Nat Hazards
DOI 10.1007/s11069-010-9658-7

ORIGINAL PAPER

A geologic study of the Juan del Grijalva landslide, the most important mass movement during the last century in Mexico

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Received: 1 December 2009 / Accepted: 26 October 2010

Abstract On November 4th 2007, along the Grijalva River in the state of Chiapas, Mexico, has occurred one of the largest landslides ever known. This landslide, known as *Juan del Grijalva*, destroyed the town of the same name, killing 20 people, and moved 55 million cubic meters of rock and debris down slope to completely block the Grijalva River. In order to understand the characteristics and factors that triggered the Juan del Grijalva landslide, geologic studies were conducted at the site. The results indicate that the landslide was composed of a lithologic sequence of thin-bedded shales and thin to medium-thick-bedded sandstones. This was faulted into several blocks dipping in the same sense as the mass movement. The main triggering factor was the increment of the pore pressure into the lithologic unit due to water saturation after 5 days of heavy rain before the incident. According to records from the last century, the Juan del Grijalva mass movement represents one of the largest mass movements recorded all over the world. The risk conditions of the area after the landslide lead to the rapid construction of an artificial channel to drain the accumulating mass of water upstream and therefore prevent a future catastrophic inundation down stream.

Keywords Mass movement · Hazard · Flash landslide · Grijalva river · Chiapas · Mexico

1 Introduction

The study area is located in the northern part of the Chiapas State, southern Mexico, at latitude 17°21′51″N and 93°23′00″W longitude (Fig. 1). The mass movement took place in

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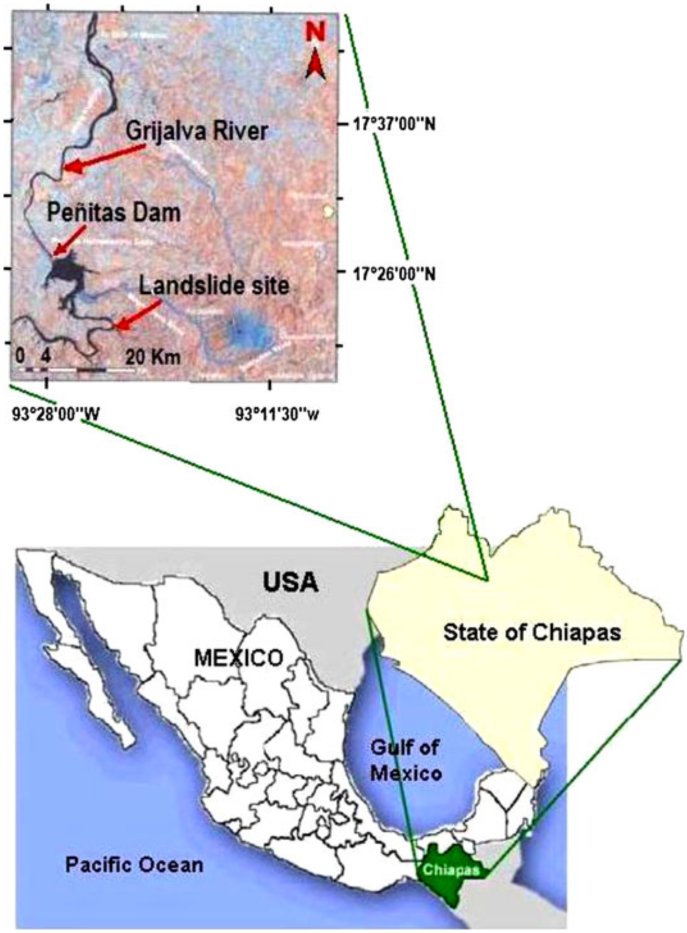

Fig. 1 Location of the Juan del Grijalva Landslide and the downstream Peñitas Dam in the Grijalva River, Chiapas State, southeastern Mexico

a hillside section of the winding Grijalva River in between the Peñitas Dam and the Malpaso Dam hydropower facilities, located 16 km downstream and 36 km upstream, respectively. These two hydroelectric power stations are part of the most important electricity supply system in Mexico.

The landslide occurred Sunday November 4th 2007, at approximately 8:30 p.m., after 5 h of heavy rain in a hilly and mountainous region. The landslide moved down slope caused by gravity pull, creating a water and mud wave 50 m high that destroyed the Juan del Grijalva town and killed 20 people. The landslide frontal part blocked the Grijalva River section (Fig. 2) with a filling material mass 800 m long and created a hazardous artificial lake upstream. On the basis of size, type of material and controlling factors, this landslide is the largest ever documented in Mexico.

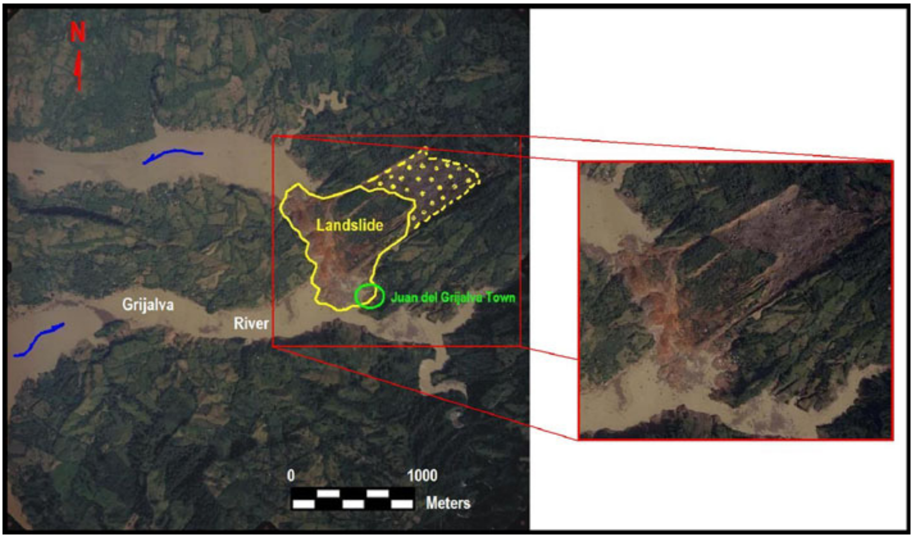

Fig. 2 Aerial photograph showing the Juan del Grijalva Landslide and the course of the obstructed loop section of the Grijalva River. Photograph taken November 6, 2007, 2 days after the incident

2 Analysis of the landslide

2.1 Geologic characteristics

Geologic mapping in the region indicates that a single stratigraphic unit constitutes both the bedrock and the landslide (Fig. 3). The unit of Miocene age is formed by thin to medium-bedded ochre-colored sandstones and very thin to thin dark gray shales. At the base of the unit, there are some layers of very coarse to pebbly sandstones and brown conglomerates. The strike of the sedimentary unit is N340 dipping between 8° and 15° southwestward, as part of the northeastern limb of the Maspac Syncline.

The surface mapping of the landslide shows the site morphology (Fig. 4) and how the material slid downward as a coherent unit, shoving the lower part outward and causing the debris to flow downhill. The front of the landslide formed a hummocky lobe that blocked the Grijalva River and stopped water from flowing downstream. The landslide moved more than 55,000,000 cubic meters of rock and debris along a horizontal distance of 500 m with about 140 m of vertical displacement (CFE, Comisión Federal de Electricidad 2008).

Based on the analysis of previous available data and recent drill cores, fieldwork, and aerial photographs, the landslide was divided into three main blocks (*Block A*, *Block B* and *Block C*) separated from the main bedrock mass. These blocks were limited by two strike slip faults located at the northern (*Falla Norte*) and southern (*Falla Sur*) parts of the landslide. The Falla Norte and Falla Sur crop-out almost parallel, with a strike of about N60°. The detachment fault surface was named *Juan del Grijalva Fault* (Fig. 5). Into the landslide itself, two steep, almost vertical, normal faults developed (*Falla Uno* and *Falla Dos*). Large blocks of rock mixed with muddy material were found inside the landslide, indicating that layers of the main stratigraphic unit were broken off along joints and planes of weakness.

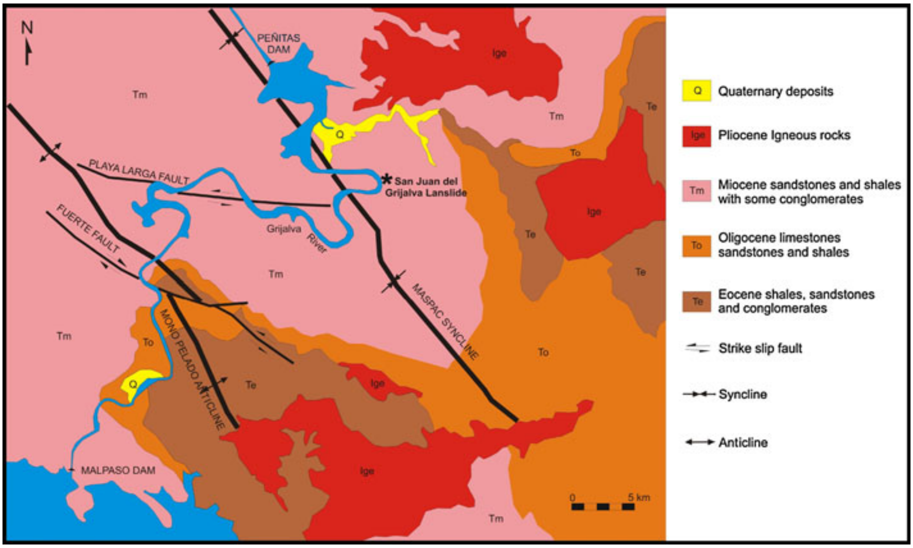

Fig. 3 Simplified regional geologic map of the area surrounding the Juan del Grijalva Landslide, Chiapas, Mexico (CFE—Comisión Federal de Electricidad 2008). Note the location of the Malpaso and Peñitas dams

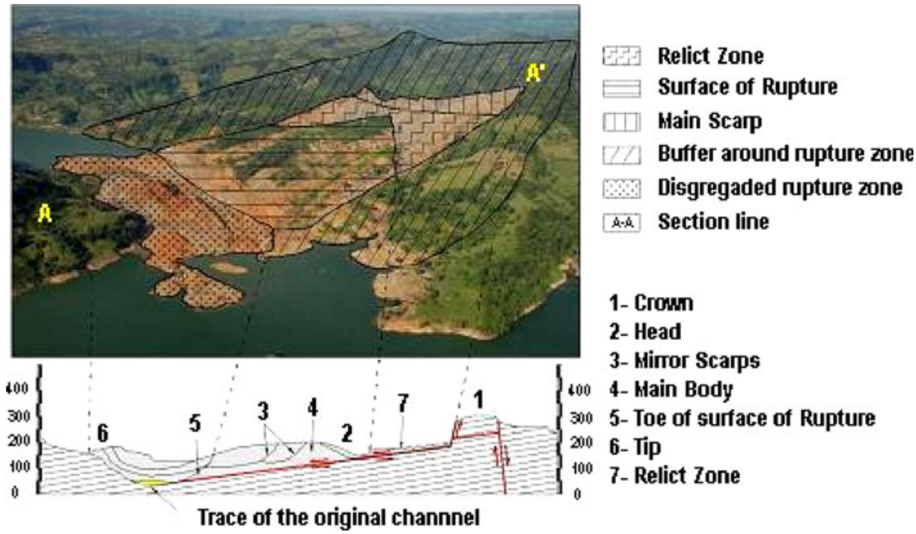

Fig. 4 Morphology of the Juan del Grijalva landslide. See the obstruction of the river course and cross-section A–A′ through the sliding zone. Nomenclature after Chacón et al. (1993)

Three sets of fractures intersect at different angles; the first set of discontinuities strike N60°E and dip 75° in NW and SE direction. It is characterized by continuous (3–10 m long), planar, and smooth surfaces striking parallel to the Falla Norte and Falla Sur. The second set of fractures is oriented N45°W with an average dip of 80° to the NE. This is a secondary set, less continuous (1–3 m long), with a planar-rough discontinuity surface. The

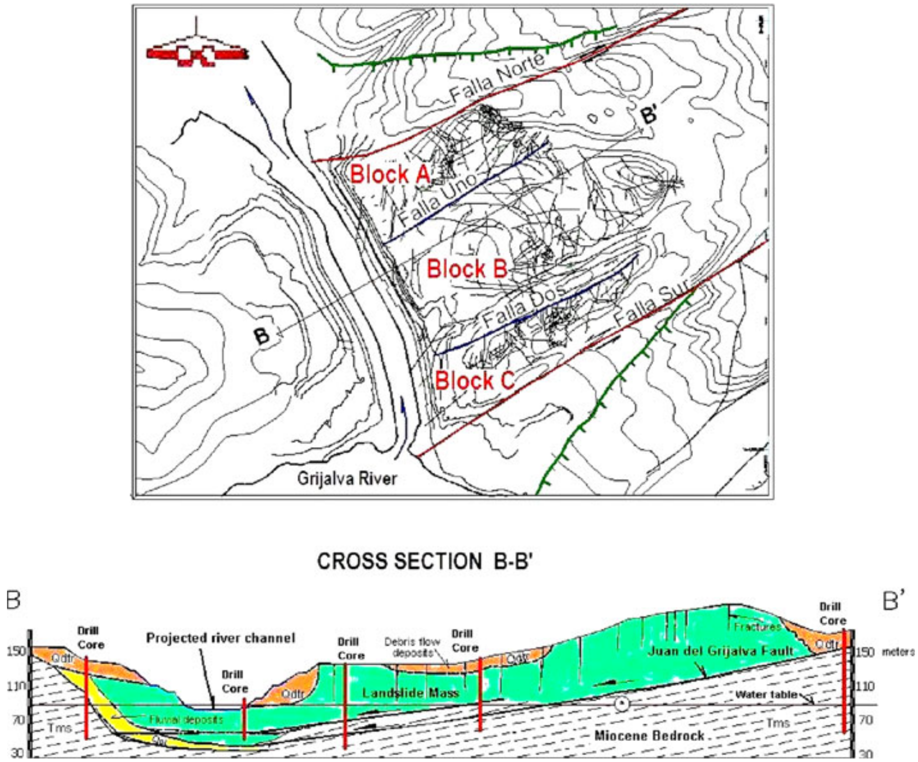

Fig. 5 Main geologic features of the Juan del Grijalva Landslide. Falla Norte and Falla Sur bound the landslide on the north and south edges, respectively, and Fallas Uno and Dos are intermediate faults. Drill cores cut the path of the Juan del Grijalva *detachment fault* and the projected artificial river channel in cross-section B–B′

third set strikes Eastward dipping 85° in N direction. This set of fractures, although not well defined, has a smooth-planar surface and is cut by the first set of discontinuities.

After the landslide event, ten exploration bore-holes were drilled (Fig. 6) and one electrical resistivity geophysical reconnaissance line survey was acquired. The objective was to determine the internal character of the landslide, specifically the geotechnical response of the ground to imposed conditions of stress, drainage, saturation, movement and removal of blocks. Based on core recovery, rock grade and fracture distribution, it was possible to discern the thickness and internal deformation in the landslide, as well as that the bedrock conditions were strong, with a bedrock mass as good as 100% rock quality in some volumes.

The most important feature in the lithologic sequence is the presence of a weathered shale layer (CFE, Comisión Federal de Electricidad 2007) found in the contact between the landslide and the bedrock along the Juan del Grijalva Fault. This weathered layer acted as a lubricant in the well-defined surface of detachment. The regional topography also increased the probability of a landslide; the lower hillsides had slopes of 8–10° parallel to the bedding surface, and summit slopes were exceptionally steep. The vertical distance between the valley floor and the summit was about 100 m. This relief profile was very susceptible to landslides.

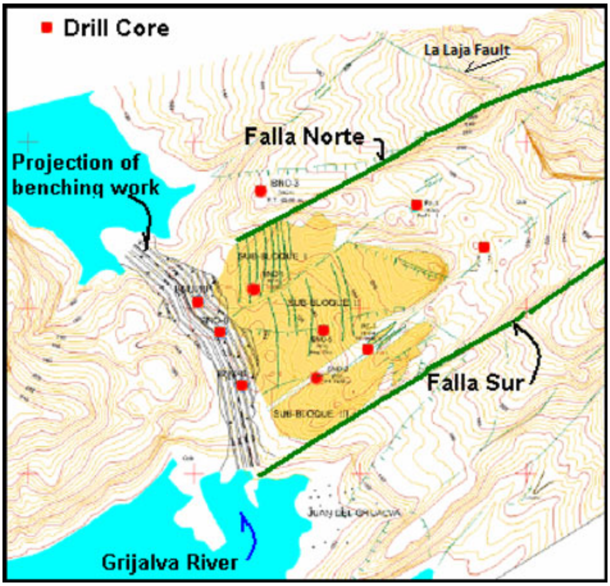

Fig. 6 Location of drill cores in the Juan del Grijalva Landslide

2.2 Triggering factors

The critical factor that triggered the Juan del Grijalva landslide was water input. This happened after 5 days of exceptionally heavy rains in this tropical region, with more than 1,000 mm of precipitation recorded. The rainfall caused water to infiltrate into the weathered shale layer, thus increasing the pore pressure. With the wet shale acting as a lubricant, the overlaying saturated sedimentary rock unit, along with the soil cover, slid down into the valley.

The geologic factors that gave the area an unstable situation were: (1) a tertiary sedimentary rock unit composed by a sandstone and shale sequence, (2) bedding planes with dip angles between 8° and 10°, parallel to hillside slopes, (3) high local relief, (4) inclined surfaces of weakness such as fractures and faults, specifically a weathered shale layer, (5) a temporary high water table at the base of the slope, and probably (6) undercutting at the base of the slope due to river current erosion. These latter factors led to an important increase in pore pressure.

2.3 Fault mechanism model

According to all previous factors, it is proposed here that the landslide gravity induced movement of the bedrock mass, followed three stages (Fig. 7).

In the first stage, before the detachment, the natural slope had a safety factor of 1.5 according to Carson and Kirkby (1972) scale. However, after 5 h of extreme rainfall, the rock composed of sandstone, shale, and unconsolidated materials absorbed water rainfall and started creep very slowly.

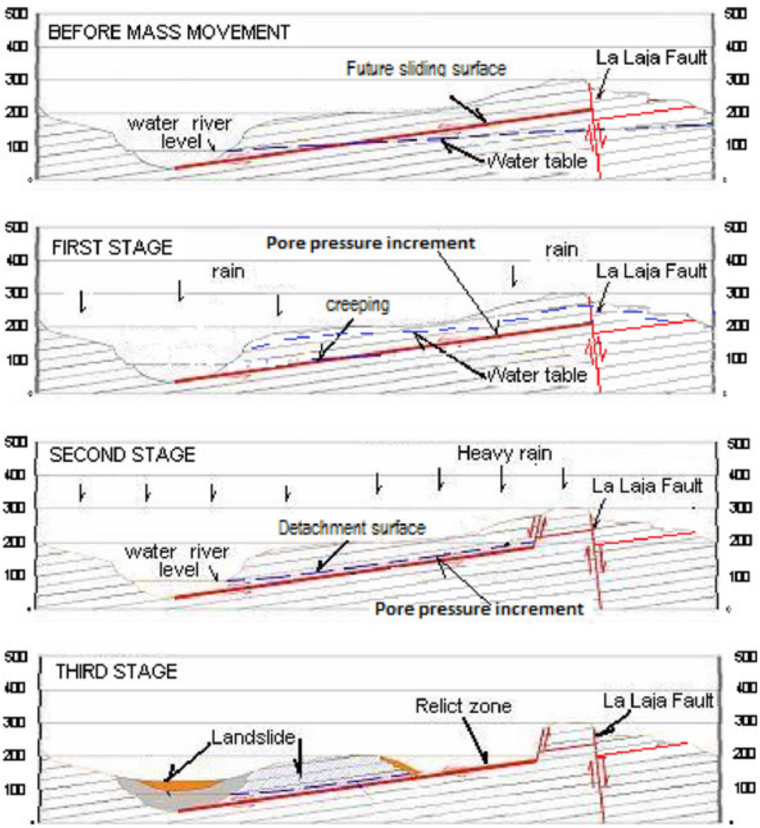

Fig. 7 Schematic stage development during the down slope movement of the Juan del Grijalva Landslide

In the second stage, the pore pressure increment due to water saturation and weight caused a suddenly slid of the slope material. The safety factor decreased and the instability limit was reached because the initial shear resistance of the rock mass was overcome.

It is important to emphasize the role of the pore pressure at the base of the landslide. The critical value for the shear resistance of a rock mass is:

$$\tau = C + (\varphi \, \sigma) \tag{1}$$

where, τ = critical shear resistance, C = cohesion, φ = internal friction angle, σ = normal effective stress.

But, if we consider there is no cohesion, and that:

$$\sigma = \sigma_{(n-p)} \tag{2}$$

where, n = normal stress and p = pore pressure, then if the pore pressure (p) increases it follows that the effective normal stress (σ) decreases (Eq. 2), and with the same shear stress it is possible to have a rupture under the same state of stress (Eq. 1). In our case, the infiltration of water increased the pore pressure thus decreasing the normal effective stress, which in turn weakened the slope stability.

During the third and final stage of the process, the lower part of the landslide was transformed into a turbulent, viscous, heavy mass of rock fragments, debris, and soil that moved downward almost instantly. The mass movement caused a river water wave 50 m high and filled up the complete watercourse valley.

3 An important landslide of the last century

Table 1 is shown in order to compare the Juan del Grijalva Landslide with several other large landslides that occurred during the twentieth century around the world (Schuster 1996). It is evident from the data shown that the most frequent triggering factor, in this type of natural process, is the extraordinary heavy rainfall.

Based on the volume of material displaced, the Juan del Grijalva Landslide becomes one of the largest events ever recorded. However, considering the number of lives claimed, it is one of the least deadly.

4 The hazardous landslide scenario

The landslide was caused by natural conditions creating a risky scenario along the Grijalva River. The flow of the river was blocked by the landslide, and an artificial reservoir was formed upstream. This accumulation of water was particularly dangerous in terms of the possible future rainstorms and a consequent rapid increase in water level that could trigger new landslides along the hillsides of the valley of the Grijalva River.

Also, an uncontrolled input of water could overtop both the blocking landslide material and/or the Peñitas Dam located 16 km downstream. In the case of a water overflow or the collapse of the Peñitas Dam, there could be a catastrophic flooding and destruction over large populated areas downstream.

Fortunately, the existence of Malpaso Dam located 36 km upstream allowed the water flow in the river to be temporally stopped. Then, an engineering program to minimize the hazard was immediately started.

Techniques for local landslide prevention, such as surface and subsurface artificial drainage, removal of materials, drilling and excavation of a main channel drain, among others, were cautiously carried out at the top and around the landslide. After a very successful 2 months of 24 h days of engineering work, both the river discharge flow and the hydroelectric power facility functions were back to normal.

5 Summary and conclusions

The Juan del Grijalva Landslide was formed by a sudden gravity sliding of a bedrock slab along a detachment or decollément surface. The climatic controlling factors of the sliding were sparse vegetation due to forest clearing, frequent heavy rainfalls, more than 1,000 mm of precipitation during 5 days previous to sliding, and bedrock and debris material water saturation (pore pressure increment).

The geologic factors that triggered the landslide were the increment of the pore pressure in the sandstones and shales at the base of the landslide, the increased weight in the rock and debris material exceeding the critical factor of the local rocks shear resistance, a thin-bedded sedimentary unit composed by shales and sandstones with bedding planes dipping

Table 1 Main landslides occurred during the twentieth century in the world

Year	Country (state/prov.)	Name and type (s)	Triggering process	Vol., m^3 [area]	Impact	Comments	References
1911	Tadzhik Rep. (formerly U.S.S.R.)	Usoy rock slide	Usoy earthquake M7.4	2.0×10^9	Destroyed Usoy village; 54 killed; dammed Murgab River, impounding 65-km-long, still-existing Lake Sarez	Casualties low because of sparse population	Bolt et al. (1975)
1919	Indonesia [Java]	Kelut lahars (volcanic mud flows)	Eruption of Kelut volcano	[185 km^2]	5,110 killed; 104 villages destroyed or damaged	Draining of crater lake caused "hot mud flows" (Van Bemmelen, 1970)	Zen and Hadikusumo (1965), Van Bemmelen (1970), Brand (1984)
1920	China [Ningxia]	Haiyuan landslides	Haiyuan earthquake	Unknown	~100,000 killed; many villages destroyed	675 large loess landslides created more than 40 lakes	Close and McCormick (1922), Feng and Guo (1985)
1921	Kazakh Rep. (formerly U.S.S.R.)	Alma-Ata debris flow	Snowmelt	Unknown	500 killed	Debris flow in valley of Alma-Atinka River	Yesenov and Degovets (1982)
1933	China [Sichuan]	Deixi landslides	Deixi earthquake M7.5	$>150 \times 10^6$	6,800 killed by landslides; 2,500 drowned when landslide dam failed	Earthquake caused several major landslides; largest formed 255-m-high dam on Min River	Li et al. (1986)
1939	Japan [Hyogo]	Mount Rokko slides and mud flows	Heavy rain	Unknown	505 dead/missing; 130,000 homes destroyed or badly damaged by mass movements and/or floods	Caused by major typhoon; 50–90% of impact of Japanese typhoons caused by mass movements	Nakano et al. (1974), Ministry of Construction (1983)
1949	Tadzhik Rep. (formerly U.S.S.R.)	Khait rock slide	Khait earthquake M7.5	Unknown	12,000–20,000 killed or missing; 33 villages destroyed	Began as rock slide; transformed into large loess and granite debris avalanche	Wesson and Wesson (1975), Jaroff (1977)
1953	Japan [Wakayama]	Arita River slides and debris/mud flows	Heavy rain	Unknown	460 dead/missing; 4,772 homes destroyed or badly damaged by mass movements/floods	Caused by major typhoon; 50–90% of impact of Japanese typhoons caused by mass movements	Ministry of Construction (1983)
1953	Japan [Kyoto]	Minamiyamashiro slides and debris/mud flows	Heavy rain	Unknown	336 dead/missing; 5,122 homes destroyed or badly damaged by mass movements/floods		Ministry of Construction (1983)

Table 1 continued

Year	Country (state/prov.)	Name and type (s)	Triggering process	Vol., m^3 [area]	Impact	Comments	References
1958	Japan [Shizuoka]	Kanogawa slides and mud/debris flows	Heavy rain	Unknown	1,094 dead/missing; 19,754 homes destroyed or badly damaged by mass movements/floods	Caused by major typhoon; 50–90% of impact of Japanese typhoons caused by mass movements	Ministry of Construction (1983)
1962	Peru [Ancash]	Nevados Huascaran debris avalanche	Unknown	13×10^6	4,000–5,000 killed; much of village of Ranrahirca destroyed	Major debris avalanche from Nevados Huascaran; average velocity 170 km/hr	McDowell and Fletcher (1962), Morales (1966)
1963	Italy (Friuli-Venezia-Griulia)	Vaiont rock slide	Filling Vaiont Reservoir	25×10^6	~2,000 killed; city of Longarone badly damaged; total damages; ~ US$200 million (1994 equiv. US$970 million)	High-velocity rock slide into Vaiont Reservoir caused 100-m wave to overtop Vaiont Dam	Kiersch (1964), Müller (1968), Hendron and Patton (1985)
1964	United States [Alaska]	1964 Alaska landslides	Prince Willam Soud earthquake M9.4	Unknown	Estimated US$180 million (1994 equiv. US$860 million) in ground failure damages	Major landslide damage in cities of Anchorage, Valdez, Whittier, Seward	Hansen (1965), Youd (1978)
1965	China [Yunnan]	Rock slide	Unknown	450×10^6	Four villages; 444 dead	Occurred at "high speed"	Li (1990)
1966	Brazil [Rio de Janeiro]	Rio de Janeiro slides, avalanches, debris/mud flows	Heavy rain	Unknown	~1,000 dead from landslides and floods	Many landslides in Rio de Janeiro and environs	Jones (1973), Da Costa Nunes et al. (1979)
1967	Brazil [Serra das Araras]	Serra das Araras slides, avalanches, debris/mud flows	Heavy rain	Unknown	~1,700 dead from landslides and floods	Many landslides in mountains SW of Rio de Janeiro	Jones (1973) Da Costa Nunes et al. (1979)
1970	Peru [Ankash]	Nevados Huascaran debris avalanche	Earthquake M7.7	Unknown	18,000 dead; town of Yungay destroyed; Ranrahirca partially destroyed	Debris avalanche from same peak as in 1962; attained average velocity of 280 km/hr	Cluff (1971), Plafker et al. (1971), Plafker and Ericksen (1978)
1974	Peru [Huancavelica]	Mayunmarca rock slide-debris avalanche	Rainfall? River erosion?	1.6×10^9	Mayunmarca village destroyed, ~ 450 killed; failure of 150-m-high landslide dam caused major downstream flooding	Debris avalanche with average velocity of 140 km/hr dammed Mantaro River	Lee and Duncan (1975), Kojan and Hutchinson (1978)

Table 1 continued

Year	Country (state/prov.)	Name and type (s)	Triggering process	Vol., m^3 [area]	Impact	Comments	References
1980	USA [Washington]	Mount St. Helens rock slide-debris avalanche	Eruption of Mount St. Helens	2.8×10^9	World's largest historic landslide; only 5–10 killed, but major destruction of homes, highways, etc.; major debris flow; deaths low because of evacuation	Evacuation saved lives; began as rock slide; deteriorated into 23-km-long debris avalanche with average velocity of 125 km/hr; surface remobilized into 95-km-long debris flow	Schuster (1983), Voight et al. (1983)
1983	USA [Utah]	Thistle debris slide	Snowmelt and heavy rain	21×10^6	Destroyed major railroad and highways; dammed Spanish Fork flooding town of Thistle; no deaths	Total losses: US$400 millon (1994 equiv. US$600 millon); 50% direct costs, 50% indirect	Kaliser (1983), University of Utah (1984)
1983	China [Gansu]	Saleshan landslide	Unknown	35×10^6	237 dead; buried four villages; filled two reservoirs	Loess landslide	Wang and Xu (1984), Li (1990)
1985	Colombia [Tolima]	Nevado del Ruiz debris flows	Eruption of Nevado del Ruiz	Unknown	Four towns and Villages destroyed; flow in valley of Lagunillas River killed more than 20,000 in city of Armero	Death toll unnecessarily large because hazard warnings not passed to residents	Voight (1990), Mileti et al. (1991)
1986	Papau New Guinea [East New Britain]	Bairaman Rock slide-debris avalanche	Bairaman earthquake M7.1	200×10^6	Village of Bairaman destroyed by debris flow from breached landslide dam; evacuation prevented casualties; huge effect on local landscape	Debris avalanche formed 210-m-high dam that impounded 50-million m^3 lake; dam failed, causing 100-m-deep-debris flow-flood downstream	King (1987), King et al. (1989)
1987	Ecuador [Napo]	Reventador landslides	Reventador earthquakes M6.1 and 6.9	$75–110 \times 10^6$	~1,000 Killed; many kms of Trans-Ecuadorian oil pipeline and highway destroyed; total losses: US$ 1 billion (1994 equiv. US$1.3 billion)	Landsliding mainly in saturated, residual soils on steep slopes; thousands of thin slides remobilized into debris flows in tributary and main drainages	Schuster (1991), Schuster et al. (1996)
1993	Switzerland	Vallemagia, Rovana River	Discharge of groundwater from artesian wells	150×10^6	Road displacement (during more than 100 years) between Cevio and Cimalmotto towns, southern swiss Alps	Landslide on metamorphic terrane. Currently stable by the use of drains	Bertola et al. (1997)

Table 1 continued

Year	Country (state/prov.)	Name and type (s)	Triggering process	Vol., m^3 [area]	Impact	Comments	References
1994	Colombia [Cauca]	Paez landslides	Paez earthquake M6.4	[259 km^2]	Several villages partially destroyed by landslides; 271 dead; 1,700 missing; 158 injured; 32,000 displaced	Thousands of thin, residual-soil slides on steep slopes turned into damaging debris flows in tributary and main drainages	Martínez et al. (1995), Schuster (1995)
1994	Italy	Corniglio Landslide (Emilia-Romangna	Heavy rain	250 × 10^6	Only affecting road access. Slide movement of 1 mm per day	10 to 23° bedding planes in a turbidity stratigraphic sequence	NASA (2009): http// disaster.ceos.org/ landslide.htm
1994	Colombia	Paez River landslides, SW Bogotá.	Heavy rain	Unknown	Destroyed houses, schools and buildings	Unknown number of lives claimed	USGS (United States Geological Survey) 2009b: www.landslides.usgs.gov/ research/other/ centralamerica.php
1998	Nicaragua	Las Casitas landslide at the base of the Casitas Volcano	Volcanic activity	Unknown	3,000 lives lost		USGS (United States Geological Survey) (2009b): www.landslides.usgs.gov/ research/other/ centralamerica.php
1999	Venezuela	Tanaguarena	Heavy rain	Unknown	Unknown	Mudflows (?)	USGS (United States Geological Survey) (2009b): www.landslides.usgs.gov/ research/other/ centralamerica.php
2000	Japan	Itaya Landslide at Yamagata	Heavy rain	Unknown	Not important movements	Saturation process at the lower slopes of the Azumaya volcanic zone	NASA (2009): http// disaster.ceos.org/ landslide.htm
2001	El Salvador	Santa Tecla	Heavy rain	Unknown	Unknown	Unknown	USGS (United States Geological Survey) (2009b): www.landslides. usgs.gov/research/other/ centralamerica.php

Table 1 continued

Year	Country (state/prov.)	Name and type (s)	Triggering process	Vol., m^3 [area]	Impact	Comments	References
2005	Venezuela	Carabellada	Heavy rain	Unknown	Unknown	Unknown	USGS (United States Geological Survey) (2009c) www.geopubs.wr.usgs.gov/open-file/of03-411
2006	USA	El Sabimo, Arizona	Heavy rain	Unknown	Unknown	Unknown	USGS (United States Geological Survey) (2009d) www.pubs.gov/of/2003/ofr-03-211
2007	Mexico	San Juan del Grilalva Landslide, Chiapas.	Heavy rain	55×10^6	Village of San Juan del Grijalva destroyed, 20 lives claimed, interruption of the most important electric power system of the country	Landsliding mainly in saturated, residual soils on steep slopes; thousands of thin slides remobilized into debris flows in tributary and main drainages	CFE (Comisión Federal de Electricidad) 2008

Adapted from Schuster 1996 and USGS (United States Geological Survey) 2009a parallel to hill slope, presence of fractures and faults in a high local relief environment, and a fluctuating water table.

As a result, several events occurred: the sudden movement of more than 55, 000, 000 m^3 of rock and debris material, the complete destruction of the Juan del Grijalva town, the death of 20 people, the blocking of the Grijalva River flow by a mass of material 800 m long, and the formation of a hazardous upstream lake.

Acknowledgments We wish to thank the CFE's geology team (GEIC) that carried out most of the field work as well as to many other colleagues that worked hard in the laboratory under the frame of a CFE priority security grant obtained during the Mexican preventional governmental program. We would like to also express our sincere thanks to the reviewers who critically reviewed our manuscript and gave constructive suggestions in improving the clarity and quality of the manuscript.

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