Failure mechanisms of large volume rock avalanches in the Andes of Central Chile: a brief discussion

Sergio A. Sepúlveda [1,2]

1 Instituto de Ciencias de la Ingeniería, Universidad de O´Higgins, Rancagua, Chile.

2 Departamento de Geología, Universidad de Chile, Santiago, Chile.

sergio.sepulveda@uoh.cl

Abstract

Large volume rock avalanche deposits are widely found in the Andes Main Range of central Chile (ca. 32°-36° S). However, their failure mechanisms are mostly unknown. Given the high seismicity of the region, located in an active subduction tectonic margin with very frequent, large magnitude interplate earthquakes, as well as some correlation of landslide distribution with regional faults, a coseismic origin has been usually proposed in the literature. Nevertheless, evidence from recent large magnitude, megathrust earthquakes in the region suggest that they may not be the most likely trigger. Coseismic triggers due to low frequency, local earthquakes in active faults seem to be a more plausible hypothesis, supported by some geotechnical back-analyses, but local paleoseismic studies are still scarce to be conclusive. In turn, the influence of paraglacial stress conditions in the glaciated uplands have not been investigated in depth, as well as the influence of hydrogeological changes, either in the long term due to climate changes or in the short term due to intense rainfall or snowmelt in mostly fractured, volcanic or volcanosedimentary rock masses. This paper reviews the literature on a number of case studies in the last couple of decades and addresses the need to test these different hypotheses with more detailed field assessment, geochronological and geotechnical modelling studies.

1 INTRODUCTION

The main range of the Andes of central Chile (ca. 32°-36° S) are commonplace for large volume rock slope failures such as rock slides and rock avalanches. Large deposits varying from millions of cubic metres up to some cubic kilometres can be found throughout fluvial and glacial valleys along the high mountain range (e.g. Abele, 1984; Antinao and Gosse, 2009; Welkner et al., 2010; Deckart et al., 2014; Moreiras and Sepúlveda, 2015; García et al., 2018). While these large deposits have been mostly mapped originally as glacial deposits, in the last decades they have been recognized as landslide deposits of post-glacial age.

While there are very few historic records of large rock slope failures (Hauser, 2002; Sepúlveda et al., 2008), their geographic distribution close to geologic faults and the high seismicity of the country, especially related to frequent, high magnitude interplate megathrust earthquakes close to the coastline and less frequent, shallow crustal earthquakes, have influenced a coseismic origin to be proposed as the most likely failure mechanism to trigger these landslides. In contrast, a climatic-related origin has been mainly proposed for similar landslides in the Argentinean side of the Andean range (Moreiras and Sepúlveda, 2015 and references therein), although lately a coseismic origin has been also considered as likely mechanism in some areas (Junquera-Torrado et al., 2019).

In this paper, we discuss the coseismic hypothesis for the origin of megalandslides in the Chilean Andes on the light of case studies and lessons from recent earthquakes in the country. The research is conducted by a bibliographic review of case studies of large volume landslides in the region, as well as the revision of landslide inventories and description of recent historic earthquakes in the country, such as the 2010 Maule and 2014 Illapel megathrust earthquakes, and the 1958 Las Melosas and 2007 Aysen shallow crustal earthquakes.

2 ROCK AVALANCHES IN CENTRAL CHILE

Large volume landslide inventories in central Chile (Antinao and Gosse, 2009; Moreiras and Sepúlveda, 2015; Figure 1) have related the origin of large volume landslides (Figure 2), mainly rock slides and rock avalanches, with a likely seismic trigger. In particular, Antinao and Gosse (2009) correlate their distribution with main geologic faults, which have been mostly not studied in detail but are thought to be potentially active (Pérez et al., 2013), while recent neotectonic studies have shown that some major faults such as the San Ramón Fault at the edge of Santiago city are geologically active (Vargas et al., 2014).

Geotechnical case studies (e.g. Garcia et al. 2018; Sepúlveda et al., 2018) based on numerical modelling have found that some of these landslides are consistent with a seismic trigger of local source, that is a shallow crustal earthquake on an active fault. However, the only example of a relatively large shallow crustal earthquake in the region is the 1958 (Mw 6.3; Alvarado et al., 200) Las Melosas earthquake in the Maipo valley, which induced a couple of large landslides (Sepúlveda et al., 2008; Figure 2) and extensive rock falling. Similarly, the 2007 (Mw 6.2) shallow Aysen earthquake in the south of Chile triggered several large rock slides in granitoids, up to 22 Mm3, close to the epicentre (Sepúlveda and Serey, 2009; Sepúlveda et al. 2010; Oppikofer et al., 2012). The low frequency (recurrence periods of thousands of years, e.g. Vargas et al., 2014) of strong (M>6) shallow crustal earthquakes on active faults in the Andes of central Chile precludes having an inventory of coseismic landslides. Back-analysis approaches, with several uncertainties on slope conditions, has to be taken to justify a seismic trigger for large slides (e.g. Sepúlveda et al., 2008; García et al., 2018).

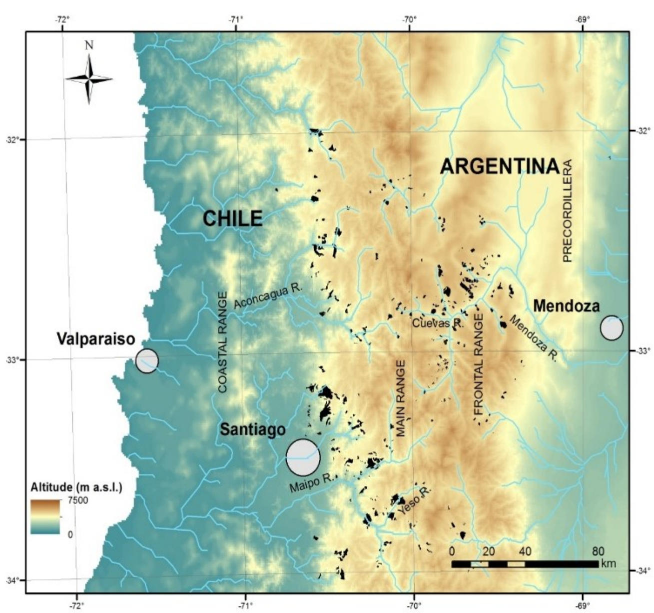

Figure 1: Large volume landslide inventory of central Chile and Argentina (modified after Sepúlveda and Moreiras, 2015)

In contrast, the 2010 (Mw 8.8) Maule subduction earthquake in front of the study region has shown that, despite the high magnitude, the number and size of landslides is relatively small, and no megalandslides were reported in the coseismic landslide inventory for that case (Serey et al., 2019). This is the largest recorded earthquake in the central Chile region, and second in the country history after the 1960, M 9.5 Valdivia earthquake. The latter triggered some large lateral spread-type failures in river valleys (San Pedro river, Davis and Karzulovic, 1963), but it did not have reports of large slope collapses in the uplands either. Similar findings have been reported for the 2014 Illapel earthquake (31.6°S), with slope failures usually limited to rock falls and shallow slides, with no large, deep-seated slides reported (Candia et al., 2017). The distance to the rupture zone of megathrust earthquakes and consequent high frequency wave attenuation seems a likely explanation for the absence of major failures in the high Main Andean range, located 50-100 km away from the rupture zones, despite the very high magnitude of the earthquakes.

On the other hand, two historic large volume rock slope failure with no seismic trigger have taken place in central Chile (Parraguirre landslide, 1987, no clear trigger, most likely snowmelt; Hauser, 2002) and southern Chile (Villa Santa Lucia landslide, 2017, rainfall trigger; Duhart et al., 2018), both with fatal consequences due to debris flows derived from the original rock avalanches. Both cases are in environments dominated by paraglacial conditions, including presence of glacier remnants at valley bottoms and probable presence of permafrost in the slopes.

The possible influence of paraglacial conditions and progressive failure as part of the failure mechanisms or controlling factors leading to slope instability in the high mountain environments are key to understand the presence of giant rock slope failures in the Chilean Andes and the landslide (and seismic?) hazard in these regions. The progressive failures in paraglacial slopes are due to the progressive deglaciation of valleys in long geologic periods, because the slope structure becomes sensitive to rock degradation due to the environment exposure, water effects, and decompression (Riva et al. 2018). This may explain many of the large postglacial landslides in the glaciated terrains, which would have been generated with or without need of seismic or rainfall triggers. This topic must be subject of deeper research for better understanding of the failure mechanisms and the potential hazard of such failures in the uplands region.

However, most rock slide deposits are located outside the LGM limits (Antinao and Gosse, 2009), thus the influence of glaciation is not the only explanation. For fluvial valleys in non-glaciated terrains, the little evidence from historic cases, in particular the absence of large landslides triggered by rainfall or megathrust earthquakes, and the geographic distribution close to faults suggest that shallow crustal earthquakes continue to be the most likely explanation.

Figure 2: Examples or large volume landslides in the region: Above, prehistoric rock avalanche deposits in Pangal valley (34.2°S, Sepúlveda et al., 2019); below: Las Cortaderas landslide reactivated during the 1958 earthquake in an old, large rock collapse deposit in the Yeso valley (33.7°S; Sepúlveda et al., 2008).

3 CONCLUSIONS

Large volume rock avalanche deposits are widely found in the Andes Main Range of central Chile. While a coseismic origin has been usually proposed in the literature, negative evidence from last large magnitude subduction earthquakes in the region suggest that they may not be the most probable trigger. Failure mechanisms related to paraglacial conditions in the glaciated uplands and/or coseismic triggers due to low frequency, local earthquakes in active faults seem to be most likely hypotheses to explain the large rock slope failures, which need to be tested with more detailed field assessment, geochronological and geotechnical modelling studies.

4 ACKNOWLEDGEMENTS

The research presented in this paper has been supported by projects Fondecyt 1201360, Fondecyt 1140317, Fondecyt 11070107, NERC-Conicyt (Newton Fund) NE/ N000315/1, IGCP 586-Y, Fondo de Investigación Científico Alto Cachapoal - Pacific Hydro Chile and Núcleo Científico Milenio en Sismotectónica y Peligro Sísmico.

5 REFERENCES

Abele, G. (1984). *Derrumbes de montaña y morenas en los Andes chilenos*. Revista de Geografía Norte Grande, 11: 17–30.

Alvarado, P., Barrientos, S., Saez, M., Astroza, M., Beck, S. (2009). *Source study and tectonic implications of the historic 1958 Las Melosas crustal earthquake, Chile, compared to earthquake damage*. Physics of the Earth and Planetary Interiors, 175:26-36.

Antinao, J. L., Gosse, J. (2009). *Large rockslides in the Southern Central Andes of Chile (32–34.58S): tectonic control and significance for Quaternary landscape evolution*. Geomorphology, 104: 117–133.

Candia G, de Pascale G, Montalva G, Ledezma C (2017) *Geotechnical aspects of the 2015 Mw 8.3 Illapel megathrust earthquake sequence in Chile*. Earthquake Spectra 33(2):709–728

Davis, S.N., Karzulovic, J. (1963). *Landslides of Lago Riñihue, Chile*. Geological Society of America Bulletin. 53: 1403-1414

Deckart, K., Pinochet, K., Sepúlveda, S.A., Pinto, L., Moreiras, S.M. (2014). *New insights on the origin of the Mesón Alto deposit, Yeso Valley, central Chile: A composite deposit of glacial and landslide processes?* Andean Geology 41 (1): 248-258.

Duhart, P., Garrido, N., Sepúlveda, V., Mella, M., Fernández, J., Quiroz, D., Hermosilla, G. (2018). *Remoción en masa de Villa Santa Lucía (16.12.17, Chaitén-Chile: características e impactos*. Actas XV Congreso Geológico Chileno, 236-238.

García, M., Pastén, C., Sepúlveda, S.A., Montalva, G., (2018). *Dynamic numerical investigation of a stepped-planar rockslide in the Central Andes, Chile.* Engineering Geology 237:64-75.

Hauser, A. (2002). *Rock avalanche and resulting debris flow in Estero Parraguirre and Río Colorado, Región Metropolitana, Chile*. In: Evans, S. G. andDegraff, J.V. (eds) Catastrophic Landslides: Effects, Occurrence, and Mechanisms. Reviews in Engineering Geology, 15:135–148.

Junquera-Torrado, S., Moreiras, S.M., Sepúlveda, S.A., (2019). *Distribution of landslides along the Andean active orogenic front (Argentinean Precordillera 31-33°S)*. Quaternary International, 512: 18-34.

Moreiras, S.M., Sepúlveda, S.A. (2015). *Megalandslides in the Andes of central Chile and Argentina (32o-34oS) and potential hazards*. In: Sepúlveda, S. A., Giambiagi, L. B., Moreiras, S. M., Pinto, L., Tunik, M., Hoke, G. D. andFarías, M. (eds) Geodynamic Processes in the Andes of Central Chile and Argentina. Geological Society, London, Special Publications, 399: 329-344.

Oppikofer, T., Hermanns, R.L., Redfield, T.F., Sepúlveda, S.A., Duhart, P., Bascuñán, I., (2012). Morphologic description of the Punta Cola rock avalanche and associated minor rockslides caused by the 21 April 2007 Aysén earthquake (Patagonia, southern Chile). Revista Asociación Geológica Argentina, 69(3): 339-353.

Pérez, A., Ruiz, J.A., Vargas, G., Rauld, R., Rebolledo, S., Campos, J. (2013) *Improving seismotectonics and seismic hazard assessment along the san Ramón fault at the eastern border of Santiago city, Chile*. Natural Hazards 71: 243– 274,

Riva, F., Agliardi, F., Amitrano, D., Crosta, G.B. (2018). *Damage-Based Time-Dependent Modeling of Paraglacial to Postglacial Progressive Failure of Large Rock Slopes.* Journal of Geophysical Research: Earth Surface, 123(1):124–141.

Serey, A., Piñero-Feliciangeli, L., Sepúlveda, S.A., Poblete, F., Petley, D.N., Murphy, W., (2019). *Landslides induced by the 2010 Chile megathrust earthquake: a comprehensive inventory and correlations with geological and seismic factors.* Landslides, 16: 1153-1165.

Sepúlveda, S. A., Astroza, M., Kausel, E., Campos, J., Casas, E., Rebolledo, S., Verdugo, R. (2008). *New findings on the 1958 Las Melosas Earthquake Sequence, Central Chile: implications for seismic hazard related to shallow crustal earthquakes in subduction zones*. Journal of Earthquake Engineering, 12–13: 432–455.

Sepúlveda, S.A., Serey, A., Lara, M., Pavez, A. Rebolledo, S. (2010). *Landslides induced by the 2007 Aysen Fjord earthquake, Chilean Patagonia.* Landslides 7: 783-792.

Sepúlveda, S.A., Lara, M., Aravena, N., Escudero, I., Vollmer, M., Serey, A. (2018). *Numerical analyses of a large earthquake-induced rock slope failure in*

Punta Cola, Chilean Patagonia. XIII Congress of the International Association of Engineering Geology and the Environment Program with Abstracts: 195-196.

Sepúlveda, S.A., Chacón D., Moreiras, S.M., Poblete, F. (2019). *Large rock avalanches and river damming hazards in the Andes of central Chile: the case of Pangal valley, Alto Cachapoa*l. Geophysical Research Abstracts, vol. 21, EGU2019-6079.

Sepúlveda, S.A., Serey, A. (2009). *Tsunamigenic, earthquake-triggered rock slope failures during the 21st of April 2007 Aisén earthquake, Southern Chile (45.5ºS)*. Andean Geology 36(1): 131-136.

Vargas, G., Klinger, Y., Rockwell, T.K., Forman, S.L., Rebolledo, S., Baize, S., Lacassin, R., Armijo, R. (2014). Probing large intraplate earthquakes at the west flank of the Andes. Geology, 42(12): 1083-1086.

Welkner, D., Eberhardt, E., Hermanns, R. L. (2010). Hazard investigation of the Portillo Rock Avalanche site, central Andes, Chile, using an integrated field mapping and numerical modelling approach. Engineering Geology, 114: 278–297.