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Developing conceptual models for the recognition of coseismic landslides hazard for shallow crustal and megathrust earthquakes in different mountain environments – an example from the Chilean Andes

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ABSTRACT

Landslides represent the most frequent geological hazard in mountainous environments. Most notably, landslides are a major source of fatalities and damage related with strong earthquakes. The main aim of this research is to show through three-dimensional engineer-friendly computer drawings, different mountain environments where coseismic landslides could be generated during shallow crustal and megathrust earthquakes in the Andes of Central Chile. From the comparison of local earthquake-induced landslide inventories in Chile, from the Mw 6.2, shallow crustal Aysén earthquake in 2007 (45.3° S) and the Mw 8.8, megathrust Maule earthquake in 2010 (32.5°S - 38.5°S), with others from abroad, as well as analysis of large, prehistoric landslide inventories proposed as likely induced by seismic activity, we have determined topographic, geomorphological, geological and seismic controlling factors in the occurrence of earthquake-triggered landslides. With these results, we have built four representative geomodels of coseismic landslide geomorphological environments in the Andes of central Chile. Each one represents the possible landslide types to be generated by a shallow crustal earthquake versus those likely to be generated by an megathrust earthquake. Additionally, the associated hazards and suggested mitigation measures are expressed in each scenario. These geomodels are a powerful tool for earthquake-induced landslide hazard assessment.

Keywords: coseismic landslides, conceptual hazard models, Chile.

INTRODUCTION

Landslides represent perhaps the most frequent geological hazard in mountainous environments due to the geological, geomorphological and geotechnical characteristics of steep upland landscapes. In tectonically-active mountain areas, landslides are a major cause of fatalities and economic losses during and after strong earthquakes (*e.g. Sepúlveda et al., 2005; Qi et al., 2010; Dai et al., 2011*).

Coseismic landslide hazard, defined as the relative probability of landslide occurrence at a specific location in a specific event, is a function of intrinsic slope characteristics (slope angle, material strength, lithology, etc.), and earthquake shaking, which acts as a significant trigger mechanism for causing landslides of all types (*Keefer 1984).* In addition to those factors influencing landsliding under ambient conditions, site conditions further influence ground motions through soil and topographic amplification (*Wang et al. 2018, Meunier et al., 2008, Sepúlveda et al. 2005*). Recent studies (*e.g.; Wartman et al., 2013; Marc et al., 2016*) suggest that they are also influenced by the seismogenic zone. *Serey et al. (2019)* observed that shallow crustal and megathrust earthquakes create fundamentally different spatial patterns and densities of landslides.

Selecting seismological inputs for slope stability analysis is challenging given the large number of difficult to quantify variables associated with coseismic landslides, which include seismic wave frequency, wave amplitude and wave interactions. This is especially complex for regional hazard assessments (*Meunier et al., 2008; Geli et al., 1988*). Several statistical methods exist for modelling regional-scale coseismic landslide hazard *(e.g., Lee et* *al., 2008; Miles and Keefer, 2000; 2007; 2009; 2009b; Jibson et al., 2000*), all of them only considering one kind of coseismic trigger, i.e shallow crustal earthquakes. Thus, a first-order form of hazard identification can prove beneficial prior to considering more complex analytical tools and different kinds of coseismic triggers. One such approach is to visualize all these variables, both conditioning and triggering factors, in the form of graphic 3D ground models, often referred to as geomodels. Such tools are also valuable in explaining complex geotechnical problems to non-specialists such as government and planning agencies.

The concept of a geomodel, and its depiction in simplified block diagrams, aims to allow visualization of the geology in three dimensions and to act as a quick introduction to new or unfamiliar ground conditions or environments (*Jackson 2016*). *Fookes (1997)* defined conceptual geological models for a number of different environments, which have been linked to hazard assessment and engineering to mitigate geohazards (e.g. *Hearn et al., 2012; Hearn and Hart, 2011; Hearn, 2018*).

Parry et al. (2014) considered that there are two fundamentally different stages for developing engineering geological models: conceptual and observational. The conceptual approach is based on understanding the relationships between engineering geological units, their likely geometry and anticipated distribution. Importantly, these models are largely based on geological concepts such as age, stratigraphy, rock type, unconformity and weathering (the 'total geological history' approach by *Fookes et al., 2000)*. The main aim of the work presented here has been to develop practitioner-friendly conceptual ground models relating to the performance of slopes subject to strong ground motions during earthquakes in different mountain environments in the Chilean Andes. These were further subdivided into slope performance during (i) megathrust earthquakes and (ii) shallow crustal earthquakes, to indicate expected slope behaviour when subjected to earthquakes of different sizes and epicentral distance. The performance of the slopes is derived from the databases outlined in *Serey et al. (2019)*. In addition to the hazards identified, potential mitigation measures are outlined based on the rock slope engineering.

COSEISMIC LANDSLIDES IN THE MOUNTAIN ENVIRONMENT OF CHILE

The Cordilleran areas in Chile constitute a major part of the landmass and contain nearly all of copper and other precious metals mining that contribute strongly to the Chilean economy. Additionally, mountain infrastructure is a vital lifeline for the flow of materials, access to markets for mountain communities and neighbour countries, and tourism. However, given the mountain conditions it is difficult to provide alternative routes in the event of lifeline disruption.

Seismically-induced landslides are a common phenomenon in the Andes, in Central and Southern Chile. This is attributed to two factors: firstly, the tectonic evolution of Chile and secondly, the glaciation of the Andes resulting in variable geological conditions. Chile can be considered the most seismically active country in the world (*Cisternas, 2011; Barrientos, 2018*); ten M8 or larger earthquakes have occurred along the Chilean coast in the past century, with a ≥M8 earthquake occurring approximately every dozen years (*Barrientos, 2018*). The second factor is that the Andes of Central and southern Chile were strongly affected by Quaternary glaciations (with many areas still covered in ice), resulting in steep topography, strong erosional features and rock masses weakened by the effects of Late-Quaternary ice action. The pattern of glaciation/deglaciation of the Andes is complex, with changes in moisture in the atmosphere combined with lowering temperatures led to a complex change in seasonal snowline variation during the late Pleistocene.

The seismotectonic setting and seismicity of Chile

The Andes of Central Chile (32.5º S to 41.5º S) are composed of a number of morphostructural units from west to east: the Coastal Cordillera, the Central Valley, the Principal Cordillera (spanning Chile and Argentina), the Frontal Cordillera, the Argentine Precordillera and the Pampean Ranges (*Jordan et al. 1983*) (Figure 1). The Principal Cordillera is a chain of high mountains that in its western part in Chilean territory mostly comprises Oligocene–Miocene continental volcaniclastic rocks, intruded by Miocene–Pliocene granitoids (*Charrier et al., 2015; Pankhurst and Hervé, 2007*). The Cordilleran environment is characterised by being an active, folded orogen with a high topographic relief and steep slopes. Cycles of high activity (driven by periods of relatively rapid uplift) that initiate periods of intense erosion as rivers cut down to lower base levels and produce steep-sided valleys. Many of these valleys have limited stability, with the immature weathered surfaces continually being eroded. Hillslopes are typically mantled with colluvium and/or taluvium that is unstable when undercut.

Several seismogenic zones are recognized in Chile: large interplate earthquakes (depths 45–55 km); large intermediate-depth earthquakes (60–200 km); shallow crustal seismicity (depths 0–20 km); and outer-rise earthquakes along the subduction margin between the Nazca and South American Plates (*Barrientos, 2018*).

Megathrust seismicity corresponds to large magnitude (above 8) interplate earthquakes in the subduction zone plate contact. Because of their comparatively high frequency of occurrence, these earthquakes are responsible for most of the historic damage. They are located along the coast from Arica (18° S) to the triple junction at Taitao Peninsula (46° S). These events take place as a result of the convergence of the Nazca beneath the South American plate at a rate of about 7.4 cm/yr (*Argus et al., 2010)*. Further south, the Antarctic plate subducts beneath the South American plate at a rate of ~8.1 cm/yr (*Lara et al., 2018*). M≥8 earthquakes are usually accompanied by notable coastal elevation changes and, depending on the amount of seafloor vertical displacement, by catastrophic tsunamis. Their rupture zones extend down to 45–53 km depth (*Tichelaar and Ruff, 1991*) and their lengths can reach well over 1000 km. Return periods for M ~ 8 (and above) events are of the order of 80–130 years for any given region in Chile, and about a dozen years when the country is considered as a whole (*Barrientos, 2018*). The latest examples of these type of earthquakes were the 2010 M 8.8 Maule, the 2014 M 8.2 Iquique, and the 2015 M 8.4 Illapel earthquakes (*Barrientos et al., 2004; Candia et al., 2017; Barrientos, 2018*). Megathrust earthquakes seem to have much longer return periods, of the order of a few centuries for any given region (*Cifuentes, 1989; Barrientos and Ward, 1990*). Recent off-fault strong ground motion indicator paleoseismological studies carried out in southern Chile indicate recurrenceintervals of ~300 years for these very large earthquakes (*Cisternas et al., 2005; Moernaut et al., 2014*).

The capacity for megathrust earthquakes to induce large numbers of landslides and mobilise large volumes of sediment was highlighted by the 1960 Valdivia (*Duke, 1960*) and the 2010 Maule (*Serey et al., 2019*) earthquakes. During the M=9.5 Valdivia earthquake extensive landsliding occurred (*Wright and Mella, 1963*). Three large landslides (2-30 Mm^3 of volume) on poorly consolidated sediments at the San Pedro River attracted particular attention due to the formation of landslide dams and the threat to the city of Valdivia c. 80 km from the slides (*Davis and Karzulovic, 1963*). *Serey et al. (2019)* provide an inventory of landslides induced by the 2010 Mw=8.8 Maule earthquake, one of the few world comprehensive, reliable inventory of coseismic landslides available for subduction zone earthquakes. In total, 1,226 landslides were mapped over a total area of c. 120,500 km^2, dominantly small disrupted slides. However, the estimated total landslide volume is only c. 10.6 M m^3. The events are unevenly distributed in the study area, the majority of landslides located in the Principal Andean Cordillera and a very constrained region near the coast on the Arauco Peninsula, forming landslide clusters (*Serey et al., 2019*). Additionally, *Candia et al.* (2017) demonstrated that there were more coseismic landslides that impacted critical infrastructure in areas with the largest fault slip at the plate boundary during the 2015 M8.4 Illapel earthquake (31.6°S).

Shallow crustal seismicity is important in seismic and coseismic hazard assessments because the strong ground motions (measured in % of gravity as peak ground accelerations, or PGA) that reach the surface due to limited distance for the seismic waves to attenuate. Shallow crustal seismicity (0–20 km) that occurs throughout Chile such as the Cordilleran region of South–Central Chile (e.g. Liquiñe-Ofqui fault zone) is a consequence of the oblique convergence of the Nazca Plate. Magnitudes up to 7.1 have been reported for earthquakes in this region (44,5°S y 73°W, 21 November 1927) (*Greve, 1964*). The Andean Principal Cordillera in the central part of Chile is also an important area with important crustal seismicity because of the risk to high population density and critical infrastructure. *Godoy et al. (1999) and Barrientos et al. (2004)* carried out structural and seismicity studies to understand this region, in which the largest recorded earthquake (less than 10 km depth) took place on 4 September 1958 (M 6.3, *Alvarado et al., 2009*), causing extensive rockfalls and a few large landslides (*Sepúlveda et al., 2008*). Shallow crustal seismicity with a relative large magnitude (> 5.5) was recently observed beneath the Andes main Cordillera at latitudes 19.6° S (Aroma; July 2001), 35.8° S (Melado River; August 2004), 38° S (Barco Lagoon; December 2006), and 45° S (Aysén Fjord; April 2007). All these events show significant strike-slip component of displacement (*Barrientos, 2018*).

In Southern Chile, The Aysén Fjord earthquake (21 April 2007, Mw 6.2) triggered over 500 landslides of different types (*Sepúlveda et al., 2010*) of which the largest was the Punta Cola rock avalanche with a volume of c. 22 Mm^3 (*Oppikofer et al., 2012*). The triggering of landslides around and into the fjord resulted in a displacement wave that killed eleven people (*Sepúlveda and Serey, 2009; Naranjo et al., 2009*).

GEOMODEL CONSTRUCTION

Data used in construction of the geomodels

Data used to develop the geomodels presented here can be divided into two broad types: landslide inventory data and limited field observation of critical lithological units. Only two comprehensive inventories of earthquake-triggered landslides exist in Chile, the shallow crustal M_w 6.2, Aysén earthquake in 2007 (45.27°S 72.66°W) (*Sepúlveda et al., 2010; Serey, 2020*) and the M_w 8.8, megathrust Maule earthquake in 2010 between 32.5° S and 38.5° S° (*Serey et al., 2019*). These inventories are representative of the landslide triggering characteristics of these two Chilean groups of seismic events. These databases were supplemented with observations from databases beyond Chile (*e.g. Marc et al., 2016; Malamud et al., 2004*) in addition to more detailed field investigations of large, historic landslides in Chile (e.g. *Sepúlveda et al., 2008*) and landslide inventories from the geologic record considered likely to have been induced by seismic activity (*Antinao and Gosse, 2009; Moreiras and Sepúlveda, 2015*). These databases contain data on topographic, geomorphological, geological and seismic controlling factors on the occurrence of earthquake-triggered landslides, which informed model construction.

Distribution and characteristic of coseismic landslides for geomodels in the Chilean Andes

It is well-established that landslides are not evenly distributed in the affected areas. Landslides tend to form clusters that may be related to geological conditions or ground motion parameters (*e.g. Serey et al., 2019; Sepúlveda et al., 2010)* or to the influence of strong ground motions coincident with fault slip distributions (*Candia et al., 2017)*). Furthermore, most occur in the Cordilleran environment where high relief and steeper slopes prevail. Examples of the landslides under investigation can be seen in Figure 2. From the analysis of databases, the following general comments can be made:

1. The most common type of landslide observed in the inventories are "disrupted" slides, consistent with observations from other earthquakes (e.g. *Keefer, 1984; Rodriguez et al., 1999; Wartman et al., 2013*).

2. Shallow disrupted slides like debris avalanches, debris slides, rock falls and rock slides, account for approximately 86% and 98% of landslides triggered by the Maule 2010 and Aysen 2007 earthquakes respectively (*Serey et al., 2019; Sepúlveda et al., 2010*) (See figure 2).

3. Relatively few slumps, deep block slides, or slow earth flows were observed from Chilean inventories. For example, less than 1% of total slides were classified as coherent slides for the Maule earthquake (*Serey et al. 2019*), and near 1% for the Aysen event (*Sepúlveda et al. 2010*)..

4. The number and distribution of coseismic landslides differs significantly between interplate/megathrust and shallow crustal earthquakes. The total number of landslides triggered for the megathrust earthquakes is substantially lower, typically by one to two orders of magnitude, than it would be expected for shallow crustal earthquakes, of a similar or even lower magnitude (*Serey et al. 2019*). This is due to strong ground motion attenuation from interplate/megathrust events that reduce the peak ground accelerations.

5. There is a difference in the size of landslides between the two different sources of seismicity. The landslides triggered by the megathrust Maule Earthquake are generally in the range of 10^2 – 10^3 m^2. Approximately 60% of coseismic landslides caused by the Maule Earthquake were in the range of 100 m^2 to 5,000 m^2. This can be contrasted with the fact that just under 50% of landslides induced during the crustal Aysen earthquake that were in the range of 5,000 m^2 to 50,000 m^2. This is likely to be a function of the amount of energy arriving at any given slope due to the attenuation from deeper sources mentioned above.

6. For megathrust earthquakes, such as those in 1960, there seems to be limited occurrence of large volume rock avalanches or rock slides. Although this type of earthquake is relatively frequent in Chile, no large volume rock avalanches have been observed to be triggered by them during the last century. However, as Chile has a high concentration of large volume rock avalanche deposits in the Andes (*Antinao and Gosse, 2009*), it is likely that these are associated with proximal shallow crustal earthquakes. Given the large distance between interplate seismicity and the Andes Principal Cordillera (c. 100-150 km in Central Chile) these seem a more likely cause than large farfield events, like the catastrophic avalanche in 1970 triggered by an M 7.9 offshore earthquake, originated from Nevados Huascarán, the highest peak in the Peruvian Andes (*Plafker and Ericksen, 1978; Evans et al. 2009*).

Factors that influence the dynamic response of hillslopes undergoing seismic shaking

The factors that influence the dynamic response of hillslopes undergoing seismic shaking (*e.g. Jibson, 2011; Newmark, 1965)* can be broadly grouped into those that influence the intensity of event-specific seismic ground motions, those that influence the strength of hillslope materials and those that influence the static shear stresses. Empirical studies have revealed a number of proxy variables that can be used to represent these factors at the regional scale (*Parker et al., 2015*).

Lithology is an important factor in the generation of coseismic landslides, being relevant mainly during megathrust events. For example, *Wartman et al. (2013)* determined that majority of landslides triggered by Mw 9.0 2011 Tohoku megathrust earthquake occurred in the youngest (Neogene) geological units of the region (Quaternary sediments and Neogene sedimentary rocks). The *Serey et al. (2019)* database indicates that for the 2010 Maule earthquake, relief exerted a dominant control on coseismic landsliding with the lithology the second most relevant conditioning factor, with more landslides in younger rocks (Quaternary deposits and Paleogene-Neogene volcanic and volcano-sedimentary rocks). This is in effect an indication on the degree of cementation and thus strength. On the other hand, in most of shallow crustal events, lithology seem not to be a primary factor to consider in the generation of landslides. For example, according by *Wang (2015)* there is no obvious correlation between landslide concentration and rock age (young or old lithology) for the 2013 Lushan and the 2008 Wenchuan earthquakes. Indeed, differences in the distributions of landslides across different lithologies arise because young or old strata are coincidentally clustered around the rupture zone of the seismogenic fault, and these rock masses are extremely fractured and underwent strong shaking.

Other factors that may have influence on the distribution of landslides are related with seismic effects on shaking in the near field, such as the hanging wall and directivity effects during strong shallow crustal earthquakes. Directivity effects are related with the rupture direction of the fault, tending to generate larger ground motions toward this direction (*Somerville et al., 1997; Somerville, 2003*). The hanging-wall effect relates with larger ground motions on the block above an inclined fault (the hanging-wall block) and is common on earthquakes along thrust faults (e.*g. Abrahamson and Somerville, 1996; Zhao et al., 2019*). The literature indicates that the landslides triggered by earthquake tending to cluster along the causative fault (*Keefer, 2000; 2002; Khazai and Sitar, 2004; Huang and Li, 2009*). For thrust faults landslide density is highest on the hanging wall (*Meunier et al., 2007*).

Ground motion was found to be the most significant factor in triggering the shallow landslides in the 1999 Mw 7.6 Chi-Chi earthquake. Overall, 74% of all slope failures occurred in regions with vertical ground motions greater than 0.2 g and 81% of all slope failures occurred in the region with mean horizontal peak ground accelerations (PGA) greater than 0.15 g (*Khazai and Sitar, 2004*). On the other hand, *Wartman et al. (2013)* compared the landslide database with ground-motion recordings of the 2011 Tohoku earthquake (Mw 9.0, megathrust event), but found no correlation between landslide intensity and ground shaking within the area affected. Similarly, in the 2010 Mw 8.8 Maule earthquake, very few landslides occurred in the area of higher intensity (VIII) and most of them were in the area of lower intensities (<V). Therefore, there was no strong correlation between landslide density and earthquake intensity (*Serey et al., 2017*) or with PGA or distance from the fault plane. There was a much stronger correlation between landslide concentration and the ratio between horizontal and vertical peak accelerations (*Serey et al., 2019*).

Densmore & Hovius (2000) recognized that earthquake-triggered landslides in rock slopes have a relatively uniform distribution on steep slopes, but in presence of topographic amplification the triggering of landslides at or near the crests is increased. Recent studies have indicated that the ground accelerations at the mountain top can be three to six times than at its foot (*Wang et al., 2012; Wang et al., 2018*), causing higher susceptibility to landsliding in the upper parts of the slopes. In the Aysen event, about two thirds of the landslides start in the upper quarter of the slope, while over 90% start in the upper half, which suggests that larger ground motions due to topographic site effects influenced the triggering of landslides during the earthquake (*Sepúlveda et al., 2010*). On the other hand, landslides induced by the Maule earthquake are not clustered close to the ridge tops, suggesting no predominant topographic site effect in their generation, although it may have played a role locally (*Serey et al., 2019*).

The above is summarized in Table 1, which shows the differences between, conditioning factors and characteristics of the coseismic landslides applied to the mountain environment of Chile for both kinds of triggers (shallow crustal and interplate/megathrust earthquakes), based on analysis of comprehensive inventories of coseismic landslides in Chile and abroad (*Serey, 2020; Zhao et al., 2019; Serey et al., 2019; Serey et al., 2017; Wang et al., 2015; Wartman et al., 2013; Gorum et al., 2011; Sepúlveda et al., 2010, Sepúlveda and Serey 2009, Meunier et al., 2007*).

CONCEPTUAL HAZARD MODELS

Using the data mentioned above, four conceptual hazard ground models were developed to guide stakeholders in the hazards faced to critical infrastructure in mountain regions. Representative geomodels describing the hazards for the Andes of Central Chile were developed, these are: Glacial Cordilleran, Fluvial Cordilleran, Plutonic Cordilleran and Mountain Front environments. The latter model is the most likely to have significant urban development because of the concentration of infrastructure. The data showing slope performance for the two different earthquake types, based on Table 1 and specific geomorphological characteristics, have then been added to the models to use in a semi-predictive capacity.

Glacial Cordilleran environment

In Central Chile, the glaciated mountain terrain is dominated by andesitic bedrock with local volcanoclastic sediments. Glacial landscapes are essentially high-latitude and/or high-altitude environments. Geomorphology in these areas is characterized by high relief and steep slopes. Furthermore, it is characterized by the presence of glacial deposits (e.g. till and glacial-fluvial deposits) and modified by periglacial processes. Rock slopes tend to be over-steepened. Rock masses quality are often fair to good, locally very good, may be highly fractured in the vicinity of lineaments or faults. Hydrothermal alteration, however, can be extreme locally and reduces the rock mass quality. Most of coseismic landslides are disrupted, principally rock falls, debris avalanches, debris slides, and rock slides. In these environments, large rock avalanches/slides could dam river valley. Landslides may occur on persistent discontinuities or glacial deposits.

Figure 3 and Figure 4 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust earthquakes respectively in a glacial cordilleran environment of Central Chilean Andes. Table 2 outlines geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a glacial cordilleran environment for each scenario.

Fluvial Cordilleran environment

Fluvial mountain terrain dominated by andesitic bedrock with local volcanoclastic sediments. Geomorphology is characterized by a strong relief, medium ranges of altitudes and medium to high gradients forming fluvial troughs (V-shaped valleys). Rock masses quality are often fair to good, locally very good, may be highly fractured near lineaments or faults. Hydrothermal alteration, however, can be extreme in places and reduce the geotechnical quality of intact rock. In these environments, large rock falls, rock avalanches/slides could dam the river valley. In this landscape, large prehistoric landslides are common, in which source areas of future rock slides may be generated by future shallow crustal events.

Figure 5 and Figure 6 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust earthquakes respectively in a fluvial cordilleran environment of Central Chilean Andes. Table 3 expresses geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a fluvial cordilleran environment for each scenario.

Plutonic Cordilleran environment

Plutonic mountain terrain dominated by intrusive igneous bedrock with local volcanoclastic sediments. This environment is characterized by a strong relief, steep slopes (medium to high ranges) and high altitudes. In general terms, plutonic rocks develop competent rock massif and tight valleys. Rock masses quality are often good to very good, may be highly fractured in the vicinity of lineaments or faults. In these environment are very common large pre-historic landslides, in which new rock slides can be generated by a future shallow crustal earthquake. In addition, large rock falls, rock avalanches/slides could dam a river valley.

Figure 7 and Figure 8 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust earthquakes respectively in a plutonic cordilleran environment of Central Chilean Andes. Table 4 outlines geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a plutonic cordilleran environment for each scenario

Mountain Front environment

Mountain front terrain, usually bordering urban areas in Central Chile, is dominated by andesitic bedrock with local volcanoclastic sediments and generally forms the at the convergence of high mountains and adjacent basins (e.g. the Santiago basin). Rock masses quality are often fair to good, locally very good, may be highly fractured in the vicinity of lineaments or faults. Hydrothermal alteration, however, can be extreme in places and reduce the geotechnical quality of intact rock. In these environments, geomorphology is characterized by a strong relief, medium ranges of altitudes and medium to high gradients. This environment presents important ravine channels, basins characterized by narrow, steep-sided valleys, in which removed materials flow directly into urban areas located in the central depression. Therefore, large rock avalanches/slides generated by a future crustal earthquake and consequently debris flows due to debris avalanche, rock falls or rock slides failures into channels could result in fatalities and infrastructure damage.

Figure 9 and Figure 10 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust earthquakes respectively in a mountain front environment of Central Chilean Andes. Table 5 outlines geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a mountain front environment for each scenario.

DISCUSSION

Landslides are an important coseismic geohazard associated with earthquakes in mountain environments and present a serious threat to communities found in these regions (*Keefer, 1984*). Indeed, in high mountain chains, 20-25% of earthquake-induced fatalities result from the effects of landslides (*Petley et al., 2006)*. By visualizing differences between conditioning factors and characteristics of coseismic landslides, using geomodels, between different triggers can be a key factor in the assessment of effective mitigation measures. From the geomodels construction, it is possible to view potential risks, consequences and possible mitigation measures for each coseismic landslides (Table 6).

Secondary hazards can be generated from large landslides, such as rock avalanches and rock slides, blocking narrow, steep-sided valleys and forming landslide dams (*Schuster, 1986*), or landslide-induced tsunamis. In some cases, landslides may pose a threat to the population and infrastructure because they dam a watercourse.

Landslide dams tend to be a feature of seismically active steep-relief mountain areas undergoing uplift and erosion or deeply dissected thick sequences of weakly consolidated sediments such as lacustrine clays. Landslide dams give rise to two important flood hazards. Upstream or back-water flooding occurs as a result of impounding of water behind the dam leading to the relatively slow inundation of an area to form a temporary dam. Downstream flooding can occur in response to failure of a landslide dam. The most frequent failure modes are overtopping because of the lack of a natural spillway or breaching due to erosion. Failure of the poorly consolidated landslide debris generally occurs within a year of dam formation. The effect of the resultant floods can be devastating, partly because of their magnitude and partly because of their unexpected occurrence (*Lee and Jones, 2004*). For example, in the 2005 Mw 7.6 Kashmir earthquake at least two river blockages occurred. The largest of the two, at Hattian Bala east of Muzaffarabad, created a dam over 100 m high (*Dunning et al., 2007*).

In Chile, the most important historical example of landslide dams took place during the giant 1960 Valdivia earthquake (Mw=9.5, megathrust earthquake). Three large landslides dammed the San Pedro River and threatened the Valdivia City. The biggest landslide removed c. 30 Mm^3 of poorly consolidated sediments, the intermediate transported 6 Mm^3 and, finally, the smallest involved the removal of 2 Mm^3 (*Davis and Karzulovic, 1963*). Given its flow, it was expected that in two months the accumulated water would exceed the landslide dam, producing a huge avalanche that would cover all of Valdivia, already devastated by the earthquake and tsunami, and the surrounding areas. To avoid this disaster, engineers and technicians from ENDESA and the MOP (Ministry of Public Works) started the so-called "Operation Riñihue", which consisted of making a channel through the undisturbed terrain, so that the water flowed as slowly as possible as it finally happened (*Lazo, 2008*). Historical records highlight this same phenomenon in the 1575 earthquake (M 8-8.5 according to *Lomnitz, 2004*), on that occasion San Pedro River was also blocked by a huge landslide in the same area (*Montessus de Ballore, 1912*), not allowing normal water drainage. The dam accumulated water for five months and finally causing a catastrophic flood taking the lives of more than 1,200 indigenous people and destroyed Valdivia city, founded by the Spaniards a couple of decades before (*Davis and Karzulovic, 1961*).

Earthquakes often leave a legacy of pseudo-stable slopes that continue for years or many decades afterward the main event. These landslides represent a direct threat themselves but also block and cut transportation infrastructure. An aspect that is often overlooked is the increased rate of sediment movement caused by the liberation of hillslope debris, an effect that could depend on the type of earthquake. In the Mw 7.6 Chi-Chi earthquake in Taiwan, a shallow crustal event, this induced aggradation of some river beds by as much as 30 m, which proved to be devastating to local communities and to hydroelectric power systems (*Petley, 2009*). On the other hand, *Tolorza et al. (2019)* demonstrated that the 2010 Mw 8.8 Maule earthquake, an megathrust event, had a limited impact on the overall concentration and transport of suspended sediment loads in the Chilean Andes, which perhaps sheds light on the influence of climate on how these systems will be behave post-events (e.g. under dry climate conditions). Thus, the seismically induced erosion and the evacuation of detached sediments are not necessarily a function of earthquake magnitude.

Despite the enormous impact potential of giant landslides, especially of those triggered during earthquakes, relatively little effort is spent to predict them. Thus, only very few case histories are known where large sites (>1 km^2) had been thoroughly investigated to assess their failure potential under dynamic conditions, in full 3D (*Havenith et al., 2017*). The major problem is the availability of cost-effective methods, both to prospect and to model such sites. Although, all of them only considered one possible seismogenic scenario, i.e. crustal shallow earthquakes. Therefore, in this manuscript, a powerful tool for earthquake-induced landslide hazard assessment applicable to urban/territorial planning and disaster prevention strategies is presented. This is a series of practitioner-friendly conceptual ground models relating to the performance of slopes subject to strong ground motions during earthquakes originated from different seismogenic scenarios (megathrust or crustal shallow earthquake) in the most characteristic mountain environments in the Chilean Andes and expresses the following.

- Main types of landslides that could be triggered, their possible spatial distribution and sizes.
- Geomorphological and geotechnical characteristics of terrain units where coseismic landslides could be located.
- Secondary hazards and suggestions of possible engineering interventions.

This methodology visualizes all factors interacting in the generation of coseismic landslides depending on seismogenic zones (megathrust or crustal shallow earthquake), and considering the low cost (in both the elaboration and the required information) it might be applied elsewhere in the country and Latin America. The continuous, poorly regulated growth of the city into the mountain environment typical in Latin America, the increasing tourism industry in mountain areas, large infrastructure projects (water supply, hydroelectricity, gas pipes, etc.) increase exposure to coseismic landslides and their secondary hazards, thus the need for these to be properly addressed in territorial planning policies and disaster prevention strategies.

It is essential to emphasize that this methodology is a conceptual approach and that it needs to be complemented with an observational model to be applied for hazard assessment at local scales, which is based on the observed and measured distribution of engineering geological units and processes. These data are related to actual space or time and are constrained by surface or sub-surface observations.

CONCLUDING REMARKS

Landslides are a substantial but often neglected aspect of megathrust and shallow crustal earthquakes in upland areas. Furthermore, in addition to killing people outright, they can also have an extremely serious impact in terms of hampering rescue operations and the delivery of assistance, situations that can vary dramatically between different triggers. Whilst earthquake-induced landslides cannot be prevented, adequate consideration of the problem in advance can allow the impact of coseismic landslides to be minimized.

Practitioner-friendly conceptual ground models relating to the performance of slopes subject to strong ground motions during megathrust or shallow crustal earthquakes in different mountain environments in the Andes of central Chile have been developed. Each model expresses important characteristics about coseismic landslide hazard (main types, spatial distribution and sizes), their potential consequences and suggestions of possible mitigation actions or engineering interventions. Due to the geological and geomorphological context, these geomodels may be replicated or adapted for other countries of Latin America. In addition, considering the low cost, both in the elaboration and the required information, these models are a very powerful tool to visualize all factors interacting in the generation of coseismic landslides.

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REFERENCES

Abrahamson NA, Somerville PG (1996) Effects of the hanging wall and footwall on ground motions recorded during the Northridge earthquake. Bull Seismol Soc Am 86(1B):S93–S99

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, Phys. Earth Planet. In. 175:26–36

Antinao, JL, Gosse J (2009) Large rockslides in the Southern Central Andes of Chile (32–34.5 S): Tectonic control and significance for Quaternary landscape evolution. Geomorphology, 104(3-4):117-133

Argus, DF, Gordon RG, Heflin MB, Ma C, Eanes RJ, Willis P, Peltier WR, Owen SE (2010) The angular velocities of the plates and the velocity of Earth's centre from space geodesy. Geophysical Journal International, 180(3):913-960

Armijo, R, Rauld R, Thiele R, Vargas G, Campos J, Lacassin R, Kausel E (2010) The West Andean thrust, the San Ramon fault, and the seismic hazard for Santiago, Chile. Tectonics, 29(2)

Barrientos S, & National Seismological Center (CSN) Team (2018) The seismic network of Chile. Seismological Research Letters, 89(2A):467-474

Barrientos S, Vera E, Alvarado P, Monfret T (2004) Crustal seismicity in central Chile. Journal of South American Earth Sciences, 16(8):759-768.

Barrientos SE, Ward SN (1990) The 1960 Chile earthquake: Inversion for slip distribution from surface deformation, Geophys. J. Int. 103:589–598

Brennan AJ, Madabhushi SG (2009) Amplification of seismic accelerations at slope crests. Canadian Geotechnical Journal 46:585-594

Candia, G., De Pascale, G.P., Montalva, G.A., Ledezma, C., (2017) Geotechnical Aspects of the 2015 Mw 8.3 Illapel Megathrust Earthquake Sequence in Chile: Earthquake Spectra. 33(2):709-728. **doi:** http://dx.doi.org/10.1193/031716EQS043M

Castedo L (2000) Hazaña del Riñihue. El Terremoto de 1960 y la Resurrección de Valdivia. Crónica de un episodio ejemplar de la Historia de Chile. Santiago, Editorial Sudamericana, 134 p.

Cifuentes IL (1989) The 1960 Chilean earthquakes, J. Geophys. Res. 94:665–680

Cisternas A (2011) El país más sísmico del mundo. Revista Anales Séptima Serie

Cisternas M, Atwater BF, Torrejón F, Sawai Y, Machuca G, Lagos M, Shishikura M (2005) Predecessors of the giant 1960 Chile earthquake. Nature, 437(7057):404

Charrier R, Ramos VA, Tapia F, Sagripanti L (2015) Tectono-stratigraphic evolution of the Andean Orogen between 31 and 37°S (Chile and Western Argentina). Geological Society Special Publications, London, 13-61

Clapperton C (1994) The quaternary glaciation of Chile: a review. Revista Chilena de Historia Natural, 67: 369 – 383

Cluff, L. S. (1971). Peru earthquake of May 31, 1970; engineering geology observations. Bulletin of the Seismological Society of America, 61(3), 511-533

Costa J E, Schuster R L (1988) The formation and failure of natural dams: Geological Society of America Bulletin, 100:1054-1068

Dai FC, Lee CF, Deng JH, Tham LG (2005) The 1786 earthquake-triggered landslkide dam and subsequent dam-break flood of the Dadu river, southwestern Chin: Geomorphology, 65:205-221

Dai FC, Xu C, Yao X, Xu L, Tu XB, Gong QM (2011) Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake. China Journal of Asian Earth Sciences 40(4):883-895

Davis SN, Karzulovic J, (1963) Landslides of Lago Riñihue, Chile. Geological Society of America Bulletin. 53(6):1403-1414

Densmore A, Hovius N (2000) Topographic fingerprints of bedrock landslides. Geology 28(4):371–374

Dunning SA, Mitchell WA, Rosser NJ, Petley DN (2007) The Hattian Bala rock avalanche and associated landslides triggered by the Kashmir Earthquake of 8 October 2005. Engineering Geology 93:130-144

Duke, CM (1960) The Chilean Earthquakes of May 1960. Science, 132(3442):1797-1802

Evans, S. G., Bishop, N. F., Smoll, L. F., Murillo, P. V., Delaney, K. B., & Oliver-Smith, A. (2009). A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970. Engineering Geology, 108(1-2), 96-118.

Fan X, Van Westen CJ, Xu G, Gorum T, Dai F, Wang G, Huang R (2009) Distribution of large landslides and landslide dams triggered by the Wenchuan earthquake, Sichuan, China: Geophysical Research Abstracts, 11

Fookes PG (1997) First Glossop Lecture: Geology for engineers: The geological model, prediction and performance. Quarterly Journal of Engineering Geology 30:293–424

Fookes PG, Baynes FJ, Hutchinson JN (2000) Total geological history: a model approach to the anticipation, observation and understanding of site conditions. In ISRM International Symposium. International Society for Rock Mechanics and Rock Engineering, 1: 370-460

Fookes PG, Pettifer G, Waltham T (2015) Geomodels in engineering geology: an introduction. Whittles Publishing.

Geli L, Bard PY, Jullien B (1988) The effect of topography on earthquake ground motion: a review and new results. Bulletin of the Seismological Society of America, 78(1):42-63

Godoy E, Yanez G, Vera E (1999) Inversion of an Oligocene volcano-tectonic basin and uplifting of its superimposed Miocene magmatic arc in the Chilean Central Andes: First seismic and gravity evidences, Tectonophysics 306:217–236

Gorum T, Fan X, van Westen CJ, Huang RQ, Xu Q, Tang C, Wang G (2011) Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan Earthquake. Geomorphology. doi:10.1016/j.geomorph.2010.12.030.

Greve F (1960). Extracto de la historia de la sismología en Chile. In Anales de la Facultad de Ciencias Físicas y Matemáticas, 17, 17.

Havenith HB, Mreyen, AS, Torgoev A, Micu M (2017) Numerical models of unstable slopes in seismic areas—based on 3D geomodels. In Workshop on World Landslide Forum (pp. 47-57). Springer, Cham.

Hauser A (2002) Rock avalanche and resulting debris flow in Estero Parraguirre and Río Colorado, Región Metropolitana, Chile. In: Evans SG, Degraff JV (eds) Catastrophic landslides: Effects, occurrence, and mechanisms. Reviews in Engineering Geology, 15:135-148

Hearn G, Wise D, Hart A, Morgan C, O'Donnell N (2012) Assessing the potential for future first-time slope failures to impact the oil and gas pipeline corridor through the Makarov Mountains, Sakhalin Island, Russia. Quarterly Journal of Engineering Geology and Hydrogeology, 45:79-88

Hearn GJ, Hart AB (2011) Geomorphological contributions to landslide risk assessment: theory and practice. In: Smith M.J., Paron P., Griffiths J. (eds) Geomorphological Mapping: Methods and Applications. Elsevier, Amsterdam, Developments in Earth Surface Processes, 15:107–148

Hearn GJ (2018) Slope hazards on the Ethiopian road network Quarterly Journal of Engineering Geology and Hydrogeology, 21 August 2018, https://0-doi-org.wam.leeds.ac.uk/10.1144/qjegh2018-058

Huang, R Q, Li WL (2009) Analysis on the number and density of landslides triggered by the 2008 wenchuan earthquanke, China. J Geol Hazards Environ Preserv, 3(20):1-7

Jackson, R. (2016). Geomodels in Engineering Geology—An Introduction. Environmental & Engineering Geoscience 22(2):171-172

Jibson RW, Harp EL, Schulz W, Keefer DF (2006) Large rock avalanches triggered by the M 7.9 Denali Fault, Alaska, earthquake of 3 November 2002. Engineering Geology 83:144-160

Jibson RW (2011) Methods for assessing the stability of slopes during earthquakes—A retrospective, Engineering Geology 122(1-2):43-50

Jibson RW, Harp EL, Michael JA (2000). A method for producing digital probabilistic seismic landslide hazard maps. Engineering Geology, 58(3-4):271-289

Jordan TE, Isacks B, Allmendinger R, Brewer J, Ramos V, Ando C (1983) Andean tectonics related to geometry of the subducted Nazca plate. Geol. Soc. Am. Bull 94:341-361

Kamp U, Owen LA, Benjamin J, Growley BJ, Khattak G A (2010) Back analysis of landslide susceptibility zonation mapping for the 2005 Kashmir earthquake: An assessment of the reliability of susceptibility zoning maps. Natural Hazards 54:1–25

Keefer DK (2002) Investigating Landslides Caused By Earthquakes – a Historical Review. Surveys in geophysics (1):473–510

Keefer DK (2000) Statistical analysis of an earthquake-induced landslide distribution—the 1989 Loma Prieta, California event. Engineering geology 58(3):231-249

Keefer, DK (1984) Landslides caused by earthquakes. Geological Society of America Bulletin 95:406-421

Khazai B, Sitar N (2004) Evaluation of factors controlling earthquake-induced landslides caused by Chi-Chi earthquake and comparison with the Northridge and Loma Prieta events. Engineering geology 71(1): 79-95

Lara LE, Reyes J, Diaz-Naveas J (2018) 40Ar/39Ar constraints on the age progression along the Juan Fernández Ridge, SE Pacific. Frontiers in Earth Science, 6:194

Lee CT, Huang CC, Lee JF, Pan KL, Lin ML, Dong JJ (2008). Statistical approach to earthquake-induced landslide susceptibility. Engineering Geology, 100(1-2):43-58

Lee EM, Jones DK (2004) Landslide risk assessment (p. 454). London: Thomas Telford.

Lomnitz C (2004) Major earthquakes of Chile: a historical survey, 1535-1960. Seismological Research Letters, 75(3):368-378

Lomnitz, C (1960) A study of the Maipo Valley earthquakes of September 4, 1958, Proc. of the 2nd World Conf. Earthquake Engineering, Vol. 1, Tokyo-Kyoto, Japan, 501–520

Mahmood I, Qureshi SN, Tariq S, Atique L, Iqbal M (2015) Analysis of landslides triggered by October 2005, Kashmir earthquake. PLoS currents, 7.

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004a) Landslide inventories and their statistical properties. Earth Surface Processes and Landforms 29(6):687-711

Marc O, Hovius N, Meunier P, Gorum T, Uchida T (2016) A seismologically consistent expression for the total area and volume of earthquake-triggered landsliding. J. Geophys. Res. Earth Surf., 121(4):640-663,

Meunier P, Hovius N, Haines AJ (2007) Regional patterns of earthquake-triggered landslides and their relation to ground motion. Geophysical Research Letters, 34, L20408, doi: 10.1029 /2007GL031337

Meunier P, Hovius N, Haines JA (2008) Topographic site effects and the location of earthquake induced landslides. Earth and Planetary Science Letters (275):221-232

Meunier P, Uchida T, Hovius N (2013) Landslide patterns reveal the sources of large earthquakes. Earth and Planetary Science Letters, 363:27-33

Miles SB, Keefer DK (2000). Evaluation of seismic slope-performance models using a regional case study. Environmental & Engineering Geoscience, 6(1):25-39

Miles SB, Keefer DK (2007) Comprehensive areal model of earthquake-induced landslides: technical specification and user guide. US Geological Survey, Open-File Rep., 2007–1072, 69

Miles SB, Keefer DK (2009) Evaluation of CAMEL—comprehensive areal model of earthquake-induced landslides. Engineering Geology, 104(1-2):1-15

Moernaut J, Van Daele M, Heirman K, Fontijn K, Strasser M, Pino M, Urrutia R, De Batist M (2014) Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south–central Chile, Journal of Geophysical Research: Solid Earth, 119(3):1607-1633

Montessus de Ballore F (1912) Historia sísmica de los Andes Meridionales al sur del paralelo XVI. Santiago de Chile: Imprenta Cervantes.

Moreiras, S. M., Sepúlveda, S. A., & González, P. (2012, October). Nuevos estudios en los grandes movimientos en masa en la alta cordillera de la cuenca del río Maipo, Chile Central. In Congreso Geológico Chileno (No. 11).

Moreiras, S. M., & Sepúlveda, S. A. (2015). Megalandslides in the Andes of central Chile and Argentina (32°–34° S) and potential hazards. Geological Society, London, Special Publications, 399(1), 329-344.

Oppikofer T, Hermanns R, Redfield TF, Sepúlveda SA, 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

Naranjo JA, Arenas M, Clavero J, Muñoz O, (2009) Mass movement-induced tsunamis:main effects during the Patagonian Fjordland seismic crisis in Aisén (45°25′S). Chile.Andean Geology 36(1):137–146

Newmark NM (1965) Effects of earthquakes on dams and embankments." Geotechnique 15(2):139-160

Pankhurst R, Hervé F (2007) Introduction and overview. The Geological Society of London, pp 1-4.

Parker RN, Hancox GT, Petley DN, Massey CI, Densmore AL, Rosser NJ (2015) Spatial distributions of earthquake-induced landslides and hillslope preconditioning in northwest South Island, New Zealand. Earth surface dynamics., 3(4):501-525

Parry (2016) Geomodels in Engineering Geology – An Introduction, P. Fookes, G. Pettifer, T. Waltham, Whittle Publishing (2015), ISBN 978-1-84995-139-5.

Petley (2009) Landslides and multi-hazards. In Landslides–Disaster Risk Reduction (pp. 435-450). Springer, Berlin, Heidelberg

Plafker G, Ericksen GE (1978) Nevados Huascaran avalanches, Peru. In Developments in Geotechnical Engineering 14:277-314 Elsevier

Qi S, Xu Q, Lan H, Zhang B, Liu J (2010) Spatial distribution analysis of landslides triggered by 2008.5.12 Wenchuan Earthquake, China Engineering Geology 116 (1–2):95-108

Rodriguez CE, Bommer JJ, Chandler RJ (1999) Earthquake induced landslide 1980-1997.Soil Dyn Earthquake Eng 18: 225-346

Santibáñez I, Cembrano J, García-Pérez T, Costa C, Yáñez G, Marquardt C, Arancibia G, González, G (2018) Crustal faults in the Chilean Andes: geological constraints and seismic potential. Andean Geology, 46(1):32-65

Sato H, Hasegawa H, Fujiwara S, Tobita M, Koarai M, Une H, Iwahashi J (2007) Interpretation of landslide distribution triggered by the 2005 Northern Pakistan earthquake using SPOT 5 imagery. Landlsides 4:113-122

Schuster RL, Salcedo DA, Valenzuela L, (2002) Overview of catastrophic landslides of South America in the twentieth century In Catastrophic landslides: Effects, occurrence, and mechanisms. Reviews in Engineering Geology 15, Geological Society of America, 1-34

Schuster RL (1986) Landslide dams: processes, risk, and mitigation. ASCE.

Sepúlveda SA, Murphy W, Petley DN (2005) Topographic controls on coseismic rock slides during the 1999 Chi-Chi Earthquake, Taiwan. Quarterly Journal of Engineering Geology and Hydrogeology 38:189-196

Sepúlveda SA, Serey A, Lara M, Pavez A, Rebolledo S (2010) Landslides induced by the 2007 Aysen Fjord earthquake, Chilean Patagonia. Landslides 7(4):483-492

Sepulveda SA, Chacón D, Moreiras S, Poblete F (2019) Large rock avalanches and river damming hazards in the Andes of central Chile: the case of Pangal valley, Alto Cachapoal, Geophysical Research Abstracts Vol. 21, EGU2019-6079

Sepúlveda SA, 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

Serey A (2020) Coseismic landslides during strong shallow crustal and large interplate earthquakes: Controlling factors and conceptual hazard geomodels. Available in http://repositorio.uchile.cl/handle/2250/102608

Serey A, Escobar P, Moya S, Sepúlveda SA, Petley D (2017) Landslide inventory of the 2010 Mw 8.8 Maule earthquake, Central Chile. 16th World Conference on Earthquake 16WCEE 2017: 1873

Serey A, Piñero-Feliciangeli L, Sepúlveda SA, Poblete F, Petley DN, Murphy W (2019) Landslides induced by the 2010 Chile megathrust earthquake: a comprehensive inventory and correlations with geological and seismic factors. Landslides, 16(6), 1153-1165

Somerville PG, Smith NF, Graves RW, Abrahamson N A (1997) Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity. Seismological Research Letters 68:199-222

Somerville PG, Graves RW (2003) Characterization of earthquake strong ground motion. In Landslide Tsunamis: Recent Findings and Research Directions, Birkhäuser Basel, 1811-1828

Tichelaar BW, Ruff LJ (1991) Seismic coupling along the Chilean subduction zone, J. Geophys. Res. 98:2017–2038.

Vargas G, Rebolledo S, Sepúlveda SA, Lahsen A, Thiele R, Townley B, Padilla C, Rauld R, Herrera M, Lara M (2013) Submarine earthquake rupture, active faulting and volcanism along the major Liquiñe-Ofqui Fault Zone and implications for seismic hazard assessment in the Patagonian Andes. Andean Geology 40(1):141-171.

Wang, G. (2015). Comparison of the landslides triggered by the 2013 Lushan earthquake with those triggered by the strong 2008 Wenchuan earthquake in areas with high seismic intensities. Bulletin of Engineering Geology and the Environment, 74(1):77-89

Wang G, Du C, Huang D, Jin F, Koo RC, Kwan JS (2018) Parametric models for 3Dtopographic amplification of ground motions considering subsurface soils.Soil Dynamics and Earthquake Engineering,115:41-54

Wang Y, Luo Y, Wang F, Wang D, Ma X, Li S, Deng X (2012) Slope seismic response monitoring on the aftershocks of the Wenchuan earthquake in the Mianzhu section. Journal of Mountain Science, 9(4):523-528

Wartman J, Dunham L, Tiwari B, Pradel D (2013) Landslides in Eastern Honshu induced by the 2011 off the Pacific Coast of Tohoku earthquake. Bulletin of the Seismological Society of America 103 (2B):1503–1521

Wright C, Mella A (1963) Modifications to the soil pattern of South-Central Chile resulting from seismic and associated phenomenona during the period May to August 1960. Bulletin of the Seismological Society of America, 53(6):1367-1402

Zhao B, Li W, Wang Y, Lu J, Li X (2019) Landslides triggered by the Ms 6.9 Nyingchi earthquake, China (18 November 2017): analysis of the spatial distribution and occurrence factors. Landslides, 16(4):765-776

Figure captions

Figure 1. Morphostructural and seismotectonic setting of Central Chilean Andes. Major crustal fault in the Chilean Andes extracted from Armijo et al. (2010) and Santibáñez et al. (2018).

Figure 2. Examples of landslides triggered by earthquakes in Chile. A: Overview of debris avalanches (2007 Aysén earthquake); B: Rock slides triggered by the 2007 Earthquake in Aysén Fjord (all in granitic rock masses of the Patagonian Batholith; cliff height c.1000 m);C and E: Debris slides (2010 Maule earthquake); D: Rock falls (2007 Aysén earthquake; cliff height c.400 m) F: Rock block slides (2007 Aysén earthquake; cliff height c.400 m).

Figure 3. Glacial cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

Figure 4. Glacial cordilleran environment. Conceptual geomodel of coseismic landslides induced by megathrust earthquake.

Figure 5. Fluvial cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

Figure 6. Fluvial cordilleran environment. Conceptual geomodel of coseismic landslides induced by megathrust earthquake

Figure 7. Plutonic cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

Figure 8. Plutonic cordilleran environment. Conceptual geomodel of coseismic landslides induced by megathrust earthquake.

Figure 9. Mountain front bordering urban area environment. Conceptual geomodel of coseismic landslide induced by shallow crustal earthquake. The urban area is represented in gray gridded.

Figure 10. Mountain front bordering urban area environment. Conceptual geomodel of coseismic landslides induced by megathrust earthquake. The urban area is represented in gray gridded.

Table 1. *Summary of most common correlations of coseismic landslides in the Chilean Andes contrasting the megathrust earthquakes with shallow crustal earthquakes (This study, Serey, et al. 2019; Sepúlveda et al. 2010)*

Conditioning Factors/ Characteristic of coseismic landslides	**Coseismic landslides triggering by**	
	megathrust earthquake	**Shallow crustal earthquake (M>4)**
Relief	Relief exerts a strongly dominant control on landsliding both in terms of preconditioning (higher, steeper slopes) and local topographic amplification of shaking.	
Bedrock lithology	Relevant conditioning factor, with more landslides in younger (normally weaker) volcanic and volcano-sedimentary rocks.	There is no obvious correlation between landslide concentration and rock age (young or old lithology), even on very resistant rocks such as granitoids.
Proximity of the fault	There is a poor correlation between landsliding and fault rupture distance (subduction zone).	The rupture plane of fault is a first-order factor in the distribution of landslides. Hanging wall and directivity effects.
Seismological parameters	Poor correlation between estimated PGA and landslide occurrence. Better correlation between landslide concentration and the ratio between horizontal and vertical peak accelerations.	Ground motion parameters would be the most significant factors, including horizontal and vertical accelerations, ground velocity, frequency content and epicentral distance.
Topographic Amplification	Moderate or local influence. Landslides generally not clustered close to the ridge tops.	Strong influence. The crowns of the landslides are generally in the uppermost part of the slopes.
Spatial distribution	Landslides are not evenly distributed in the affected area, tending to the formation of clusters of landslides.	
	-	Landslides tend to be limited to the epicentral area.
Type of coseismic landslide	Disrupted slides. Most of them, rock falls and debris slides.	Disrupted slides. Most of them, debris avalanches, rock falls, debris slides and rock slides/avalanches.
N° landslides	The total number of landslides triggered for the megathrust earthquakes is substantially lower, typically by one to two orders of magnitude, than it would be expected for shallow crustal earthquakes of a similar or even lower magnitude.	

Table 2. *Terrain characteristics and coseismic landslide hazards for the Glacial Cordilleran environment.*

Terrain facet	**Terrain element**	**Site characteristics**	**Main coseismic landslide type (after Hungr et al. 2014)**		**Secondary hazards**	**Engineering intervention / risk reduction strategies**
			Shallow crustal earthquake	**megathrust earthquake**		
Glacial andesitic slopes	Ridges	Ridges characterised by thin soil deposits with bedrock at or close to the surface; rock mass may be frost shattered and highly fractured, or hydrothermally altered. Likely to be a poor to fair quality rock mass at shallow depths but good to very good deeper. This is likely to mitigate against deep seated landslides.	Rock falls; debris falls; rock block topples; debris topples;	Rock falls; debris falls; rock topples; debris topples;	Creation of sediment supply for debris flow activation.	None, at best reactive. In ridges close to infrastructure it may be necessary to remove loose material on a periodic basis.
	Interfluve slopes	Slopes formed with engineering soils of variable thickness along the slope profile. Dominantly glacial materials, although may have been reworked. Glacial deposits may be mantled by colluvium/talus. Rock mass could present surface-parallel fracture systems in rock (sheet joints), oversteepened slopes and U-shaped valley.	Rock slides, debris slides; debris avalanches. Ancient rock slides can be reactivated.	Debris slides; debris avalanches.	Rock slides may create landslide dams in tributary valleys.	Local stakeholders should carry out inspections after an earthquake. It may prove impossible to access blockages and these will need a monitoring plan.
	Stream channels	Dominated by intercalations of coarse fluvial materials, glacial debris and slope wash deposits. In high slopes (>2000 m) these may contain rock glaciers.	Possible debris flows due to debris avalanche failures into stream channels.	---	Debris flow initiation in tributary valleys creating landslide dams in main valleys.	Monitoring. Infrastructure owners/ stakeholders should consider inspections after strong earthquakes to monitor sediment build-up.
	Cross element	Mixture of the terrain elements (see relevant site characteristics above).	Large rockslides with an origin on upper reaches of glaciated cordillera which spans multiple terrain units.	---	Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding.	Reactive – stakeholders should develop a mitigation plan that includes large landslides resulting in loss of access and long-term planning.
Cordillera river systems	Rock River channel	The river channel slopes are formed in bedrock which has been excavated by valley glaciers; rock mass may be locally frost shattered and hydrothermally altered.	Debris slides, rock falls.	Rock falls.	High turbidity in the river. Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding. Potential breeching of landslide dams creating downstream flooding and problems of suspended sediment in water supply and damage to hydroelectric infrastructure.	Downstream towns and villages should provide evacuation routes and indicate refuge zones in the event of a valley blocking landslide. HEP owners may need to monitor sediment flux post earthquake to reduce risk of damage to turbines.
	Glacial debris river channel	River channel slopes are formed in ice-contact debris and alluvial deposits which are locally over-steepened. These may be mantled by alluvial fans. Glacial soils may be reworked and stratified.	Debris slides, debris falls. There is potential for local liquefaction in alluvial soils.	Debris falls.		

Table 3. *Terrain characteristics and coseismic landslide hazards for the Fluvial Cordilleran environment*

Terrain facet	**Terrain element**	**Site characteristics**	**Main coseismic landslide type (after Hungr et al., 2014)**		**Secondary hazards**	**Engineering intervention / risk reduction strategies**
			Shallow crustal earthquake	**Megathrust earthquake**		
Fluvial andesitic slopes	Ridges	Ridges characterised by thin residual soil deposits with bedrock at or close to the surface; rock mass may be highly fractured by thermal oscillation, may be hydrothermally altered. Likely to be a fair to poor quality rock mass.	Rock falls; rock block slides; debris falls; topples.	Rock falls.	Creation of sediment supply for debris flow activation.	Consider installation of ring netting to control sediment supply to rivers. An inspection and maintenance plan will be required to avoid these becoming a hazard in their own right.
	Interfluve slopes	Rock mass composed of volcanosedimentary bedrock often fair to good quality, may be highly fractured in the vicinity of lineaments or faults. Steep slopes and V shaped valley. They may have the scar of ancient events of mass removals. Slopes formed with engineering soils of variable thickness along the long profile. Dominantly alluvial materials and colluvium.	Rock slides; rock avalanches; debris slides; debris avalanches; Rock falls. Ancient rock slides can be reactivated.	Debris slides; debris avalanches.	Rock slides may create landslide dams in tributary or principal valleys.	Local stakeholders should carry out inspections after an earthquake. It may prove impossible to access blockages and these will need a monitoring and long-term planning is needed .
	Stream channels	Dominated by intercalations of coarse fluvial materials, alluvial deposits and colluvium.	Possible debris flows due to debris avalanche, rock falls or rock slides failures into stream channels.	---	High turbidity events in the channels.	Monitoring. Infrastructure owners/ stakeholders should consider inspections after strong earthquakes to monitor sediment build-up.
	Cross element	Mixture of the terrain elements (see relevant site characteristics above).	Large rockslides or rock avalanches with an origin on upper reaches of Cordillera which spans multiple terrain units.	---	Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding.	Inspections required after shaking. Local action plan for community evacuation should be considered. In the event of large landslide dams local communities may need to refer the matter to Central Government via Ministry of Public Works. Urgent action needed and long-term
Cordillera river systems	Rock River channel	The river channel slopes are formed in bedrock which has been excavated by river or ancient glaciers, may be hydrothermally altered.	Debris slides, rock falls.	Rock falls; debris slides.	Extreme high turbidity events in the river. Large slide mass creates temporary dam. Breaching is a major hazard	

	Fluvio-alluvial debris river channel	River channel slopes are formed in debris and alluvial deposits which can be locally over-steepened. These may be mantled by colluvium materials.	Debris slides. There is potential for local liquefaction in granular materials likes sandy or silty soils.	Debris slides.	leading to downstream flooding.	planning.

Table 4. *Terrain characteristics and coseismic landslide hazards for the Plutonic Cordilleran environment*

Terrain facet	Terrain element	Site characteristics	Main coseismic landslide type (after Hungr et al., 2014).		Secondary hazards	Engineering interventions/ risk reduction strategies
			Shallow crustal earthquake	**Megathrust earthquake**		
Plutonic slopes	Ridges	Ridges characterised by thin residual soil deposits with bedrock at or close to the surface; rock mass may be highly fractured by thermal oscillation, may be hydrothermally altered. Variable rock mass geotechnical quality.	Rock falls; rock block slides.	Rock falls.	Creation of sediment supply for debris flow activation.	None. Reactive at best. Inspection of sediment build-up after earthquakes with higher priority after a local shallow crustal event and long-term planning is needed.
	Interfluve slopes	Rock mass compound of plutonic bedrock often good to very good geotechnical quality, steep slopes and cliffs. It may be highly fractured, present stress-relief fractures parallel to a cliff face, or hydrothermally altered, in the vicinity of lineaments or faults. Slopes formed with engineering soils of variable thickness along the long profile. Dominantly fluvio-alluvial materials and colluvium deposits.	Rock slides; rock avalanches; debris slides; debris avalanches; Rock falls.	Debris slides; debris avalanches.	Rock slides may create landslide dams in tributary or principal valleys.	Local stakeholders should carry out inspections after an earthquake. It may prove impossible to access blockages and these will need a monitoring plan.
	Stream channels	Glacial valley: Dominated by intercalations of coarse fluvial materials, glacial debris and slope wash deposits. Fluvial valley: Dominated by intercalations of coarse fluvial materials, alluvial deposits and colluvium.	Possible debris flows due to debris avalanche, rock falls or rock slides failures into stream channels.	---	High turbidity events in the channels. Debris flow initiation in tributary valleys creating landslide dams in main valleys.	Inspections required after shaking. Local action plan for community evacuation should be considered. In the event of large landslide dams local communities may need to refer the matter to Central Government via Ministry of Public Works. Urgent action needed and long-term planning.
	Cross element	Mixture of the terrain elements (see relevant site characteristics above).	Large rockslides or rock avalanches with an origin on upper reaches of cordillera which spans multiple terrain units.	---	Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding.	
Cordillera river systems	Rock River channel	The river channel slopes are formed in bedrock which has been excavated by river or valley glaciers.	Debris slides, rock falls.	Rock falls; Debris slides.	Extreme high turbidity events in the river. Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding. Potential breeching of landslide dams creating downstream flooding.	
	Debris river channel	River channel slopes are formed in debris and alluvial deposits which can be locally over-steepened. These may be mantled by colluvium materials.	Debris slides. There is potential for local liquefaction in granular materials likes sandy or silty soils.	Debris slides.		

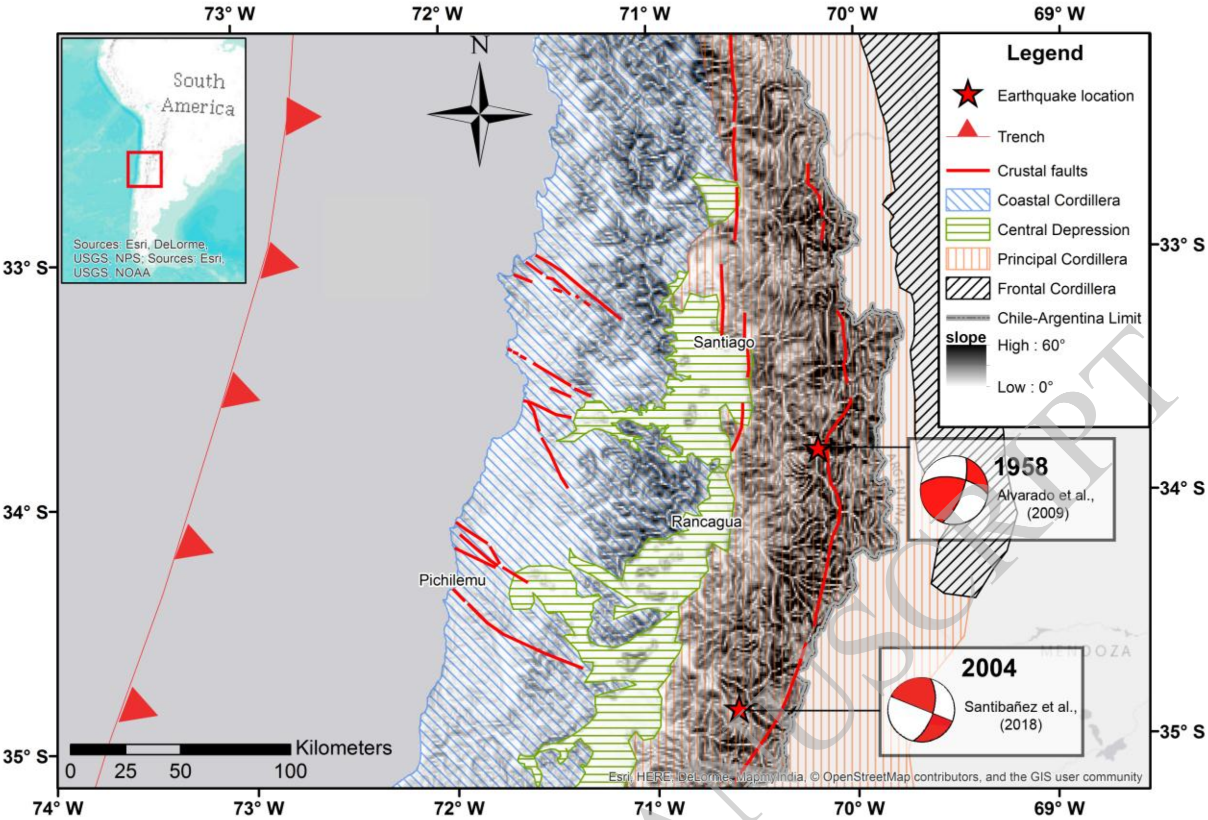
Table 5. *Terrain characteristics and coseismic landslide hazards for the Mountain Front environment*.

Terrain facet	**Terrain element**	**Site characteristics**		**Main coseismic landslide type (after Hungr et al., 2014)**		**Secondary hazards**	**Engineering interventions / risk reduction strategies**
				Shallow crustal earthquake	**Megathrust earthquake**		
Fluvial andesitic slopes	Ridges	Ridges characterised by thin residual soil deposits with bedrock at or close to the surface; rock mass may be highly fractured by thermal oscillation. Likely to locally be a poor to fair quality rock mass.		Rock falls; rock block slides; debris falls; toppling.	Rock falls.	Creation of sediment supply for debris flow activation.	Reactive. Monitoring needed after earthquake. This should be a higher priority after local shallow crustal earthquakes and long-term planning is needed.
	Interfluve slopes	Rock mass composed by volcanosedimentary bedrock, often fair to good, steep slopes. They may have the scar of ancient events of mass removals. Slopes formed with engineering soils of variable thickness along the long profile. Dominantly fluvio-alluvial materials and colluvium.		Rock slides; rock avalanches; debris slides; debris avalanches; Rock falls.	Debris slides; debris avalanches.	Rock slides may create landslide dams.	Monitoring. Slopes adjacent to important infrastructure / property may require intervention for public safety. Drapped netting systems should be considered as a means of mitigating small scale failures.
	Channels	Stream	Dominated by intercalations of coarse fluvial materials, alluvial deposits and colluvium.	Debris flows due to debris avalanche, rock falls or rock slides failures into stream channels.	---	High turbidity events in the channels.	Close to large urban areas check dams or netting should be considered. These should be inspected after shaking to ensure capacity is not being exceeded.
		Ravine	Narrow, steep-sided valley. Dominated by intercalations of coarse alluvial deposits and colluvium.	Debris flows due to debris avalanche, rock falls or rock slides failures into stream channels. Debris avalanches due to rock falls, debris slides or rock slides failures into channels. Rock avalanches or large rockslides with origin on upper reaches of ravine channels.	---		Inspections required after shaking. Local action plan for community evacuation should be considered. In the event of large landslide dams local communities may need to refer the matter to Central Government via Ministry of Public Works. Urgent action needed and long-term planning.
	Cross element	Mixture of the terrain elements (see relevant site characteristics above).		Large rockslides or rock avalanches with an origin on upper reaches of cordillera which spans multiple terrain units.	---	Large slide mass creates temporary dam. Breaching is a major hazard leading to downstream flooding.	

Table 6. *Potential risks and suggested mitigation measures for coseismic landslides to be generated in the mountain environment of Chile.*

Coseismic landslides	Potential Consequences	Risk Level (*)	Mitigation
Rock avalanche	Valley blockage, destruction of lifeline infrastructure, impact on mountain community.	Low due to infrequency of these events. Risk is likely to be higher as a result of a shallow crustal earthquake.	Evacuation plan for valley blockage.
Rock slides	Damage to local lifelines and road blockages. Difficulty in access for emergency services in the event of a local event. Economic losses due to closure of mine roads. Risk to individual road users.	Moderate to High in the event of shallow crustal seismicity, lower in the event of megathrust earthquakes due to large epicentral distances.	For important routes engineering intervention may be needed. Netting systems, localized rock bolting and retaining structures considered for critical routes. For higher hazard zones long-term planning as a tool for risk reduction is needed.
Rock falls	Injury and loss of life to users. Potential lifeline damage to single and multiple block rock falls.	Moderate (subduction zone event) to high (shallow crustal) event.	Critical infrastructure for mineral transport, important access roads (e.g. access to hospitals etc) should be protected. For higher hazard zones "no stopping" zones should be considered and long-term planning is needed for considered other risk reduction options.
Debris avalanches	Valley blockage, destruction of lifeline infrastructure, impact on mountain community.	Low	Slope regrading could be considered in specific areas. More detailed hazard analysis considered.
Debris slides	Damage to local lifelines and road blockages. Difficulty in access for emergency services in the event of a local event. Economic losses due to closure of mine roads. Risk to individual road users.	Low for megathrust earthquakes but moderate for shallow crustal events.	Slope regrading could be considered in specific areas. More detailed hazard analysis considered and long-term planning.
Flows	Likely only to cause localized damage due to liquefaction related movement during shaking but debris flow activation could cause damage to infrastructure / HEP schemes during storm or snow melt after earthquake	Low during shaking but hazard becomes elevated during winter or spring.	Monitoring and inspection. Consider check system for critical infrastructure.
Lateral spreads	Localised sliding only as the presence of liquefiable materials is going to be limited.	Low.	Monitoring and reactive maintenance.

(*) Infrastructure vulnerability is assumed in generic actual location.



73° W
72° W
71° W
70° W
69° W
N
South America
Sources: Esri, DeLorme, USGS, NPS; Sources: Esri, USGS, NOAA
Legend
Earthquake location
Trench
Crustal faults
Coastal Cordillera
Central Depression
Principal Cordillera
Frontal Cordillera
Chile-Argentina Limit
slope
High : 60°
Low : 0°
33° S
34° S
35° S
Santiago
Rancagua
Pichilemu
1958
Alvarado et al., (2009)
2004
Santibañez et al., (2018)
MENDOZA
Kilometers
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50
100
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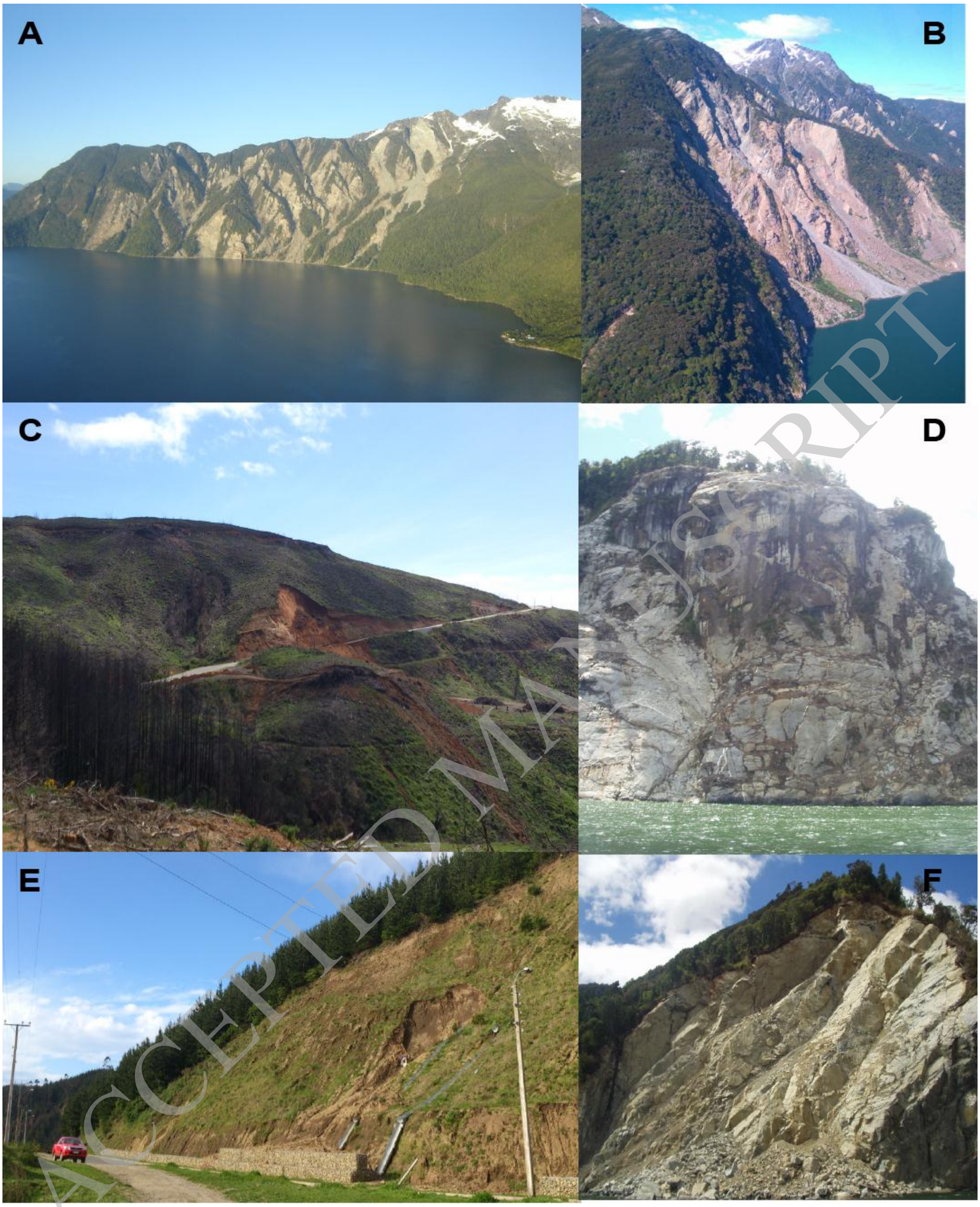
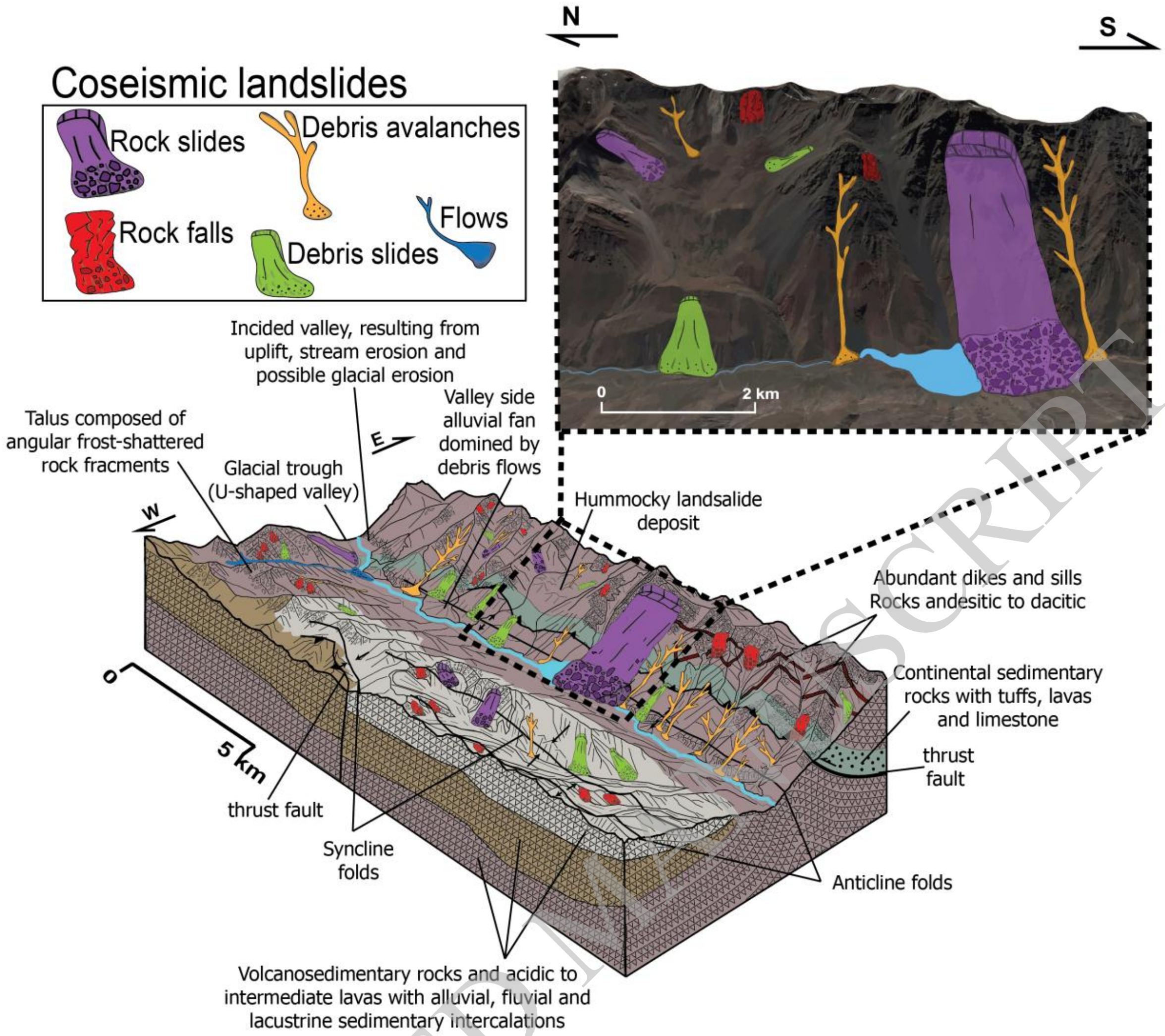
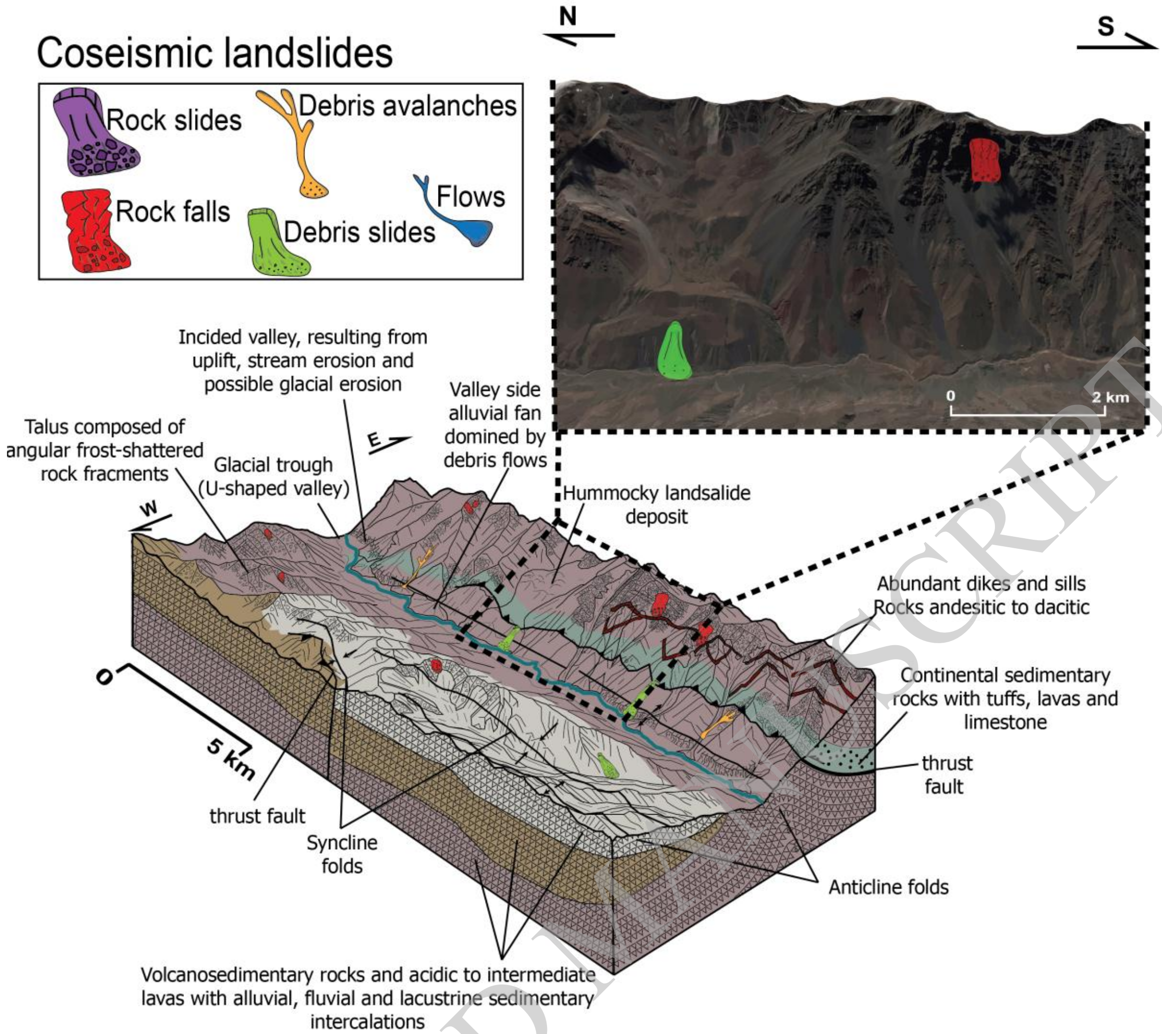
74° W

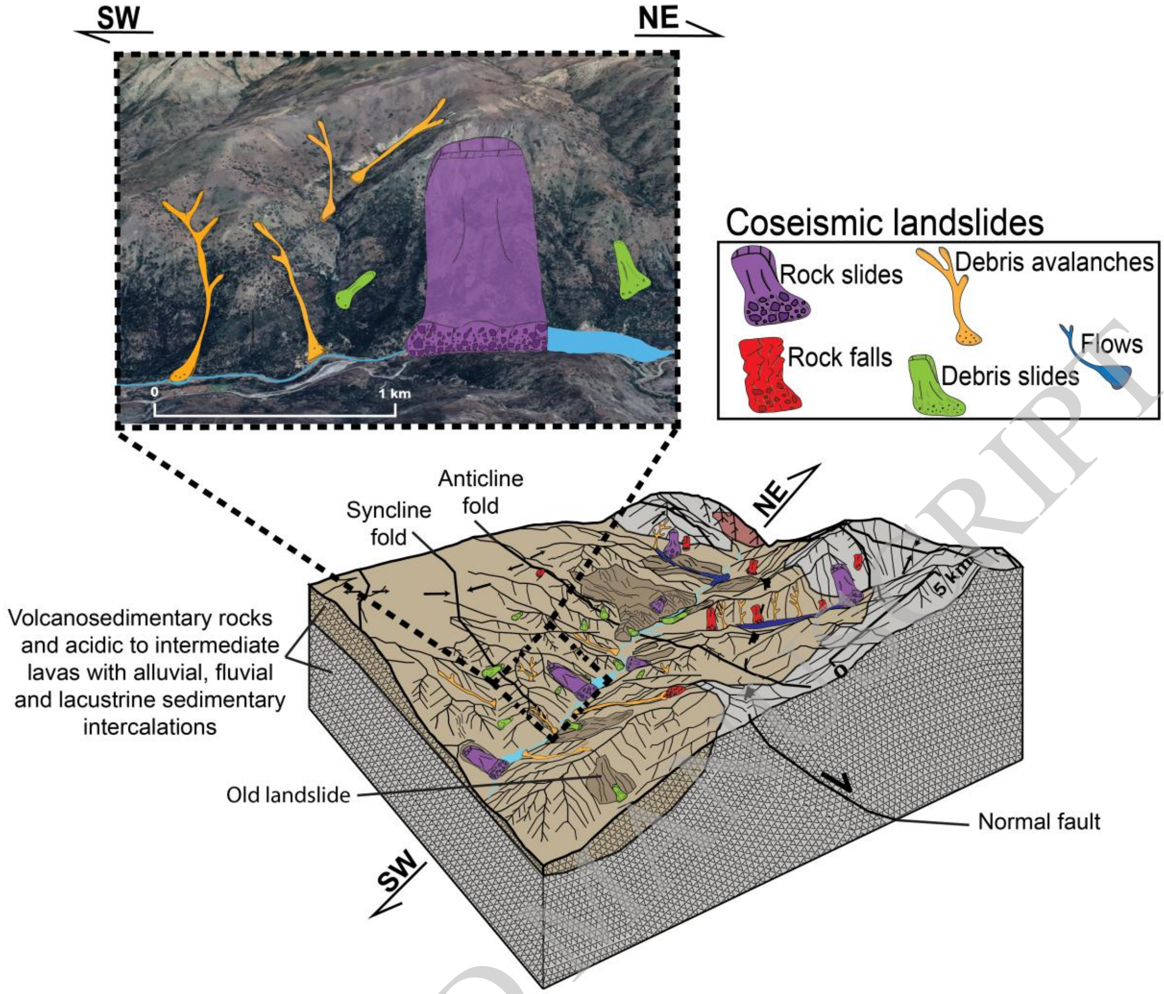

A
B
C
D
E
F

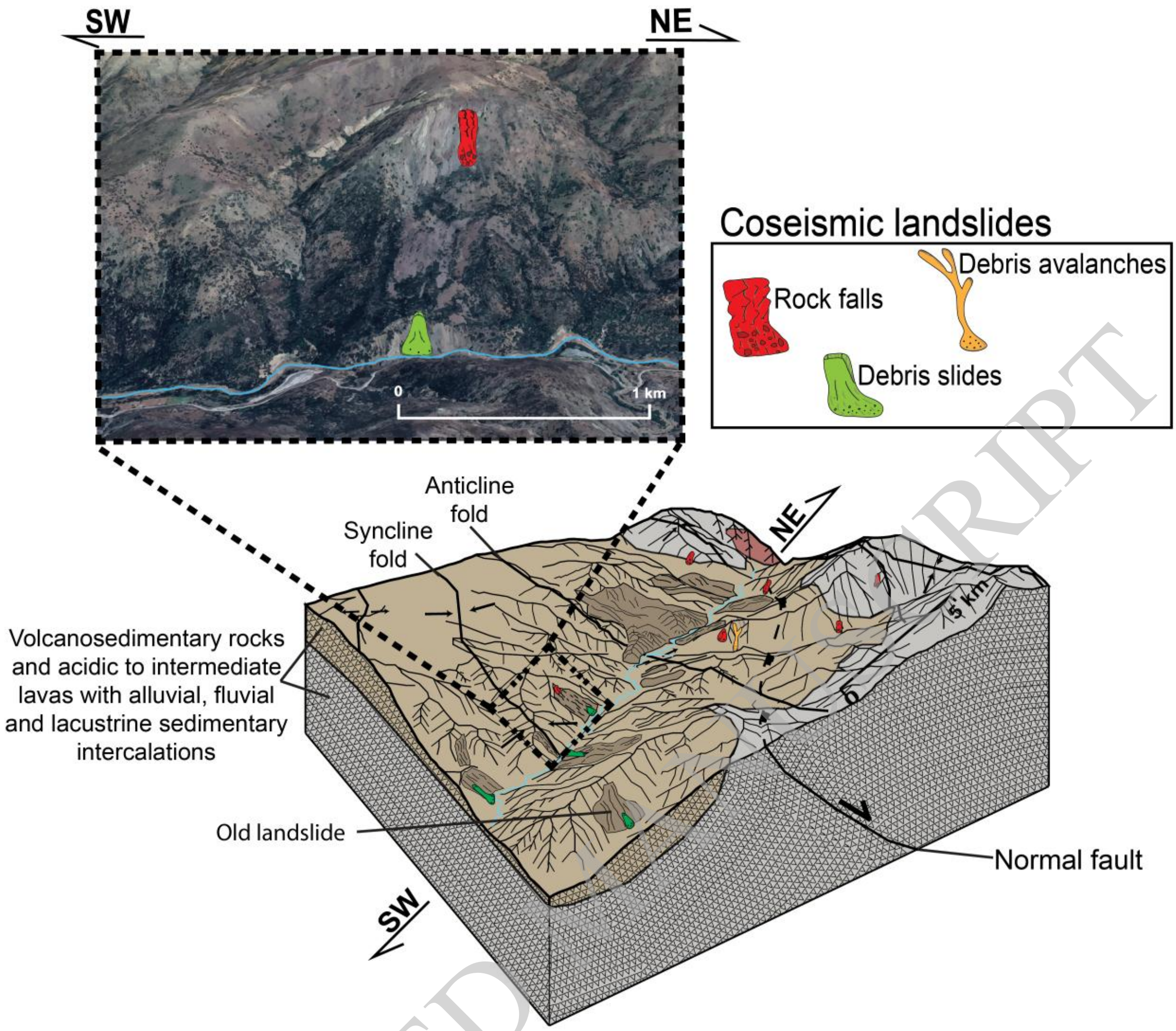


Coseismic landslides
Rock slides
Debris avalanches
Flows
Rock falls
Debris slides
N
S
0
2 km
Incided valley, resulting from uplift, stream erosion and possible glacial erosion
Talus composed of angular frost-shattered rock fracments
Glacial trough (U-shaped valley)
Valley side alluvial fan domined by debris flows
E
W
Hummocky landsalide deposit
Abundant dikes and sills Rocks andesitic to dacitic
Continental sedimentary rocks with tuffs, lavas and limestone
thrust fault
0
5 km
thrust fault
Syncline folds
Anticline folds
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations

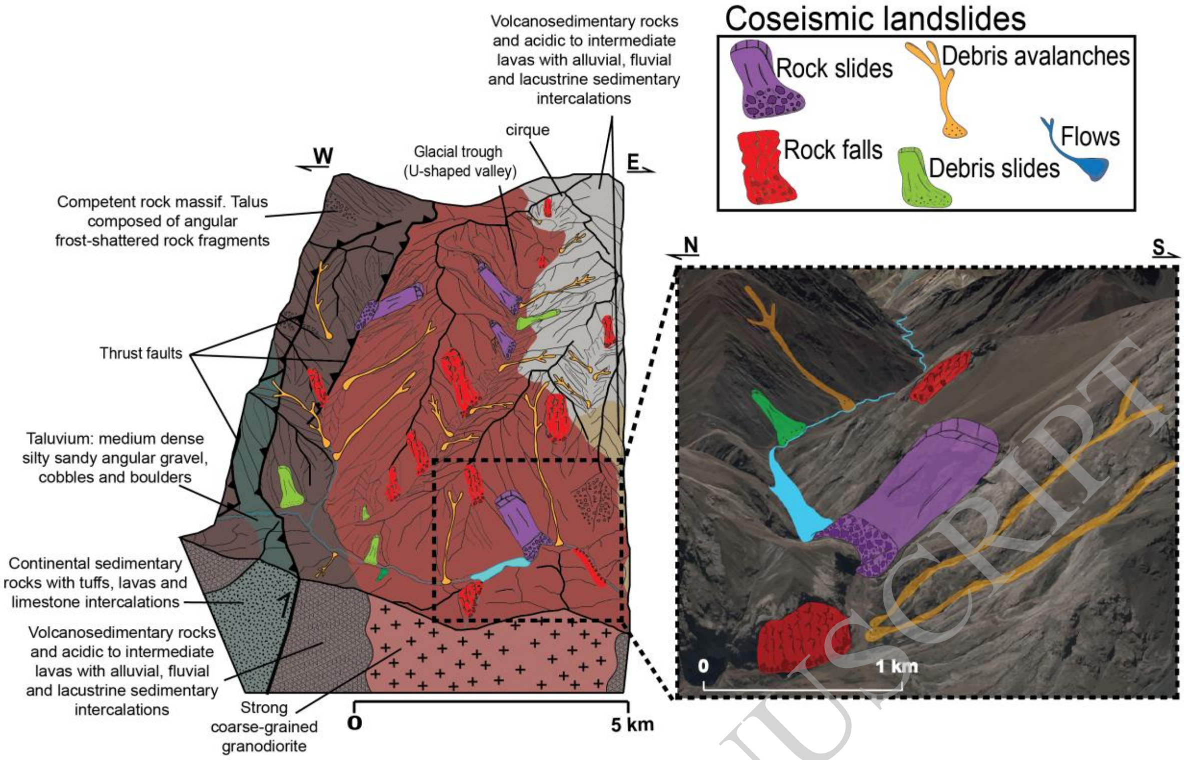


Coseismic landslides
Rock slides
Debris avalanches
Flows
Rock falls
Debris slides
N
S
0
2 km
Incided valley, resulting from uplift, stream erosion and possible glacial erosion
Valley side alluvial fan domined by debris flows
Talus composed of angular frost-shattered rock fracments
Glacial trough (U-shaped valley)
E
W
Hummocky landsalide deposit
Abundant dikes and sills
Rocks andesitic to dacitic
Continental sedimentary rocks with tuffs, lavas and limestone
thrust fault
0
5 km
thrust fault
Syncline folds
Anticline folds
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations

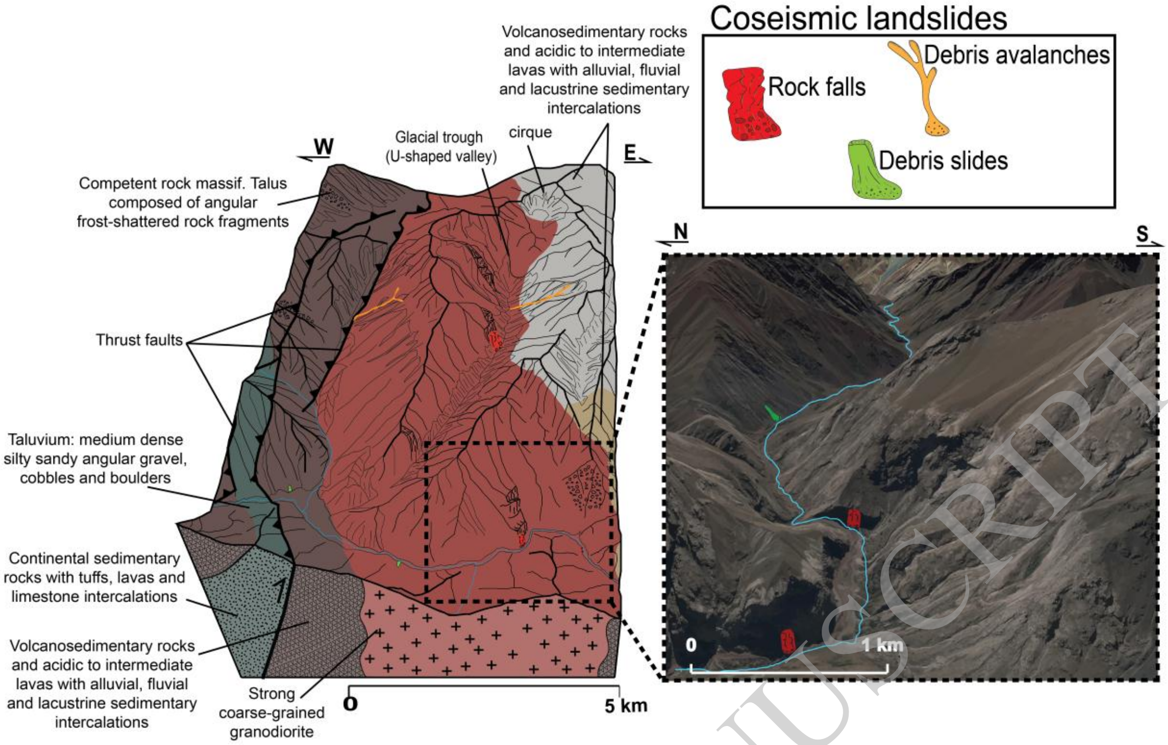

SW
NE
0
1 km
Coseismic landslides
Rock slides
Debris avalanches
Rock falls
Debris slides
Flows
Anticline fold
Syncline fold
NE
5 km
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Old landslide
Normal fault
SW



SW
NE
0
1 km
Coseismic landslides
Rock falls
Debris avalanches
Debris slides
Anticline fold
Syncline fold
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Old landslide
Normal fault
NE
SW
5 km



Coseismic landslides
Rock slides
Debris avalanches
Rock falls
Debris slides
Flows
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
cirque
Glacial trough (U-shaped valley)
W
E
N
S
Competent rock massif. Talus composed of angular frost-shattered rock fragments
Thrust faults
Taluvium: medium dense silty sandy angular gravel, cobbles and boulders
Continental sedimentary rocks with tuffs, lavas and limestone intercalations
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Strong coarse-grained granodiorite
0
5 km
0
1 km


Coseismic landslides
Rock falls
Debris avalanches
Debris slides
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Glacial trough (U-shaped valley)
cirque
W
E
N
S
Competent rock massif. Talus composed of angular frost-shattered rock fragments
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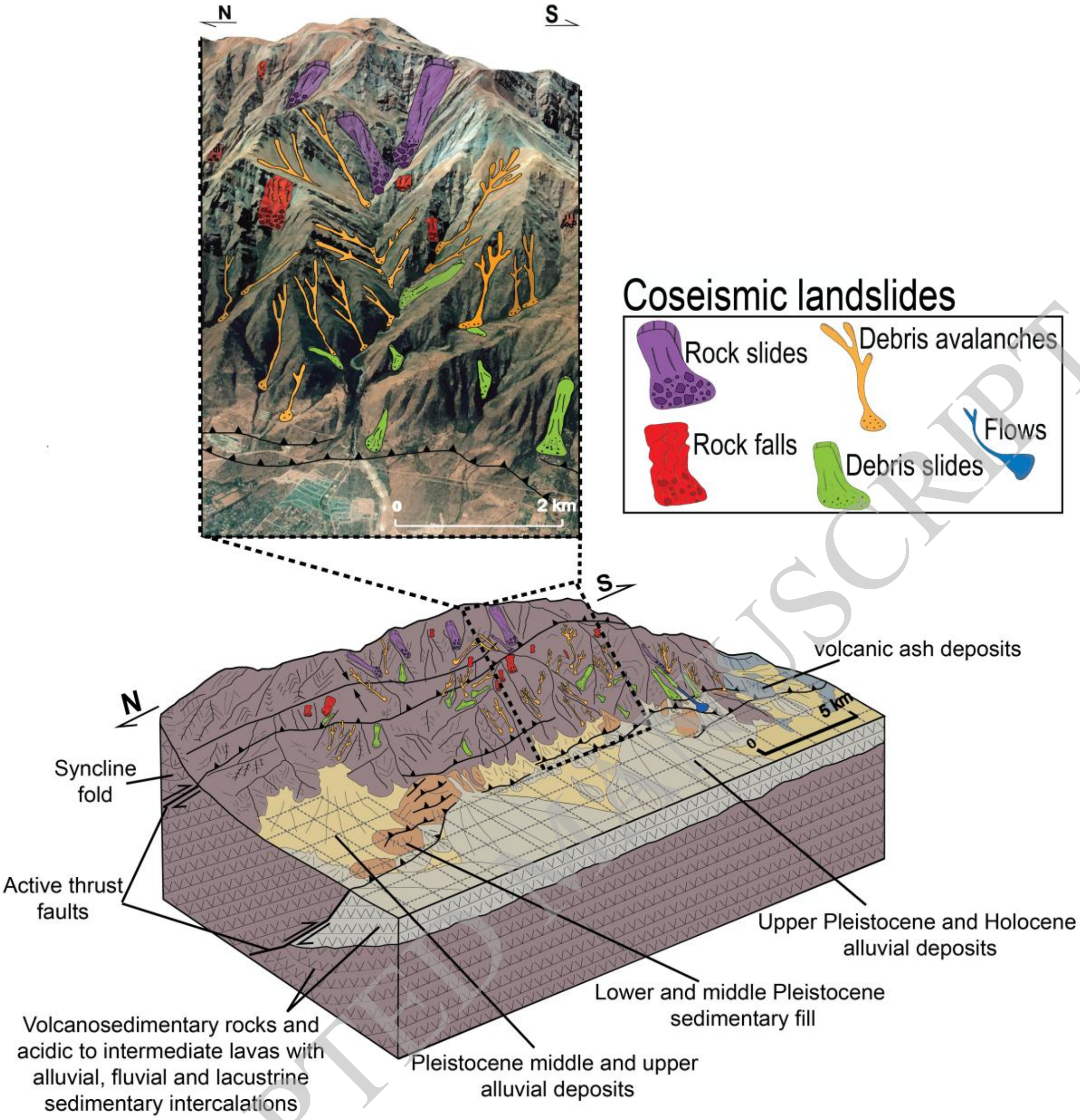
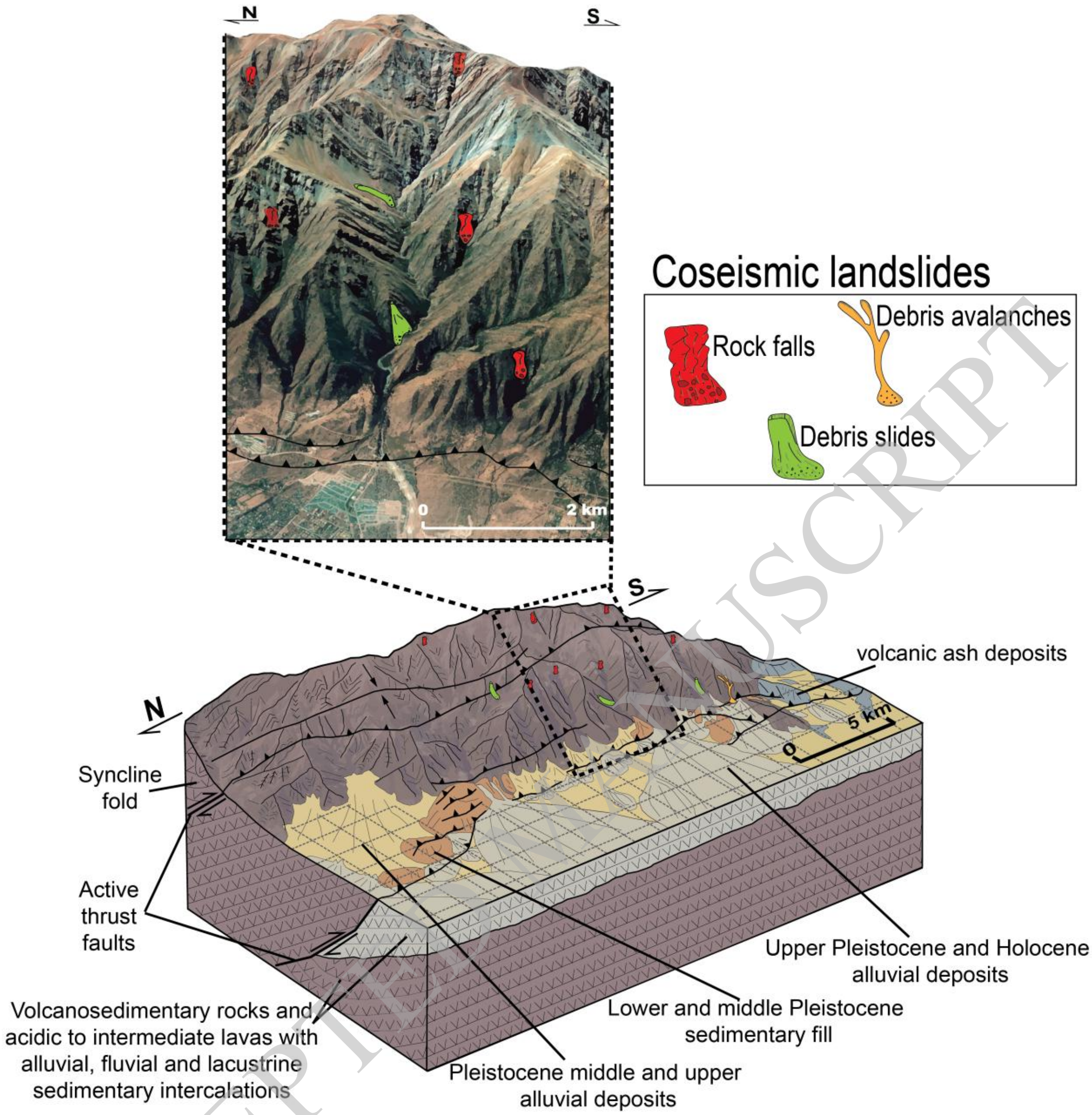
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Strong coarse-grained granodiorite
0
5 km
0
1 km


N
S
0
2 km
Coseismic landslides
Rock slides
Debris avalanches
Flows
Rock falls
Debris slides
S
N
volcanic ash deposits
5 km
0
Syncline
fold
Active thrust
faults
Upper Pleistocene and Holocene
alluvial deposits
Lower and middle Pleistocene
sedimentary fill
Volcanosedimentary rocks and
acidic to intermediate lavas with
alluvial, fluvial and lacustrine
sedimentary intercalations
Pleistocene middle and upper
alluvial deposits


N
S
0
2 km
Coseismic landslides
Rock falls
Debris avalanches
Debris slides
S
N
volcanic ash deposits
0
5 km
Syncline fold
Active thrust faults
Volcanosedimentary rocks and acidic to intermediate lavas with alluvial, fluvial and lacustrine sedimentary intercalations
Pleistocene middle and upper alluvial deposits
Lower and middle Pleistocene sedimentary fill
Upper Pleistocene and Holocene alluvial deposits