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LARGE VOLUME LANDSLIDES IN THE CENTRAL ANDES OF CHILE AND ARGENTINA (32º-34ºS) AND RELATED HAZARDS

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ABSTRACT

Large landslides are a common geomorphological feature of the Central Andes of Chile and Argentina. The highlands usually present landslide relicts of different types and volumes located in glacial valleys, including outsized rock slides and avalanches of millions of cubic metres up to cubic kilometres of volume. Even though the main trigger mechanisms of these events are not clear yet, being mostly interpreted as seismic in Chile and ambiguously climatic or seismic in Argentina, there is no doubt about their key role in the geomorphological evolution of Central Andes. Besides the direct hazard of landsliding in slope areas and surroundings, usually with little population, large volume landslides can also induce indirect hazards far away from the landslide original site, due to rock avalanches and/or debris flows, reaching inhabited places and threatening critical facilities for large cities such as Santiago or Mendoza. Landslide dams have formed lakes of different size, which slopes are susceptible to rock avalanches that may fall into the lakes producing catastrophic flooding downstream due to dam overtopping or failure. Examples of historic events in the Central Andes are revised and a preliminary description of hazards in the study area along with identification of necessary research for full hazard and risk assessment are presented.

INTRODUCTION

Demographic situation of Central Andes show an irregular population distribution concentrated in capital cities located at the foothills of mountain ranges at both sides of the Central Andes. Such is the case of Santiago (Chile) and Mendoza (Argentina) with about 6 and 1.5 million inhabitants, respectively (Fig. 1). Less populated villages are installed in the mountainous environment, which may have reduced the probable impact of landslides in the past. Historical damages have been mainly reported for communication belts such as the Transandino railway and the international road N°7 between both countries (Moreiras & Coronato, 2010). However, a progressive increase of the region vulnerability is denoted as a consequence of pressure in growing population with its inevitable urbanization

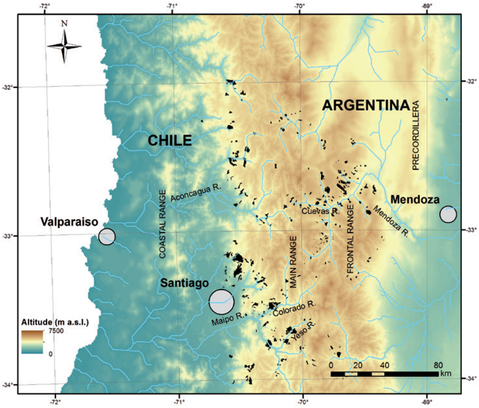

Fig. 1 - Hypsometric map of the Central Andes at 32°-34° with large volume landslide inventory (black polygons) (modified from Moreiras & Sepúlveda, 2013)

combined with development of tourist activities and further facilities. Many water reservoirs have been built in the mountain environment in last decades for water supply and electric power generation for main cities and mining activities. These structures are also used for controlling river floods and irrigation of productive oasis on the arid eastern side of the Andes.

Increasing vulnerability of the study area makes fundamental to identify and understand the behaviour of landslides and their main triggering mechanisms in the past, to prevent Andean communities that may be affected in downstream valleys as it is well-known that rock avalanches or huge landslides could reach great distances. In this paper we summarize the state of the art about large volume in the Andes at 32°-34°S, revise some examples of historic events in the Central Andes are revised and discuss on the related hazards that Andean communities may face in the future.

LARGE VOLUME LANDSLIDES IN THE STUDY AREA

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Central Andes at the latitude of the study area (32-34º S), are composed of different morphostructural and geological provinces. They are (from west to east) the Coastal Range, the Main Range, the Frontal Range and the Precordillera (Fig. 1). The Coastal Range is mainly formed by Paleozoic and Cenozoic intrusive bodies and volcanosedimentary Mesozoic and Cenozoic rocks covered by Pliocene-Quaternary alluvium (Gana *et alii,* 1996; Wall *et alii*, 1996, 1999; Sellés & Gana, 2001). The Main Range (Thiele, 1980; Ramos, 1996; Wall *et alii*, 1999; Fock, 2005) is formed by Eocene to Miocene volcanic rocks of Farellones and Abanico formations in Chile, intruded by Miocene granitic bodies, and the Aconcagua volcanic complex in Argentina. These rocks overlay Jurassic and Cretaceous marine and volcaniclastic rocks in Chile, which correlate with the Mendoza Group in the Argentinean side. The border area presents the current volcanic arc from about the 33ºS southward, including some active volcanoes. Structurally, this sector was developed by thin-skinned structures such as the Aconcagua fold and thrust belt (AFTB) (Ramos *et alii*, 1996), some of which present seismic activity (Sepúlveda *et alii,* 2008). The Frontal Cordillera is composed of volcanic and sedimentary units formed during the Gondwanides orogeny in the Late Paleozoic to early Mesozoic, including some andesitic, granitic and rhyolitic subvolcanic rocks (Ramos *et alii*, 1996). Older marine and foreland basin sedimentary Paleozoic rocks crop out in the Precordillera range, an Andean thrust-and-fold belt sequence with a typical thin-skinned structure.

Between 28-33°S, this segment of the Central Andes has a distinctive, flat slab plate tectonic setting, while south of 33º there is a normal subduction with volcanic activity. The present convergence rate between the subducted Nazca plate and the South American plate averages about 6-7 cm per year (Kharazade & Klotz, 2003), and a thrust tectonics predominates in the region since about 22 Ma (Pilger, 1984; Ramos, 1988). As a consequence of progressively Orogen front migration towards to the east, main active faulting is recorded in the eastern Andes foothill at present, characterised by an intense neotectonic activity (Costa *et alii*, 2000; Moreiras & Sepúlveda, 2013).

LARGE VOLUME LANDSLIDE INVENTORY AND CHRONOLOGY

Moreiras & Sepúlveda (2013) revised a series of previous publications and together with new mapping produced a large-volume landslide inventory for this region (Fig. 1). At least 650 km^2 of this region are affected by megalandslides. They are concentrated in the Main and Frontal ranges, while they are not recognized in the Coastal Cordillera and only a few in the Precordillera (Moreiras & Sepúlveda 2013). The large volume landslides are of different types, usually located in glacial valleys, including large rock slides and rock avalanches of volumes up to some cubic kilometres. Most of these geoforms were initially described as glacial moraines, being reinterpreted as mass movements since the eighties (e.g. Abele, 1984; Moreiras & Sepúlveda, 2013 and references therein). There are still a large number of deposits that have not been studied in detail to assure their glacial or landslide origin. In some cases, recent studies suggest that some of giant deposits, such as the Mesón Alto deposit in the Yeso valley in Chile, are of a polygenetic nature, with rock avalanches covering moraine deposits (Deckart *et alii*, 2013). Likewise, the La Engorda deposit described ambiguously as a moraine (Thiele, 1980) and then as a huge Holocene landslide (Antinao, 2008; Antinao & Gosse, 2009) have been recently interpreted as several rock avalanches over two glacial events (Gonzalez, 2010; Moreiras *et alii*, 2012).

A Pleistocene age was generally assumed for the large landslides in this portion of the Central Andes. However, recent studies mainly based on radiocarbon and cosmogenic datings reveal younger ages, most of them ranging from about 4 ky to 15 ky (Moreiras & Sepúlveda, 2013 and references therein). Megalandslides older than Late Pleistocene are rare, commonly, assigned from relative ages based on stratigraphy or tephrochronology.

Hypotheses about triggering mechanisms of large landslides vary between the Chilean and Argentinean Andes. Whereas a seismic cause is proposed for most events in the Chilean side, palaeo-climate is assumed as the main conditioning factor for Argentinean landslides (Moreiras & Sepúlveda, 2013). The landslide distribution usually relates to traces of regional faults and seismic activity has been detected in the AFTB, although actual neotectonic activity of these faults has not been investigated in depth. Scarcity of very large volume failures in the highlands during historic large subduction earthquakes against occurrence of such failures during shallow earthquakes in the study area and southern Chile reinforce the hypothesis of shallow seismic sources as the most likely origin of earthquake-induced landslides in the area (Sepúlveda *et alii*, 2008, 2010, 2012). Meanwhile, the tentative role of debuttressing and isostatic rebounding after glacier retreat may be correlated with a Holocene age of a majority of palaeo-landslides, although some ages seem to be too young to attribute this mechanism as a main cause of the failures (Poschinger, 2002; Moreiras & Sepúlveda, 2013).

HISTORIC LANDSLIDES AND POTENTIAL LANDSLIDE AREAS

The hazards related to large volume landslides in the Central Andes have not been studied in depth, except by a few exceptions (Moreiras, 2004, 2005; Stumpf, 2008; Moreiras 2009; Fauqué *et alii*, 2009a, 2009b; Welkner *et alii,* 2010). For instance, in the Chilean side, most attention have been paid to debris flows induced by heavy rainfall, commonly associated to El Niño events (Sepúlveda *et alii*, 2006), which are more frequent and have badly affected urban areas in Santiago, the last in 1993 killing about 30 people (Naranjo & Varela, 1996; Hauser, 2000). Meanwhile, rock falls and debris flows have affected historically mountain roads in Argentina interrupting vehicles traffic, damaging infrastructure and resulting in some fatalities. First fatality was reported in 1790 when a fallen block caused the death of the muleteer, Santiago Molina, in Cortaderas site located in the Mendoza river valley (Moreiras & Coronato, 2010). The international road Nº 7 that anciently connects Mendoza (Argentina) with Santiago (Chile) runs along this valley. In 1976 a collapse fell on a car killing 2 tourists (Moreiras, 2004). Debris flows resulting on fatalities in mountain roads in both countries are common. Instead, megalandslides are extreme events of high magnitude - low frequency that are usually not registered in the historic record of a community but are present in the natural, geological record of the area where it is emplaced. In such cases, the short-term, historical records do not reflect the long-term behaviour of a hazard, because the relationship between magnitude and frequency changes over time, concept known as non-stationarity (Nott, 2006). The consequence of the occurrence of such extreme events can be catastrophic, causing disasters of very high social impact. In our study area and neighbour regions of the central Andes there are a few cases of historic events that can show some effects of large volume landslides, which must be considered along with geological study of prehistoric events for a correct hazard assessment.

In Chile, recent examples are two landslides triggered by the 1958 earthquake and the 1987 Parraguirre landslide and debris flow. On the 4th of September 1958, a sequence of 3 shallow crustal earthquakes of magnitude between 6.3 and 6.9 (Lomnitz, 1960; Alvarado *et alii*, 2008) affected the Andean Main Cordillera around the confluence of the Yeso, Volcán and Maipo rivers. The 1958 earthquakes triggered an important number of landslides, particularly rock falls, and some larger movements, including two soil slumps known as Las Cortaderas landslide (15-20x10^6 m^3, Fig. 2), located in the Yeso Valley, and El Manzanito landslide (4x10^6 m^3) located in the Maipo Valley, about 9 km north and 6 km south of the main shock epicentre, respectively (Sepúlveda *et alii*, 2008). The first destroyed the road to the Yeso dam and blocked the Yeso river, forming a small lake that lasted for a few years, until the natural dam was broken by the river (Borde, 1966), while the second destroyed a hydroelectric channel that carried water

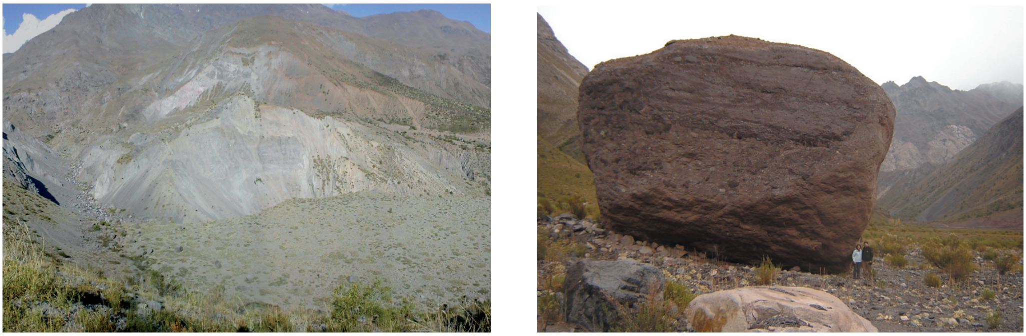

Fig. 2 - Left: Deposits of 1958 Las Cortaderas landslide triggered by the Las Melosas earthquake in central Chile. The front scarp is that eroded by the Yeso River after dam break, the back scarp is the 1958 landslide release zone. Right: Giant block deposited by the 1987 Parraguirre debris flow in the Colorado River. The boulder (about 2700 t, Hauser, 2002) has been described to have moved for several kilometres from its original position (authors for scale)

to the Queltehues power station. The two events were studied by Sepúlveda *et alii* (2008), who carried out geotechnical back-analyses and concluded that peak ground accelerations of the order of 1g were required to trigger the failures. A second historic example in the Chilean Andes in the study area is the 29th November 1987 Parraguirre river event (Hauser, 2002 and references therein). A ca. $6x10^6$ m^3 rock slide in a heavily fractured andesite, limestone and gypsum slope, with a thin slab shape of about 1000 m long at 4350 m a.s.l. suddenly collapsed with no specific seismic or rain trigger. The height drop was almost 1 km. The slide evolved into a rock avalanche that fell on top of rock glaciers at the valley bottom, becaming a debris flow due to incorporation of snow, ice and sediments, with an estimated total volume of $15x10^6$ m^3. The flow travelled over 50 km with frontal waves 20-30 m high, killing at least 37 people and destroying a power plant under constructions and seriously damaging a second one (Hauser, 2002). The proposed cause for this event is a combination of quick snowmelt of a large amount of snow (in a year with El Niño), chemical weathering of the sedimentary rocks and deglaciation. Despite the resulting debris flow transported very large boulders

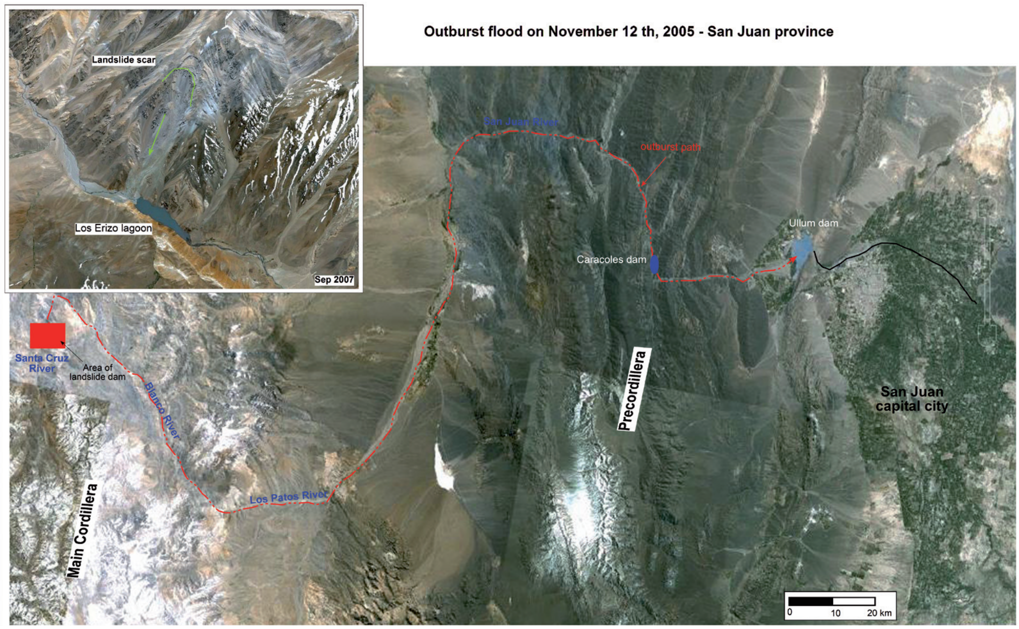

Fig. 3 - Path of outburst flood occurred in 2005 when Los Erizos dammed lake collapsed

(Fig. 2), the deposit left by this flow is small compared to prehistoric deposits in the stratigraphic record in the valley (HAUSER, 2002), which suggest that events of much higher energy have occurred in the past, reflecting that this solely event is not fully representative of the hazard for the region.

In Argentina there are not historic events in the study area, but some important ones have been reported both North and South, indicating the effects these kinds of hazards may produce. A landslide dam called Los Erizos located at the Santa Cruz (Blanco River's headwater, San Juan province, 31º 41`S) generated an outburst flood on the San Juan River when collapsed on November 12th, 2005 (Fig. 3). The streamflow of San Juan River reached over 1000 m^3/s. This violent flow caused severe damages downslope destroying bridges and roads, and isolating many people in the mountain areas. The just-built Caracoles dam was severely damaged and the Ullum reservoir, located 180 km from the failure area was affected. As consequence water became turbid in few minutes, affecting the drinking water system of the San Juan capital city. Even though the existence of impounded lake was reported by employees of mining companies, yet nobody warned of this hazardous situation. This outburst flow reached to 32,1 million cubic meters in about 67 minutes and run 254 km downstream in 12 hours (D`ODORICO *et alii*, 2009).

The major and probable most drastic outburst in Argentina was recorded in 1914 when the Carri Lauquen Lake (36º 30´S), Neuquén province collapsed generating an extraordinary outburst flood on the Barrancas River (GROEBER, 1916; GONZÁLEZ DÍAZ *et alii,* 2001; HERMANNS *et alii*, 2004a, 2004b). The lake had been dammed by a landslide dated 2 ky (GONZÁLEZ DÍAZ *et alii*, 2005). The dam collapse occurred overnight when 2 billion m^3 of water were drained from the lake reducing its original 21-km-long to 5.6 km. Likewise its surface was lowered about 95 m (GROEBER,1916). The resulting debris flow/flood ran over 300 km channeled into the Barrancas River reaching the Colorado River and devastating two villages and downstream valleys (Fig. 4). Many cultivated fields with wheat, corn, and alfalfa along these rivers were buried by mud and debris. Twenty years later farmlands still had not recovered (GROEBER, 1933, SCHUSTER *et alii*, 2002). Several animal farms completely disappeared and the flow wiped out railway stations, railway lines, and roads located along the Colorado River. As well debris flow dammed the

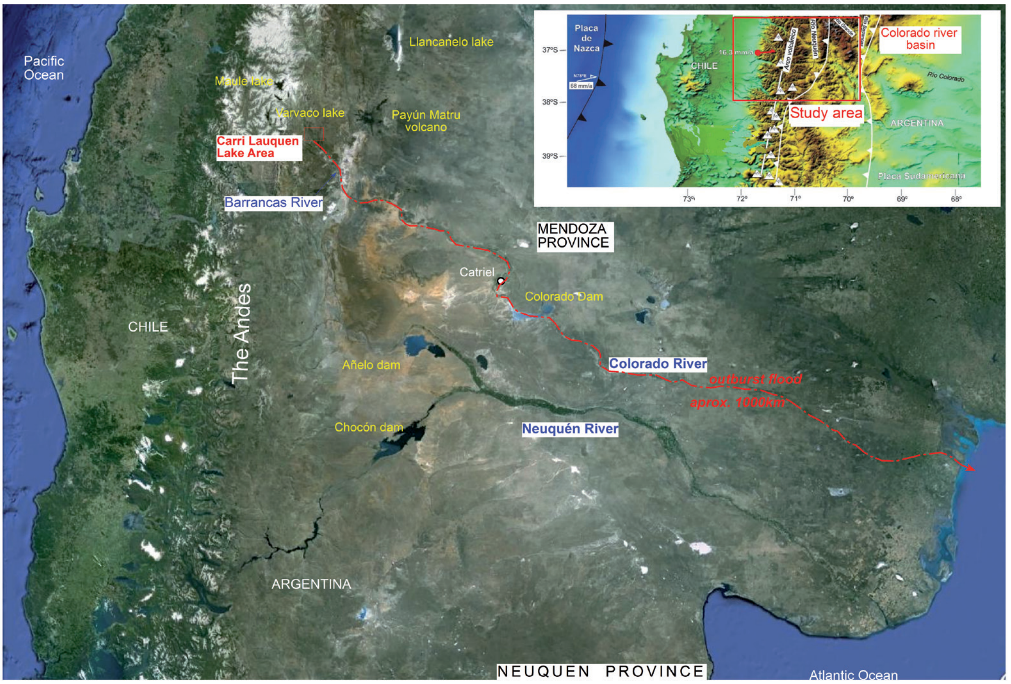

Fig. 4 - Outburst flood generated by the collapse of the Carri Lauquen Lake (36º 30´S), Neuquén province on December 29th, 1914 draining 2 billion m^3 of water and affecting the valleys of Barrancas and Colorado rivers

Quili-Malalal River, forming a tiny lagoon 200 m long and 25 m wide, that disappeared quickly. The overflow also triggered several landslides. In all, 175 fatalities were reported, and more than 100 persons disappeared. A turbidity event was recognized in the Atlantic Ocean distant about 1,000 km from the original source area (Schuster & Highland, 2001).

These historic events show the potential of catastrophic large volume landslides in the study area, mainly due to rock slides and rock avalanches in glacial valleys that can produce large debris flows or landslide or glacial dam break that can cause outburst floods. Lack of collective memory generally underestimated the potential hazard of these catastrophic events.

Another potential hazard is a Vajont-like event, with slope failure on existent lakes or water reservoirs that can produce catastrophic flooding downstream due to dam overtopping or dam failure. This kind of hazard must be investigated in places such the Laguna Negra lake and Yeso reservoir in Chile, or the Potrerillos reservoir in Mendoza. In the latter, some smaller slides of not more than 500 thousand cubic meters have been already identified, possibly triggered by volume fluctuation due to its fill and discharge (Moreiras *et alii,* 2010). In all cases, the effects of the landslide reaches far beyond the landslide site, posing a real risk for local communities and infrastructure such a water supply for the large cities of Santiago and Mendoza, land irrigation channels, hydroelectric plants and roads, as well as tourist infrastructure.

CONCLUDING REMARKS

A great number of large volume landslides can be recognized in the Central Andes of Chile and Argentina. Most of them have not been studied in detail. Understanding the effect of landslide failure mechanisms, the chronology of occurrence and the relationships with other geomorphic processes in the area of study will allow a better assessment of the potential of future events and the risk involved for the local community and infrastructure. Furthermore, understanding of dam breaking mechanics and effects after a landslide event is also important, as the runout of the flow that originates from its rupture could easily reach inhabited villages and tourist resorts located downstream along the main rivers and disrupt strategic infrastructure for capital cities such as Santiago or Mendoza.

Detailed geomorphological analyses of large landslides, combined with geochronological analyses and vulnerability assessments of potentially affected communities and strategic infrastructure are fundamental to improve our understanding of these low frequency-high impact events. The results of such studies will be useful for regional and local territorial planning as well as for design of emergency protocols for authorities and services companies and development of local risk assessments. Furthermore, early detection of unstable areas that have not failed yet will allow future slope monitoring for design and implementation of early warning systems.

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