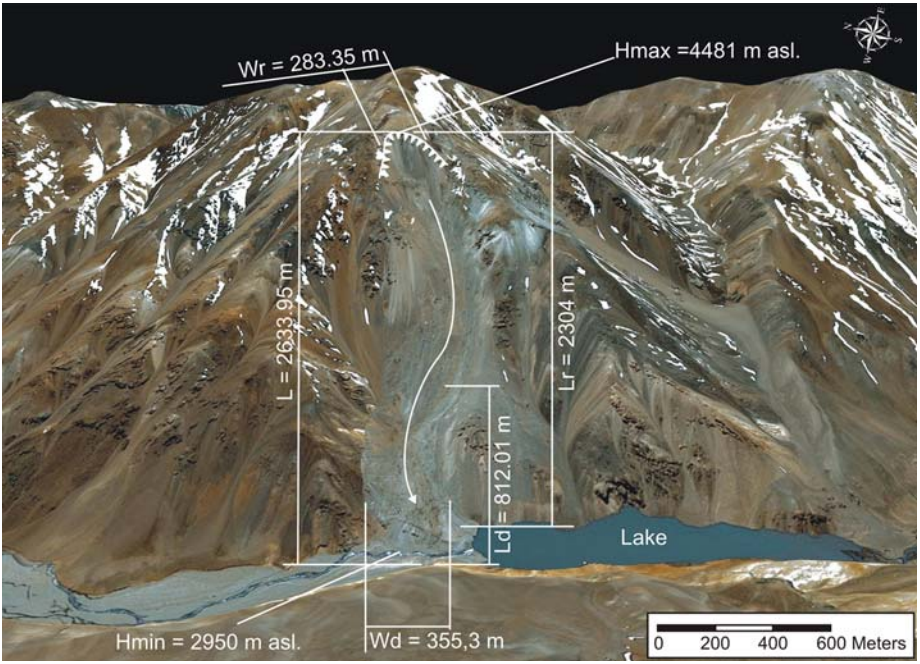

Fig. 3 3D view and geometric analysis of the debris-rock slide in western flank of Cordillera de Santa Cruz

– Estimated volume (*V*): probable volume of the debris-rock slide deposit.

Finally, a digital 3D model of elevations was elaborated that allowed visualizing the actual morphology of the debris-rock slide (Fig. 3).

4 The debris-rock slide of Santa Cruz river

A debris-rock slide is characterized by unconsolidated rock and soil that has moved downslope along a relatively shallow failure plane. The depth of such a plane in this kind of movements varies from 1 to 4 m, with the particular feature of having a longer sliding distance than its mass depth (Selby 1993). Debris-rock slides form steep, unvegetated scars (depressions) in the head region and irregular, hummocky deposits (when present) in the toe region. The probability of sliding is low where bedrock is exposed, except where weak bedding planes and extensive bedrock joints and fractures parallel the slope, as occurred in the studied area. Debris slides are most likely to occur on slopes greater than 65% where unconsolidated colluvium overlies a shallow bedrock

Between years 2001 and 2005, a debris-rock slide took place (Fig. 4a) that occluded the deep valley of Santa Cruz river, originating a natural dam where the river formed a 1.5-km impoundment (Fig. 4b). The debris-rock slide covers an area of about 0.84 km^2; the estimated total length of the slide is 2,633 m; and its width is 283 m. This section has a half-circle shape that defines the main scarp; the actual area of the main body deposit covers 0.24 km^2. The length of the displaced material is 812 m, significantly shorter than the total length of 2,633 m measured from the crown. It has a toe (2,950 m) to crown

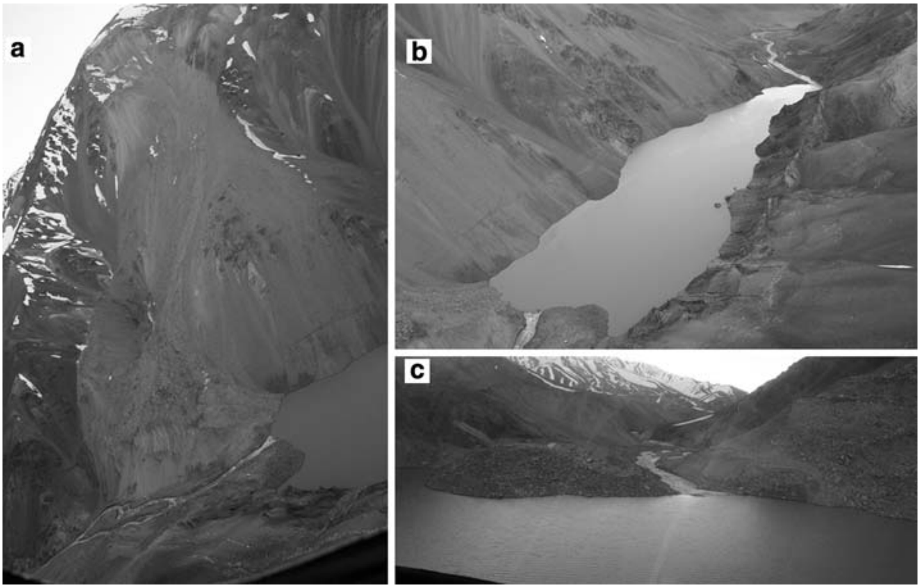

Fig. 4 **a** Debris-rock slide in western flank of Cordillera de Santa Cruz, caused blockages in Santa Cruz river. **b** Landslide-dammed lake after the flash flood. **c** Debris-rock slide deposits forming the natural dam, after the collapse (photographs taken in November 2005)

(4,481 m) height of 1,531 m, with a steep slope. These features, along with the large cover of detritus and loose material on the hillsides originated by the periglacial climate of this region, are the conditioning factors for mass wasting phenomena. The deposit covers an area of approximately 0.24 km^2 with an estimated volume of 12×10^6 m^3. This is a poorly supported chaotic deposit conformed mainly by blocks and angular and sub-angular detritus of various sizes, embedded in a fine-grained matrix. Its composition is heterogeneous, presenting volcanic breccias predominantly rhyolites, tuffs, sandstones, and conglomerates (Fig. 4c). In addition to the main scarp, there exist multiple landslide scars that pose potential rupture surfaces, with which the probability of new rock slide occurrences is greatly increased (active mass wasting; Fig. 5). After having analyzed the map of slopes for both margins of Río Santa Cruz, it can be noted that the creek shows an asymmetric profile, with an abrupt eastern side and a much less inclined western hillside. Since the prevailing wind direction is W–NW, the western side of the Cordillera Santa Cruz performs like an orographical barrier that promotes the snow accumulation phenomena on its western side, increasing cryoclastism.

The evolution of the debris-rock slide on the eastern margin of Santa Cruz river can be analyzed by means of a multi-temporal study with air photographs and LandSat and Spot satellite imagery for the period May 1962–April 2008.

Photographs taken in 1962 show a small landslide eroded at its foot by Rio Santa Cruz. The length of the main scarp is 322.67 m (Fig. 6a). In the LandSat TM image of April 1990, the main scarp has increased its length to 437.98 m, though there is no significant increase in slided material volume (Fig. 6b). In the LandSat ETM+ image of February 28, 2000, the deposit covers a greater area though it does not quite close the creek totally. The length of the main scarp is 562.37 m (Fig. 6c). In the Spot image of April 2008, after the

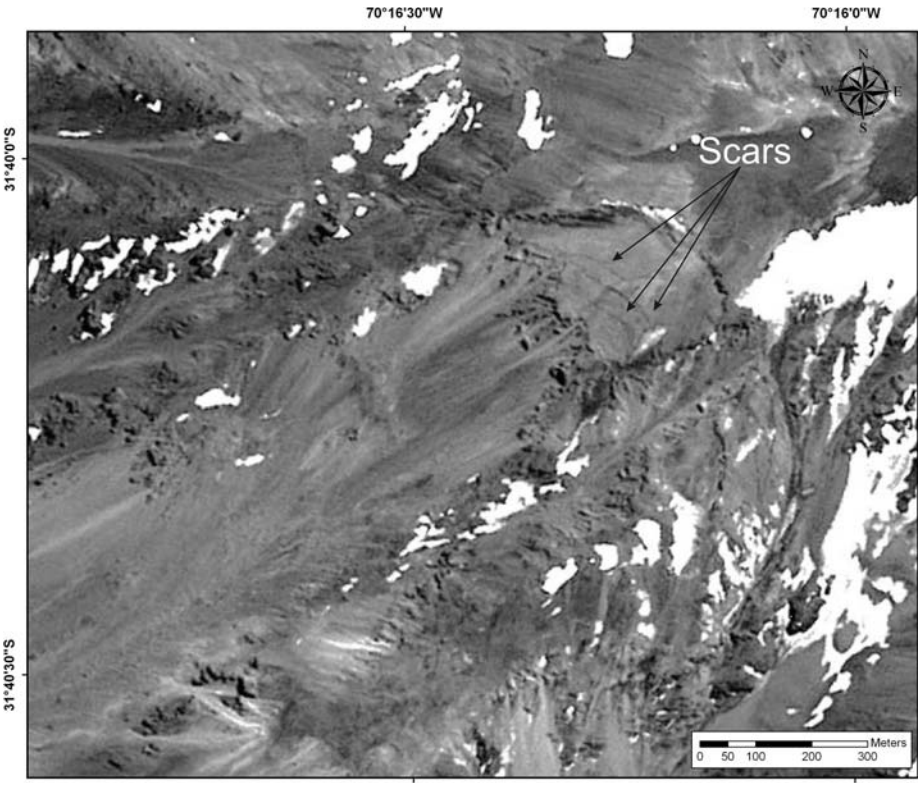

Fig. 5 Active scars on the top of the landslide

collapse of the natural dam, it is possible to recognize new zones for probable dam rupture on the crown sector. The length of the main scarp is 709.89 m and the lake remains (Fig. 6d).

5 The flash flood of November 12, 2005

In the 2001–2005 period, the debris-rock slide located on the eastern margin of the creek built up as a natural dam which closed the Santa Cruz river. The impounded water formed a small lake measuring about 41 hm^3 of water volume, almost 2.4 km long, 296 m wide, in average, and 15 m deep. At 4:00 PM, on November 12, 2005, the natural dam breached off, originating a violent flash flood. A dynamic front wave travelled down the lower stretch of Santa Cruz river, then it was channeled down by the Blanco river, arrived at the locality Las Juntas, where the Blanco discharges into Los Patos river which, in turn, runs lengthwise the Barreal-Calingasta Valley. The flood continued its race down the San Juan river and finally arrived at Ullum Dam, near the City of San Juan. Some signs that evidenced the sudden discharge were the opening of a breach in the natural dam, the erosion of the distal portions of the alluvial fans which correspond to the small tributaries of Río Santa Cruz, and the terraced levels created by the aggradation of the rupture flood and later erosion by the distal part of the flow (Figs. 3, 4). The historical records of the San

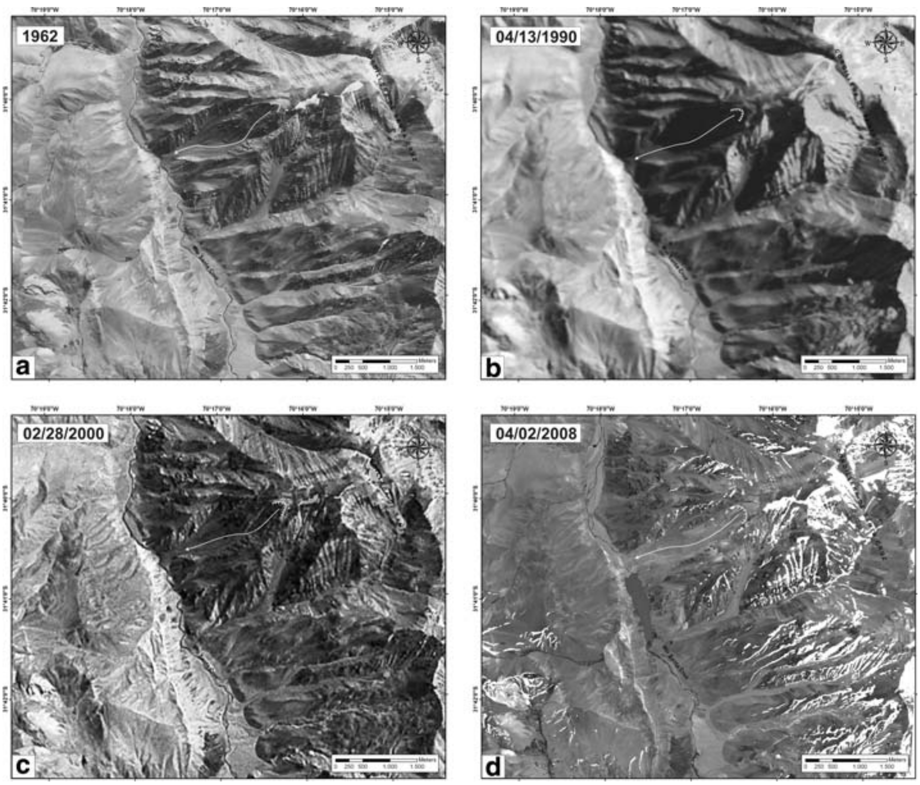

Fig. 6 Multitemporary evolution of the landslide by comparing **a** air photos (1962) and satellite images **b** 1990, **c** 2000, and **d** 2008

Juan river with a mean stream flow of 65 m^3/s (Departamento Hidráulica 2005) tell of only two instances of flash floods of such magnitude during the twentieth century, specifically, those of January 1915 (745 m^3/s) and December 1919 (774 m^3/s). According to the Departamento Hidráulica del Gobierno de la Provincia (Hydraulics Department of the Province Government 2005), the flash flood caused a flowrate increase from 130 to 1000 m^3/s in just a few hours, a situation that had never been seen before by the people of the affected areas. The flashflood lasted 10 h. At the beginning, the flood speed reached 40 km/h, from the Puesto El Molle, located on the Blanco river, further upstream the Las Juntas river joint, down to Barreal town. This distance of 80 km was traveled by the flood in 2 h. From Barreal to Calingasta locality, a 40-km stretch, the flood took 5 h, which means that its speed lowered to 6 km/h. From Calingasta to Caracoles artificial dam, a 70-km distance, the water mass took 8 h. Here, the speed increased a bit, up to almost 9 km/h (Fig. 7).

6 Damages by the flash flood

The one-lane fording bridge over Los Patos river at Sorocayente, which links Barreal with Calingasta and Tamberías, was swept almost totally. On the countryside, serious damage

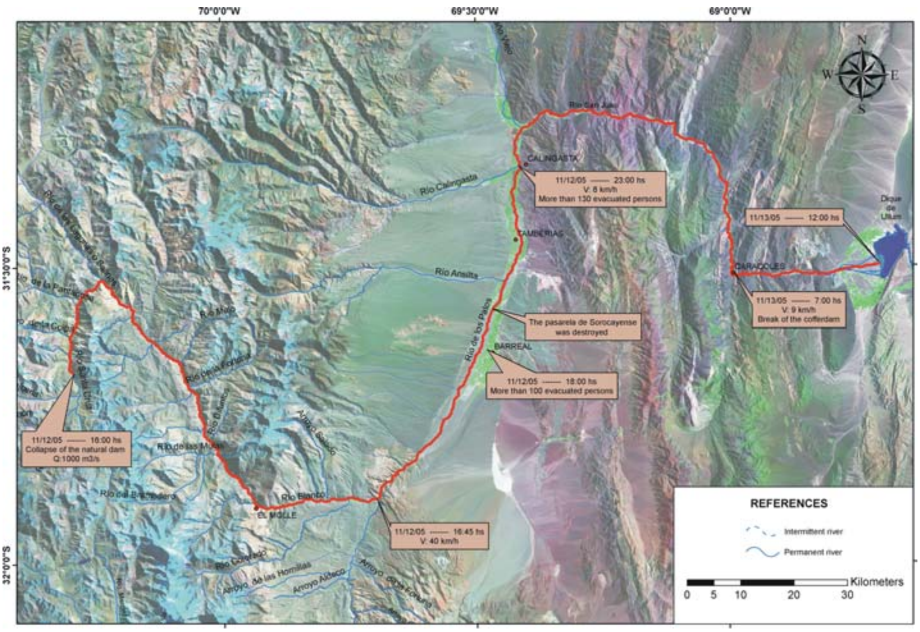

Fig. 7 Flash-flood path on November 2005, with the damages produced on his route

was caused to farms, fruit groves, and some houses in the localities of Calingasta and Barreal. The water intakes for irrigation and freshwater for human consumption were also destroyed. In total, 247 persons had to be evacuated to safer places. On the San Juan river, along the stretch where the Los Caracoles Dam Project is being built (at about 60 km from the city of San Juan), the diverging cofferdam of the works was breached; this is an artificial embankment built on the riverbed to diverge the waters into a tunnel so as to keep the construction areas for the dam dry and free from river water. The water volume started to drain through the other tunnel built on the margin of the dam. This construction had been designed to channel down a maximum flowrate of 700 m^3/s, i.e., the discharge capacity of the tunnel. Since the flash-flood flowrate grew over 1000 m^3, the water overtopped the cofferdam and reached the very base of the dam, thus severely flooding the works site. Many pieces of equipment (earthwork equipment, cranes, hoists, etc.) and some mobile office quarters were destroyed (Diario de Cuyo 2005). In the morning of November 13, the flood reached the Ullum lake, carrying along a heavy load of sediment which caused the haulting of power generation that feeds the city of San Juan electric power network. The water intakes of the potabilizing plant that filters and distributes drinkable water to San Juan and neighboring localities had to be closed as well, which caused a 20% decrease to the normal flow output during many hours.

7 Discussion

Dam failures potentially could result from a seismic shaking, catastrophic overtopping caused by a landslide entering the lake from the valley wall at high velocity, surface erosion caused by natural overtopping by the rising lake, instability caused by lake pressure against the dam, or slope instability of the dam flanks.

The flash flood of November 12, 2005 may have been brought about in two stages. Initially, the occurrence of a debris-rock slide that accumulated into a natural dam obstructing the Santa Cruz river, and a later collapse of this dam as a result of the high pressure exerted by the water volume (lake). The existence of promoting material, such as tuff, sandstone, and conglomerates affected by strong cryoclastism, in addition to the lack of vegetation, and a favorable stratification were factors that contributed to generate the debris-rock slide. The high slope values shown on the western flank of the Cordillera Santa Cruz, on the stretch where the dam grew, also promoted the generation of the slide.

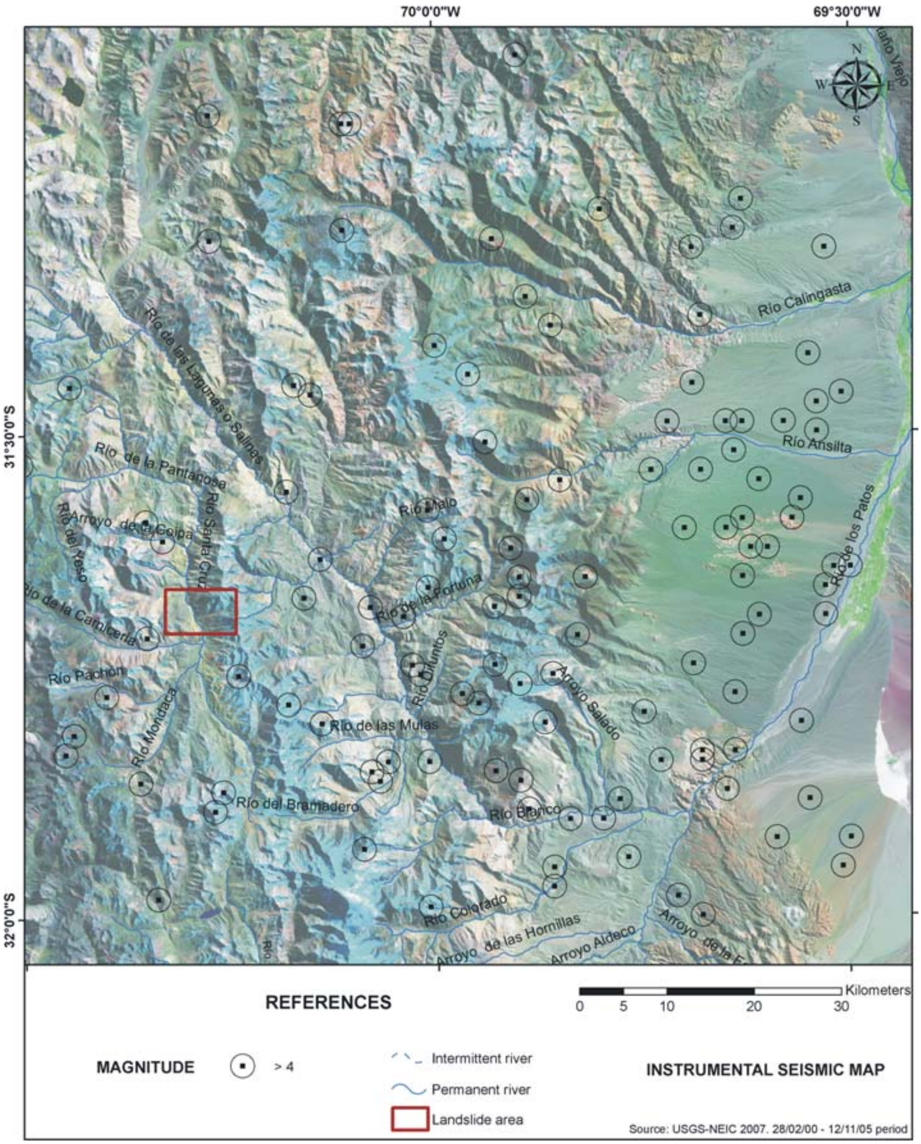

Fig. 8 Instrumental seismic map from USGS/NEIC 2007 catalog, ($M_s > 4$, 1923–2005)

Another conditioning factor was the water content. This is a main factor for releasing mass-removal phenomena. An increased water content causes higher pore-pressure within the material, thus promoting the water flow through the affected terrain. This condition generates a decrease in shear strength of the accumulated material, in addition to increasing its weight and influencing on its strength qualities. The intense snowstorms that fell in the region during May–August 2005 may have increased the weight of the hillside material, thus promoting the generation of debris-rock slide. On the other hand, during October and November 2005, the records showed unusual temperatures over 35°C that may have contributed to snowmelting larger snowpack masses and, thus, to a faster filling of the dam and its subsequent collapse.

The geomorphology of this mountain region is an important parameter for mass removal processes. Abele (1974) pointed out the importance of periglacial processes for slope instability, where the freezing–thawing process enables the occurrence of creeks and, therefore, to the production of detritus. The natural dam collapse that gave rise to the flash flood may have also been caused by a detritus cone falling into the water mass as it is observed in the sector of the lake, with the presence of numerous debris cones (Figs. 3, 4b), and as it was described by Hermanns et al. (2004, 2008) in the Provinces of Neuquén and Salta (western Argentina), or by a detritus flow, as mentioned by Penna et al. (2007, 2008), in the northern corner of the Province of Neuquén.

Seismic activity is also a main reason for triggering mass-removal processes (Keefer 1984, 2002). Keefer (1984) made a landslide classification based on the terminology proposed by Varnes (1978) and established that the smallest earthquake capable of triggering a slide is of M_s 4 magnitude. Even though the seismic events recorded for the region are rather scarce for recent periods, it was nonetheless possible to find for the period 1931–2007 two seisms of magnitude $M_s > 5$ and 160 events of M_s 4–5, whereas for the 28/02/2000–12/11/2005 period, 32 events of M_s 4–5 (USGS/NEIC 2007) were recorded; no earthquake of $M_s > 5$ was recorded (Fig. 8). Such small and deep (>100 km) earthquakes were located far from the landslide site and did not have a sufficiently large magnitude to cause ground acceleration affecting the slopes of Cordillera de Santa Cruz. So, the landslide was probably triggered by high pore water pressures associated with the rapid snowmelt of the above-normal snowpack.

8 Conclusion

Through the above study, we identified on the eastern slope of the Santa Cruz river a debris-rock slide responsible for temporally obstructing the course of this river with a naturally formed dam and an associated lake.

The collapse of this dam, which discharged part of the stored water, originated a destructive-type flash flood whose effects were observed hundreds of kilometres downstream. The debris-rock slide has been recognized through air photographs of the 1960s; it evolved until creating the natural dam between 2001 and November 2005, when the dam breaching took place.

The large snowpack accumulation during the winter of 2005 and the fast thawing-off process in spring time, after a period of unusually high temperatures (>35°C), caused a fast overtopping of the natural dam and its subsequent collapse with a flash flood that caused great damages to main localities of the Department of Calingasta and Caracoles Hydropower Project dam on the San Juan river.

On the western flank of the Cordillera de Santa Cruz, there are numerous mass wasting processes and talus rock-glaciers. These slides could generate new natural dams down the creek, with their temporary ponds and small lakes that, in case of collapsing, could trigger new flash floods.

In the debris-rock slide sector, the presence of minor scarps points to the instability of the hill slope and to the great probability of new rock and detritus slide occurrences that may close the creek again. On the other hand, the lake formed between years 2001 and 2005 was discharged only in part which means that, at present, it is possible to observe that it still keeps a ponding length longer than 1.5 km and a sizable stored water volume.

On account of the above exposed facts, the study conclusions suggest as necessary a monitoring program of the slopes and hillsides of Santa Cruz river, by means of satellite images and air photography during different seasons of the year, and in consecutive years. This first measure should go along with field surveillance in order to know in detail the evolution of these phenomena and the characteristics of the deposits caused by landslides.

Acknowledgments The authors especially thank the anonymous reviewers for their helpful comments. They also thank R. Martinez and J. Ruiz who provided historical data and photographies of this extreme event on the study area. Finally, the authors acknowledge funding received from PIP 6267 of Consejo Nacional de Investigaciones Científicas y Ténicas (CONICET) to support this research

References

Abele G (1974) Bergstürze in den Alpen: the Verbreitung, Morphologie und Folgeerscheinun-gen. Wissenschaftliche Alpenvereinshefte, Heft 25, Munchen

Alonso R, Wayne W (1992) Riesgos geológicos en el norte Argentino, Congreso Geologico Boliviano. Bol 27:213–216

Cruden D, Varnes D (1996) Landslides types and processes. In: Turner AK, Schuster RL (eds) Landslides: investigation and mitigation. Transportation Research Board, National Research Council, Washington, pp 36–75

Departamento Hidráulica (Hydraulics Department) (2005) Aluvión de los días 12 y 13 de noviembre del 2005. Unpublished report, 16 pp

Diario de Cuyo Newspaper November (2005) http://www.diariodecuyo.com.ar

Dikau R, Brunsden D, Schrott L, Ibsen M (1996) Landslide recognition, Report no. 1. European Commission Environment Programme, Contract no. EV5V-CT94-0454. Identification, Movement and Causes, Chichester, 251 pp

González Díaz EF, Giaccardi AD, Costa CH (2001) La avalancha de rocas del río Barrancas (Cerro Pelán), norte del Neuquén: su relación con la catástrofe del río Colorado (29/12/1914). Rev Asoc Geol Argent 56(4):466–480

Groeber P (1916) Informe sobre las causas han producido las crecientes del Río Colorado (territorios del Neuquen y La Pampa) en 1914, Ministerio de Agricultura de la Nación (Argentina), Dirección General de Minas. Buenos Aires. Geología e Hidrología, Serie B (Geología), Bull 11, pp 1–29

Groeber P (1933) Confluencia de los Río Grande y Barrancas (Mendoza y Neuquén). Ministerio de Agricultura de la Nación (Argentina), Dirección de Minas y Geología, Buenos Aires, Bull 38, pp 1–72

Hermanns RL, Niedermann S, Ivy-Ochs S, Kubik P (2004) Rock avalanching into a landslide-dammed lake causing multiple dam failure in Las Conchas valley (NW Argentina)—evidence from surface exposure dating and stratigraphic analyses. Landslides 1(2):113–122. doi:10.1007/s10346-004-0013-5

Hermanns RL, Folguera A, Penna I, Naumann R, Niedermann S (2006) Morphologic characterization of giant flood deposits downriver landslide dams in the Northern Patagonian Andes. Geophys Res Abstr 8:09181

Hermanns RL, Folguera A, Penna IM, González Díaz FE, Fauque L, Niedermann S (2008) Landslides damns in Central Andes of Argentina (northern Patagonia and the Argentine northwest). In: Evans S, Hermanns R, Strom A, Scarascia Mugnozza G (eds) NATO, Series Publication Security of Natural and Artificial Rock Slide Dams, Springer, Berlin, pp 113–122

IAHS-UNESCO-WMO (1974) Flash floods. In: Proceedings of the Paris symposium, Publication no. 112

Igarzábal AP (1979) Los flujos densos de la Quebrada de Escoipe. Proc VII Congr Geol Argent 2:109–117

Keefer DK (1984) Landslides caused by earthquakes. Bull Geol Soc Am 95:406–421. doi:10.1130/0016-7606(1984)95<406:LCBE>2.0.CO;2

Keefer DK (2002) Investigating landslides caused by earthquakes—a historical review. Surv Geophys 23:473–510

Kimio I, Toshio M, Tatsuhei I, Yoshihisa K (2005) Outbursts and disasters of Takaisoyama and Hose landslide dams (1892) in East Shikoku. J Jpn Soc Eros Control Eng 58(4):3–12

Koeppen W (1931) Grundriss der Klimakunde, vol 12. Walter de Gruyter Co., Berlin, 388 pp

Lencinas A (1982) Características estructurales del extremo sur de la Cordillera Sanjuanina, Argentina. 5° Congreso Latinoamericano de Geología. Actas 1:489–498

Lliboutry L, González O, Simken J (1958) Les glaciers du désert chilien. Assoc Int Hydrol Sci 46:291–300

Minetti J, Barbieri P, Carleto M, Poblete A, Sierra E (1986) El régimen de precipitación de la provincia de San Juan. Informe técnico 8. CIRSAJ-CONICET, San Juan

Moreiras S, Banchig A (2008) Eventos de deslizamientos-endicamientos reiterados de ocurrencia histórica. Cuenca del río Villavil, Sierra de Aconquija, Andalgalá, Catamarca. 17° Congreso Geológico Argentino. Actas 1:257–258

National Weather Service (2006) U.S. NOAA's. Definitions of flash flood. www.srh.noaa.gov/mrx/hydro/flooddef.php

Penna IM, Hermanns RL, Folguera A (2007) Determinación del área inmediata afectada por el desagote de la Laguna Navarrete, provincia de Neuquén (36°30′ S–71° O). Rev Asoc Geol Argent 62(3):460–466

Penna IM, Hermanns R, Folguera A (2008) Remoción en masa y colapso catastrófico de diques naturales generados en el frente orogénico andino (36°–38° S): Los casos Navarrete y río Barrancas. Rev Asoc Geol Argent 63(2):172–180

Pérez D (1995) Estudio geológico del Cordón del Espinacito y regiones adyacentes, Provincia de San Juan. Tesis Doctoral de la Universidad de Buenos Aires. Unpublished, 262 pp

Selby MJ (1993) Hillslope materials and processes, 2nd edn. Oxford University Press, New York, 451 pp

Sepúlveda SA (2000) Methodology for debris flow hazard evaluation in mountainous environments. Comunicaciones 51:3–18 (in Spanish)

USGS (2000) Shuttle Radar Topography Mission, 3 Arc Second, Global Land Cover Facility, University of Maryland, College Park, Maryland

USGS/NEIC (2007) National Earthquake Information Center, World Data Center A for Seismology, Global Earthquake Search. United States Geological Survey, National Earthquake Information Center. http://www.neic.cr.usgs.gov/neis/epic/epic_global.html

Varnes D (1978) Slope movement. Types and processes, Chap. 2. In: Schuster R, Krizek R (eds) Landslides: analysis and control. Transportation Research Board Special Report 176, National Academy of Sciences, Washington, DC, pp 11–33

Wayne WJ (1987) Aluviones al acecho. El Tribuno Newspaper, Salta, Argentina, pp 6–7