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

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5
6 Alejandra Serey^{1,2*}, Sergio A. Sepúlveda^{1,2}, William Murphy³, David N. Petley⁴, Gregory De Pascale¹

7
8 ¹ *Departamento de Geología, Universidad de Chile.*

9 ² *Instituto de Ciencias de la Ingeniería, Universidad de O'Higgins.*

10 ³ *School of Earth and Environment, University of Leeds.*

11 ⁴ *Department of Geography, University of Sheffield.*

12 **alejandra.serey@gmail.com*

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15
16 **ABSTRACT**

17
18 Landslides represent the most frequent geological hazard in mountainous environments. Most notably, landslides are a
19 major source of fatalities and damage related with strong earthquakes. The main aim of this research is to show through
20 three-dimensional engineer-friendly computer drawings, different mountain environments where coseismic landslides
21 could be generated during shallow crustal and megathrust earthquakes in the Andes of Central Chile. From the
22 comparison of local earthquake-induced landslide inventories in Chile, from the Mw 6.2, shallow crustal Aysén
23 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
24 abroad, as well as analysis of large, prehistoric landslide inventories proposed as likely induced by seismic activity, we
25 have determined topographic, geomorphological, geological and seismic controlling factors in the occurrence of
26 earthquake-triggered landslides. With these results, we have built four representative geomodels of coseismic landslide
27 geomorphological environments in the Andes of central Chile. Each one represents the possible landslide types to be
28 generated by a shallow crustal earthquake versus those likely to be generated by an megathrust earthquake.
29 Additionally, the associated hazards and suggested mitigation measures are expressed in each scenario. These
30 geomodels are a powerful tool for earthquake-induced landslide hazard assessment.

31
32 Keywords: coseismic landslides, conceptual hazard models, Chile.

33
34
35 **INTRODUCTION**

36
37 Landslides represent perhaps the most frequent geological hazard in mountainous environments due to the geological,
38 geomorphological and geotechnical characteristics of steep upland landscapes. In tectonically-active mountain areas,
39 landslides are a major cause of fatalities and economic losses during and after strong earthquakes (*e.g. Sepúlveda et al.,*
40 *2005; Qi et al., 2010; Dai et al., 2011*).

41
42 Coseismic landslide hazard, defined as the relative probability of landslide occurrence at a specific location in a specific
43 event, is a function of intrinsic slope characteristics (slope angle, material strength, lithology, etc.), and earthquake
44 shaking, which acts as a significant trigger mechanism for causing landslides of all types (*Keefer 1984*). In addition to
45 those factors influencing landsliding under ambient conditions, site conditions further influence ground motions through
46 soil and topographic amplification (*Wang et al. 2018, Meunier et al., 2008, Sepúlveda et al. 2005*). Recent studies (*e.g.;*
47 *Wartman et al., 2013; Marc et al., 2016*) suggest that they are also influenced by the seismogenic zone. *Serey et al.*
48 *(2019)* observed that shallow crustal and megathrust earthquakes create fundamentally different spatial patterns and
49 densities of landslides.

50
51 Selecting seismological inputs for slope stability analysis is challenging given the large number of difficult to quantify
52 variables associated with coseismic landslides, which include seismic wave frequency, wave amplitude and wave
53 interactions. This is especially complex for regional hazard assessments (*Meunier et al., 2008; Geli et al., 1988*).
54 Several statistical methods exist for modelling regional-scale coseismic landslide hazard (*e.g., Lee et al., 2008; Miles*
55 *and Keefer, 2000; 2007; 2009; 2009b; Jibson et al., 2000*), all of them only considering one kind of coseismic trigger,
56 i.e shallow crustal earthquakes. Thus, a first-order form of hazard identification can prove beneficial prior to
57 considering more complex analytical tools and different kinds of coseismic triggers. One such approach is to visualize
58 all these variables, both conditioning and triggering factors, in the form of graphic 3D ground models, often referred to
59 as geomodels. Such tools are also valuable in explaining complex geotechnical problems to non-specialists such as
60 government and planning agencies.

61
62 The concept of a geomodel, and its depiction in simplified block diagrams, aims to allow visualization of the geology in
63 three dimensions and to act as a quick introduction to new or unfamiliar ground conditions or environments (*Jackson*
64 *2016*). *Fookes (1997)* defined conceptual geological models for a number of different environments, which have been
65 linked to hazard assessment and engineering to mitigate geohazards (e.g. *Hearn et al., 2012; Hearn and Hart, 2011;*
66 *Hearn, 2018*).

67
68 *Parry et al. (2014)* considered that there are two fundamentally different stages for developing engineering geological
69 models: conceptual and observational. The conceptual approach is based on understanding the relationships between
70 engineering geological units, their likely geometry and anticipated distribution. Importantly, these models are largely
71 based on geological concepts such as age, stratigraphy, rock type, unconformity and weathering (the ‘total geological
72 history’ approach by *Fookes et al., 2000*). The main aim of the work presented here has been to develop practitioner-
73 friendly conceptual ground models relating to the performance of slopes subject to strong ground motions during
74 earthquakes in different mountain environments in the Chilean Andes. These were further subdivided into slope
75 performance during (i) megathrust earthquakes and (ii) shallow crustal earthquakes, to indicate expected slope
76 behaviour when subjected to earthquakes of different sizes and epicentral distance. The performance of the slopes is
77 derived from the databases outlined in *Serey et al. (2019)*. In addition to the hazards identified, potential mitigation
78 measures are outlined based on the rock slope engineering.

80 COSEISMIC LANDSLIDES IN THE MOUNTAIN ENVIRONMENT OF CHILE

81
82 The Cordilleran areas in Chile constitute a major part of the landmass and contain nearly all of copper and other
83 precious metals mining that contribute strongly to the Chilean economy. Additionally, mountain infrastructure is a vital
84 lifeline for the flow of materials, access to markets for mountain communities and neighbour countries, and tourism.
85 However, given the mountain conditions it is difficult to provide alternative routes in the event of lifeline disruption.

86
87 Seismically-induced landslides are a common phenomenon in the Andes, in Central and Southern Chile. This is
88 attributed to two factors: firstly, the tectonic evolution of Chile and secondly, the glaciation of the Andes resulting in
89 variable geological conditions. Chile can be considered the most seismically active country in the world (*Cisternas,*
90 *2011; Barrientos, 2018*); ten M8 or larger earthquakes have occurred along the Chilean coast in the past century, with a
91 \geq M8 earthquake occurring approximately every dozen years (*Barrientos, 2018*). The second factor is that the Andes of
92 Central and southern Chile were strongly affected by Quaternary glaciations (with many areas still covered in ice),
93 resulting in steep topography, strong erosional features and rock masses weakened by the effects of Late-Quaternary ice
94 action. The pattern of glaciation/deglaciation of the Andes is complex, with changes in moisture in the atmosphere
95 combined with lowering temperatures led to a complex change in seasonal snowline variation during the late
96 Pleistocene.

98 The seismotectonic setting and seismicity of Chile

99
100 The Andes of Central Chile (32.5° S to 41.5° S) are composed of a number of morphostructural units from west to east:
101 the Coastal Cordillera, the Central Valley, the Principal Cordillera (spanning Chile and Argentina), the Frontal
102 Cordillera, the Argentine Precordillera and the Pampean Ranges (*Jordan et al. 1983*) (Figure 1). The Principal
103 Cordillera is a chain of high mountains that in its western part in Chilean territory mostly comprises Oligocene–
104 Miocene continental volcanoclastic rocks, intruded by Miocene–Pliocene granitoids (*Charrier et al., 2015; Pankhurst*
105 *and Hervé, 2007*). The Cordilleran environment is characterised by being an active, folded orogen with a high
106 topographic relief and steep slopes. Cycles of high activity (driven by periods of relatively rapid uplift) that initiate
107 periods of intense erosion as rivers cut down to lower base levels and produce steep-sided valleys. Many of these
108 valleys have limited stability, with the immature weathered surfaces continually being eroded. Hillslopes are typically
109 mantled with colluvium and/or taluvium that is unstable when undercut.

110
111
112 Several seismogenic zones are recognized in Chile: large interplate earthquakes- (depths 45–55 km); large intermediate-
113 depth earthquakes (60–200 km); shallow crustal seismicity (depths 0–20 km); and outer-rise earthquakes along the
114 subduction margin between the Nazca and South American Plates (*Barrientos, 2018*).

115
116 Megathrust seismicity corresponds to large magnitude (above 8) interplate earthquakes in the subduction zone plate
117 contact. Because of their comparatively high frequency of occurrence, these earthquakes are responsible for most of the
118 historic damage. They are located along the coast from Arica (18° S) to the triple junction at Taitao Peninsula (46° S).
119 These events take place as a result of the convergence of the Nazca beneath the South American plate at a rate of about

120 7.4 cm/yr (*Argus et al., 2010*). Further south, the Antarctic plate subducts beneath the South American plate at a rate of
121 ~8.1 cm/yr (*Lara et al., 2018*). $M \geq 8$ earthquakes are usually accompanied by notable coastal elevation changes and,
122 depending on the amount of seafloor vertical displacement, by catastrophic tsunamis. Their rupture zones extend down
123 to 45–53 km depth (*Tichelaar and Ruff, 1991*) and their lengths can reach well over 1000 km. Return periods for $M \sim 8$
124 (and above) events are of the order of 80–130 years for any given region in Chile, and about a dozen years when the
125 country is considered as a whole (*Barrientos, 2018*). The latest examples of these type of earthquakes were the 2010 M
126 8.8 Maule, the 2014 M 8.2 Iquique, and the 2015 M 8.4 Illapel earthquakes (*Barrientos et al., 2004; Candia et al.,*
127 *2017; Barrientos, 2018*). Megathrust earthquakes seem to have much longer return periods, of the order of a few
128 centuries for any given region (*Cifuentes, 1989; Barrientos and Ward, 1990*). Recent off-fault strong ground motion
129 indicator paleoseismological studies carried out in southern Chile indicate recurrence intervals of ~300 years for these
130 very large earthquakes (*Cisternas et al., 2005; Moernaut et al., 2014*).

131
132 The capacity for megathrust earthquakes to induce large numbers of landslides and mobilise large volumes of sediment
133 was highlighted by the 1960 Valdivia (*Duke, 1960*) and the 2010 Maule (*Serey et al., 2019*) earthquakes. During the
134 $M=9.5$ Valdivia earthquake extensive landsliding occurred (*Wright and Mella, 1963*). Three large landslides (2-30 Mm^3
135 of volume) on poorly consolidated sediments at the San Pedro River attracted particular attention due to the formation
136 of landslide dams and the threat to the city of Valdivia c. 80 km from the slides (*Davis and Karzulovic, 1963*). *Serey et al.*
137 *(2019)* provide an inventory of landslides induced by the 2010 $M_w=8.8$ Maule earthquake, one of the few world
138 comprehensive, reliable inventory of coseismic landslides available for subduction zone earthquakes. In total, 1,226
139 landslides were mapped over a total area of c. 120,500 km^2 , dominantly small disrupted slides. However, the estimated
140 total landslide volume is only c. 10.6 $M m^3$. The events are unevenly distributed in the study area, the majority of
141 landslides located in the Principal Andean Cordillera and a very constrained region near the coast on the Arauco
142 Peninsula, forming landslide clusters (*Serey et al., 2019*). Additionally, *Candia et al. (2017)* demonstrated that there
143 were more coseismic landslides that impacted critical infrastructure in areas with the largest fault slip at the plate
144 boundary during the 2015 $M8.4$ Illapel earthquake (31.6°S).

145
146 Shallow crustal seismicity is important in seismic and coseismic hazard assessments because the strong ground motions
147 (measured in % of gravity as peak ground accelerations, or PGA) that reach the surface due to limited distance for the
148 seismic waves to attenuate. Shallow crustal seismicity (0–20 km) that occurs throughout Chile such as the Cordilleran
149 region of South–Central Chile (e.g. Liquiñe–Ofqui fault zone) is a consequence of the oblique convergence of the Nazca
150 Plate. Magnitudes up to 7.1 have been reported for earthquakes in this region (44,5°S y 73°W, 21 November 1927)
151 (*Greve, 1964*). The Andean Principal Cordillera in the central part of Chile is also an important area with important
152 crustal seismicity because of the risk to high population density and critical infrastructure. *Godoy et al. (1999)* and
153 *Barrientos et al. (2004)* carried out structural and seismicity studies to understand this region, in which the largest
154 recorded earthquake (less than 10 km depth) took place on 4 September 1958 (M 6.3, *Alvarado et al., 2009*), causing
155 extensive rockfalls and a few large landslides (*Sepúlveda et al., 2008*). Shallow crustal seismicity with a relative large
156 magnitude (> 5.5) was recently observed beneath the Andes main Cordillera at latitudes 19.6° S (Aroma; July 2001),
157 35.8° S (Melado River; August 2004), 38° S (Barco Lagoon; December 2006), and 45° S (Aysén Fjord; April 2007).
158 All these events show significant strike-slip component of displacement (*Barrientos, 2018*).

159
160 In Southern Chile, The Aysén Fjord earthquake (21 April 2007, M_w 6.2) triggered over 500 landslides of different types
161 (*Sepúlveda et al., 2010*) of which the largest was the Punta Cola rock avalanche with a volume of c. 22 Mm^3 (*Oppikofer*
162 *et al., 2012*). The triggering of landslides around and into the fjord resulted in a displacement wave that killed eleven
163 people (*Sepúlveda and Serey, 2009; Naranjo et al., 2009*).

164 165 GEOMODEL CONSTRUCTION

166 167 **Data used in construction of the geomodels**

168
169 Data used to develop the geomodels presented here can be divided into two broad types: landslide inventory data and
170 limited field observation of critical lithological units. Only two comprehensive inventories of earthquake-triggered
171 landslides exist in Chile, the shallow crustal M_w 6.2, Aysén earthquake in 2007 (45.27°S 72.66°W) (*Sepúlveda et al.,*
172 *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.,*
173 *2019*). These inventories are representative of the landslide triggering characteristics of these two Chilean groups of
174 seismic events. These databases were supplemented with observations from databases beyond Chile (e.g. *Marc et al.,*
175 *2016; Malamud et al., 2004*) in addition to more detailed field investigations of large, historic landslides in Chile (e.g.
176 *Sepúlveda et al., 2008*) and landslide inventories from the geologic record considered likely to have been induced by
177 seismic activity (*Antinao and Gosse, 2009; Moreiras and Sepúlveda, 2015*). These databases contain data on

178 topographic, geomorphological, geological and seismic controlling factors on the occurrence of earthquake-triggered
179 landslides, which informed model construction.

180 181 **Distribution and characteristic of coseismic landslides for geomodels in the Chilean Andes**

182
183 It is well-established that landslides are not evenly distributed in the affected areas. Landslides tend to form clusters that
184 may be related to geological conditions or ground motion parameters (e.g. *Serey et al., 2019; Sepúlveda et al., 2010*) or
185 to the influence of strong ground motions coincident with fault slip distributions (*Candia et al., 2017*). Furthermore,
186 most occur in the Cordilleran environment where high relief and steeper slopes prevail. Examples of the landslides
187 under investigation can be seen in Figure 2. From the analysis of databases, the following general comments can be
188 made:

189
190 1. The most common type of landslide observed in the inventories are “disrupted” slides, consistent with observations
191 from other earthquakes (e.g. *Keefer, 1984; Rodriguez et al., 1999; Wartman et al., 2013*).

192
193 2. Shallow disrupted slides like debris avalanches, debris slides, rock falls and rock slides, account for approximately
194 86% and 98% of landslides triggered by the Maule 2010 and Aysen 2007 earthquakes respectively (*Serey et al., 2019;*
195 *Sepúlveda et al., 2010*) (See figure 2).

196
197 3. Relatively few slumps, deep block slides, or slow earth flows were observed from Chilean inventories. For example,
198 less than 1% of total slides were classified as coherent slides for the Maule earthquake (*Serey et al. 2019*), and near 1%
199 for the Aysen event (*Sepúlveda et al. 2010*).

200
201 4. The number and distribution of coseismic landslides differs significantly between interplate/megathrust and shallow
202 crustal earthquakes. The total number of landslides triggered for the megathrust earthquakes is substantially lower,
203 typically by one to two orders of magnitude, than it would be expected for shallow crustal earthquakes, of a similar or
204 even lower magnitude (*Serey et al. 2019*). This is due to strong ground motion attenuation from interplate/megathrust
205 events that reduce the peak ground accelerations.

206
207 5. There is a difference in the size of landslides between the two different sources of seismicity. The landslides triggered
208 by the megathrust Maule Earthquake are generally in the range of $10^2 - 10^3$ m². Approximately 60% of coseismic
209 landslides caused by the Maule Earthquake were in the range of 100 m² to 5,000 m². This can be contrasted with the
210 fact that just under 50% of landslides induced during the crustal Aysen earthquake that were in the range of 5,000 m² to
211 50,000 m². This is likely to be a function of the amount of energy arriving at any given slope due to the attenuation from
212 deeper sources mentioned above.

213
214 6. For megathrust earthquakes, such as those in 1960, there seems to be limited occurrence of large volume rock
215 avalanches or rock slides. Although this type of earthquake is relatively frequent in Chile, no large volume rock
216 avalanches have been observed to be triggered by them during the last century. However, as Chile has a high
217 concentration of large volume rock avalanche deposits in the Andes (*Antinao and Gosse, 2009*), it is likely that these are
218 associated with proximal shallow crustal earthquakes. Given the large distance between interplate seismicity and the
219 Andes Principal Cordillera (c. 100-150 km in Central Chile) these seem a more likely cause than large farfield events,
220 like the catastrophic avalanche in 1970 triggered by an M 7.9 offshore earthquake, originated from Nevados Huascarán,
221 the highest peak in the Peruvian Andes (*Plafker and Ericksen, 1978; Evans et al. 2009*).

222 223 224 **Factors that influence the dynamic response of hillslopes undergoing seismic shaking**

225
226 The factors that influence the dynamic response of hillslopes undergoing seismic shaking (e.g. *Jibson, 2011; Newmark,*
227 *1965*) can be broadly grouped into those that influence the intensity of event-specific seismic ground motions, those that
228 influence the strength of hillslope materials and those that influence the static shear stresses. Empirical studies have
229 revealed a number of proxy variables that can be used to represent these factors at the regional scale (*Parker et al.,*
230 *2015*).

231
232 Lithology is an important factor in the generation of coseismic landslides, being relevant mainly during megathrust
233 events. For example, *Wartman et al. (2013)* determined that majority of landslides triggered by Mw 9.0 2011 Tohoku
234 megathrust earthquake occurred in the youngest (Neogene) geological units of the region (Quaternary sediments and
235 Neogene sedimentary rocks). The *Serey et al. (2019)* database indicates that for the 2010 Maule earthquake, relief
236 exerted a dominant control on coseismic landsliding with the lithology the second most relevant conditioning factor,
237 with more landslides in younger rocks (Quaternary deposits and Paleogene-Neogene volcanic and volcano-sedimentary

238 rocks). This is in effect an indication on the degree of cementation and thus strength. On the other hand, in most of
239 shallow crustal events, lithology seem not to be a primary factor to consider in the generation of landslides. For
240 example, according by Wang (2015) there is no obvious correlation between landslide concentration and rock age
241 (young or old lithology) for the 2013 Lushan and the 2008 Wenchuan earthquakes. Indeed, differences in the
242 distributions of landslides across different lithologies arise because young or old strata are coincidentally clustered
243 around the rupture zone of the seismogenic fault, and these rock masses are extremely fractured and underwent strong
244 shaking.

245
246 Other factors that may have influence on the distribution of landslides are related with seismic effects on shaking in the
247 near field, such as the hanging wall and directivity effects during strong shallow crustal earthquakes. Directivity effects
248 are related with the rupture direction of the fault, tending to generate larger ground motions toward this direction
249 (Somerville et al., 1997; Somerville, 2003). The hanging-wall effect relates with larger ground motions on the block
250 above an inclined fault (the hanging-wall block) and is common on earthquakes along thrust faults (e.g. Abrahamson
251 and Somerville, 1996; Zhao et al., 2019). The literature indicates that the landslides triggered by earthquake tending to
252 cluster along the causative fault (Keefer, 2000; 2002; Khazai and Sitar, 2004; Huang and Li, 2009). For thrust faults
253 landslide density is highest on the hanging wall (Meunier et al., 2007).

254
255 Ground motion was found to be the most significant factor in triggering the shallow landslides in the 1999 Mw 7.6 Chi-
256 Chi earthquake. Overall, 74% of all slope failures occurred in regions with vertical ground motions greater than 0.2 g
257 and 81% of all slope failures occurred in the region with mean horizontal peak ground accelerations (PGA) greater than
258 0.15 g (Khazai and Sitar, 2004). On the other hand, Wartman et al. (2013) compared the landslide database with
259 ground-motion recordings of the 2011 Tohoku earthquake (Mw 9.0, megathrust event), but found no correlation
260 between landslide intensity and ground shaking within the area affected. Similarly, in the 2010 Mw 8.8 Maule
261 earthquake, very few landslides occurred in the area of higher intensity (VIII) and most of them were in the area of
262 lower intensities (<V). Therefore, there was no strong correlation between landslide density and earthquake intensity
263 (Serey et al., 2017) or with PGA or distance from the fault plane. There was a much stronger correlation between
264 landslide concentration and the ratio between horizontal and vertical peak accelerations (Serey et al., 2019).

265
266 Densmore & Hovius (2000) recognized that earthquake-triggered landslides in rock slopes have a relatively uniform
267 distribution on steep slopes, but in presence of topographic amplification the triggering of landslides at or near the crests
268 is increased. Recent studies have indicated that the ground accelerations at the mountain top can be three to six times
269 than at its foot (Wang et al., 2012; Wang et al., 2018), causing higher susceptibility to landsliding in the upper parts of
270 the slopes. In the Aysen event, about two thirds of the landslides start in the upper quarter of the slope, while over 90%
271 start in the upper half, which suggests that larger ground motions due to topographic site effects influenced the
272 triggering of landslides during the earthquake (Sepúlveda et al., 2010). On the other hand, landslides induced by the
273 Maule earthquake are not clustered close to the ridge tops, suggesting no predominant topographic site effect in their
274 generation, although it may have played a role locally (Serey et al., 2019).

275
276 The above is summarized in Table 1, which shows the differences between, conditioning factors and characteristics of
277 the coseismic landslides applied to the mountain environment of Chile for both kinds of triggers (shallow crustal and
278 interplate/megathrust earthquakes), based on analysis of comprehensive inventories of coseismic landslides in Chile
279 and abroad (Serey, 2020; Zhao et al., 2019; Serey et al., 2019; Serey et al., 2017; Wang et al., 2015; Wartman et al.,
280 2013; Gorum et al., 2011; Sepúlveda et al., 2010, Sepúlveda and Serey 2009, Meunier et al., 2007).

281 282 283 **CONCEPTUAL HAZARD MODELS**

284
285 Using the data mentioned above, four conceptual hazard ground models were developed to guide stakeholders in the
286 hazards faced to critical infrastructure in mountain regions. Representative geomodels describing the hazards for the
287 Andes of Central Chile were developed, these are: Glacial Cordilleran, Fluvial Cordilleran, Plutonic Cordilleran and
288 Mountain Front environments. The latter model is the most likely to have significant urban development because of the
289 concentration of infrastructure. The data showing slope performance for the two different earthquake types, based on
290 Table 1 and specific geomorphological characteristics, have then been added to the models to use in a semi-predictive
291 capacity.

292 293 **Glacial Cordilleran environment**

294
295 In Central Chile, the glaciated mountain terrain is dominated by andesitic bedrock with local volcanoclastic sediments.
296 Glacial landscapes are essentially high-latitude and/or high-altitude environments. Geomorphology in these areas is

297 characterized by high relief and steep slopes. Furthermore, it is characterized by the presence of glacial deposits (e.g. till
298 and glacial-fluvial deposits) and modified by periglacial processes. Rock slopes tend to be over-steepened. Rock masses
299 quality are often fair to good, locally very good, may be highly fractured in the vicinity of lineaments or faults.
300 Hydrothermal alteration, however, can be extreme locally and reduces the rock mass quality. Most of coseismic
301 landslides are disrupted, principally rock falls, debris avalanches, debris slides, and rock slides. In these environments,
302 large rock avalanches/slides could dam river valley. Landslides may occur on persistent discontinuities or glacial
303 deposits.

304
305 Figure 3 and Figure 4 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust
306 earthquakes respectively in a glacial cordilleran environment of Central Chilean Andes. Table 2 outlines
307 geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a glacial
308 cordilleran environment for each scenario.

309
310
311 **Fluvial Cordilleran environment**

312
313 Fluvial mountain terrain dominated by andesitic bedrock with local volcanoclastic sediments. Geomorphology is
314 characterized by a strong relief, medium ranges of altitudes and medium to high gradients forming fluvial troughs (V-
315 shaped valleys). Rock masses quality are often fair to good, locally very good, may be highly fractured near lineaments
316 or faults. Hydrothermal alteration, however, can be extreme in places and reduce the geotechnical quality of intact rock.
317 In these environments, large rock falls, rock avalanches/slides could dam the river valley. In this landscape, large
318 prehistoric landslides are common, in which source areas of future rock slides may be generated by future shallow
319 crustal events.

320
321 Figure 5 and Figure 6 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust
322 earthquakes respectively in a fluvial cordilleran environment of Central Chilean Andes. Table 3 expresses
323 geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a fluvial
324 cordilleran environment for each scenario.

325
326
327 **Plutonic Cordilleran environment**

328
329 Plutonic mountain terrain dominated by intrusive igneous bedrock with local volcanoclastic sediments. This
330 environment is characterized by a strong relief, steep slopes (medium to high ranges) and high altitudes. In general
331 terms, plutonic rocks develop competent rock massifs and tight valleys. Rock masses quality are often good to very
332 good, may be highly fractured in the vicinity of lineaments or faults. In these environment are very common large pre-
333 historic landslides, in which new rock slides can be generated by a future shallow crustal earthquake. In addition, large
334 rock falls, rock avalanches/slides could dam a river valley.

335
336 Figure 7 and Figure 8 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust
337 earthquakes respectively in a plutonic cordilleran environment of Central Chilean Andes. Table 4 outlines
338 geomorphological characteristics of terrain and possible coseismic landslides that could be triggered in a plutonic
339 cordilleran environment for each scenario

340
341 **Mountain Front environment**

342
343 Mountain front terrain, usually bordering urban areas in Central Chile, is dominated by andesitic bedrock with local
344 volcanoclastic sediments and generally forms the at the convergence of high mountains and adjacent basins (e.g. the
345 Santiago basin). Rock masses quality are often fair to good, locally very good, may be highly fractured in the vicinity of
346 lineaments or faults. Hydrothermal alteration, however, can be extreme in places and reduce the geotechnical quality of
347 intact rock. In these environments, geomorphology is characterized by a strong relief, medium ranges of altitudes and
348 medium to high gradients. This environment presents important ravine channels, basins characterized by narrow, steep-
349 sided valleys, in which removed materials flow directly into urban areas located in the central depression. Therefore,
350 large rock avalanches/slides generated by a future crustal earthquake and consequently debris flows due to debris
351 avalanche, rock falls or rock slides failures into channels could result in fatalities and infrastructure damage.

352
353 Figure 9 and Figure 10 show conceptual geomodels of coseismic landslides induced by shallow crustal and megathrust
354 earthquakes respectively in a mountain front environment of Central Chilean Andes. Table 5 outlines geomorphological

355 characteristics of terrain and possible coseismic landslides that could be triggered in a mountain front environment for
356 each scenario.

357 358 359 **DISCUSSION**

360
361 Landslides are an important coseismic geohazard associated with earthquakes in mountain environments and present a
362 serious threat to communities found in these regions (*Keefer, 1984*). Indeed, in high mountain chains, 20-25% of
363 earthquake-induced fatalities result from the effects of landslides (*Petley et al., 2006*). By visualizing differences
364 between conditioning factors and characteristics of coseismic landslides, using geomodels, between different triggers
365 can be a key factor in the assessment of effective mitigation measures. From the geomodels construction, it is
366 possible to view potential risks, consequences and possible mitigation measures for each coseismic landslides (Table
367 6).

368
369 Secondary hazards can be generated from large landslides, such as rock avalanches and rock slides, blocking narrow,
370 steep-sided valleys and forming landslide dams (*Schuster, 1986*), or landslide-induced tsunamis. In some cases,
371 landslides may pose a threat to the population and infrastructure because they dam a watercourse. Landslide dams
372 tend to be a feature of seismically active steep-relief mountain areas undergoing uplift and erosion or deeply dissected
373 thick sequences of weakly consolidated sediments such as lacustrine clays. Landslide dams give rise to two important
374 flood hazards. Upstream or back-water flooding occurs as a result of impounding of water behind the dam leading to
375 the relatively slow inundation of an area to form a temporary dam. Downstream flooding can occur in response to
376 failure of a landslide dam. The most frequent failure modes are overtopping because of the lack of a natural spillway
377 or breaching due to erosion. Failure of the poorly consolidated landslide debris generally occurs within a year of dam
378 formation. The effect of the resultant floods can be devastating, partly because of their magnitude and partly because
379 of their unexpected occurrence (*Lee and Jones, 2004*). For example, in the 2005 Mw 7.6 Kashmir earthquake at least
380 two river blockages occurred. The largest of the two, at Hattian Bala east of Muzaffarabad, created a dam over 100 m
381 high (*Dunning et al., 2007*).

382
383 In Chile, the most important historical example of landslide dams took place during the giant 1960 Valdivia earthquake
384 (Mw=9.5, megathrust earthquake). Three large landslides dammed the San Pedro River and threatened the Valdivia
385 City. The biggest landslide removed c. 30 Mm³ of poorly consolidated sediments, the intermediate transported 6 Mm³
386 and, finally, the smallest involved the removal of 2 Mm³ (*Davis and Karzulovic, 1963*). Given its flow, it was expected
387 that in two months the accumulated water would exceed the landslide dam, producing a huge avalanche that would
388 cover all of Valdivia, already devastated by the earthquake and tsunami, and the surrounding areas. To avoid this
389 disaster, engineers and technicians from ENDESA and the MOP (Ministry of Public Works) started the so-called
390 "Operation Riñihue", which consisted of making a channel through the undisturbed terrain, so that the water flowed as
391 slowly as possible as it finally happened (*Lazo, 2008*). Historical records highlight this same phenomenon in the 1575
392 earthquake (M 8-8.5 according to *Lomnitz, 2004*), on that occasion San Pedro River was also blocked by a huge
393 landslide in the same area (*Montessus de Ballore, 1912*), not allowing normal water drainage. The dam accumulated
394 water for five months and finally causing a catastrophic flood taking the lives of more than 1,200 indigenous people and
395 destroyed Valdivia city, founded by the Spaniards a couple of decades before (*Davis and Karzulovic, 1961*).

396
397 Earthquakes often leave a legacy of pseudo-stable slopes that continue for years or many decades afterward the main
398 event. These landslides represent a direct threat themselves but also block and cut transportation infrastructure. An
399 aspect that is often overlooked is the increased rate of sediment movement caused by the liberation of hillslope debris,
400 an effect that could depend on the type of earthquake. In the Mw 7.6 Chi-Chi earthquake in Taiwan, a shallow crustal
401 event, this induced aggradation of some river beds by as much as 30 m, which proved to be devastating to local
402 communities and to hydroelectric power systems (*Petley, 2009*). On the other hand, *Tolorza et al. (2019)*
403 demonstrated that the 2010 Mw 8.8 Maule earthquake, an megathrust event, had a limited impact on the overall
404 concentration and transport of suspended sediment loads in the Chilean Andes, which perhaps sheds light on the
405 influence of climate on how these systems will be behave post-events (e.g. under dry climate conditions). Thus, the
406 seismically induced erosion and the evacuation of detached sediments are not necessarily a function of earthquake
407 magnitude.

408
409 Despite the enormous impact potential of giant landslides, especially of those triggered during earthquakes, relatively
410 little effort is spent to predict them. Thus, only very few case histories are known where large sites (>1 km²) had been
411 thoroughly investigated to assess their failure potential under dynamic conditions, in full 3D (*Havenith et al., 2017*).
412 The major problem is the availability of cost-effective methods, both to prospect and to model such sites. Although, all
413 of them only considered one possible seismogenic scenario, i.e. crustal shallow earthquakes. Therefore, in this

414 manuscript, a powerful tool for earthquake-induced landslide hazard assessment applicable to urban/territorial planning
415 and disaster prevention strategies is presented. This is a series of practitioner-friendly conceptual ground models
416 relating to the performance of slopes subject to strong ground motions during earthquakes originated from different
417 seismogenic scenarios (megathrust or crustal shallow earthquake) in the most characteristic mountain environments in
418 the Chilean Andes and expresses the following.

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

423
424 This methodology visualizes all factors interacting in the generation of coseismic landslides depending on seismogenic
425 zones (megathrust or crustal shallow earthquake), and considering the low cost (in both the elaboration and the required
426 information) it might be applied elsewhere in the country and Latin America. The continuous, poorly regulated growth
427 of the city into the mountain environment typical in Latin America, the increasing tourism industry in mountain areas,
428 large infrastructure projects (water supply, hydroelectricity, gas pipes, etc.) increase exposure to coseismic landslides
429 and their secondary hazards, thus the need for these to be properly addressed in territorial planning policies and disaster
430 prevention strategies.

431
432 It is essential to emphasize that this methodology is a conceptual approach and that it needs to be complemented with an
433 observational model to be applied for hazard assessment at local scales, which is based on the observed and measured
434 distribution of engineering geological units and processes. These data are related to actual space or time and are
435 constrained by surface or sub-surface observations.

436 437 **CONCLUDING REMARKS**

438
439 Landslides are a substantial but often neglected aspect of megathrust and shallow crustal earthquakes in upland areas.
440 Furthermore, in addition to killing people outright, they can also have an extremely serious impact in terms of
441 hampering rescue operations and the delivery of assistance, situations that can vary dramatically between different
442 triggers. Whilst earthquake-induced landslides cannot be prevented, adequate consideration of the problem in advance
443 can allow the impact of coseismic landslides to be minimized.

444
445 Practitioner-friendly conceptual ground models relating to the performance of slopes subject to strong ground motions
446 during megathrust or shallow crustal earthquakes in different mountain environments in the Andes of central Chile have
447 been developed. Each model expresses important characteristics about coseismic landslide hazard (main types, spatial
448 distribution and sizes), their potential consequences and suggestions of possible mitigation actions or engineering
449 interventions. Due to the geological and geomorphological context, these geomodels may be replicated or adapted for
450 other countries of Latin America. In addition, considering the low cost, both in the elaboration and the required
451 information, these models are a very powerful tool to visualize all factors interacting in the generation of coseismic
452 landslides.

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688 **Figure captions**

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

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

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

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

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

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

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

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

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

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

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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 breaching 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.
	Interfluvial 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 planning.
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 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 planning.
	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.		

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.
	Interfluvial 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.	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.
		Fluvial valley: Dominated by intercalations of coarse fluvial materials, alluvial deposits and colluvium.				
	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.	
	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 like sandy or silty soils.	Debris slides.	Breaching is a major hazard leading to downstream flooding. Potential breaching of landslide dams creating downstream flooding.	

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.	
	Interfluvial 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.

Figure 1. Morphostructural and seismotectonic setting of Central Chilean Andes. Major crustal fault in the Chilean Andes with evidence of neotectonics activity

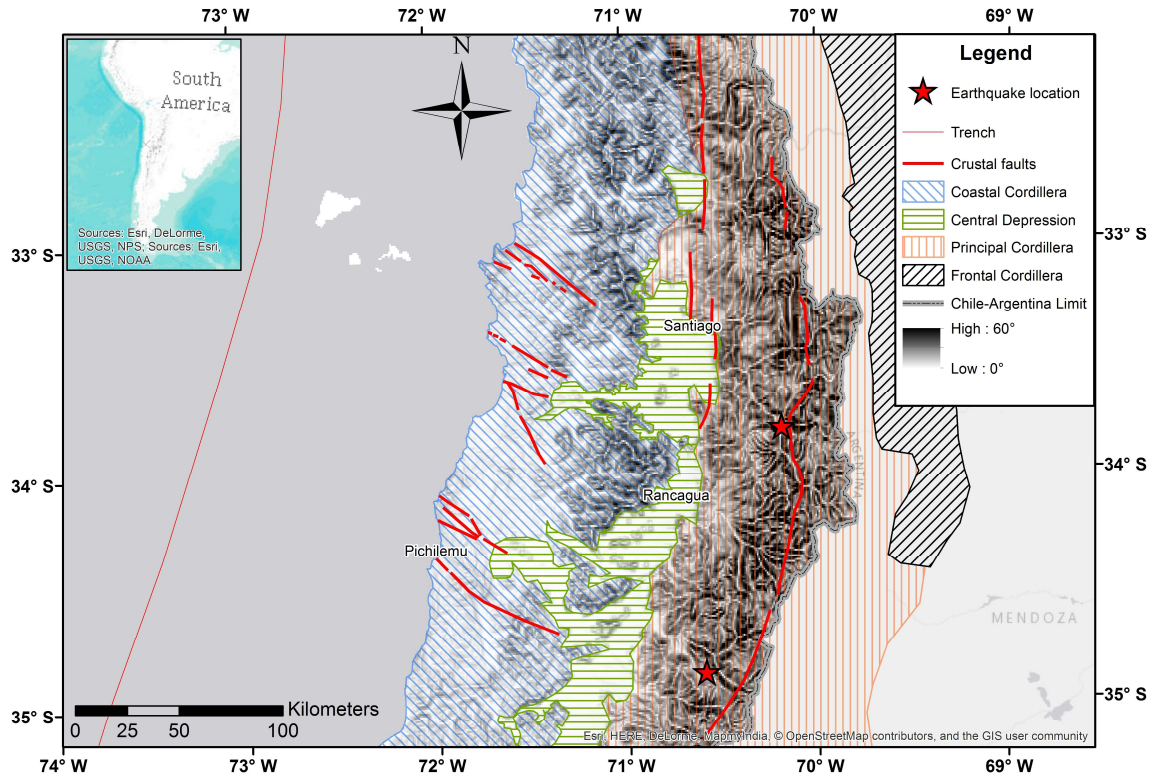


Figure 2. Examples of landslides triggered by earthquakes in Chile. A: Overview of debris avalanches (2007 Aysen earthquake); B: Rock slides triggered by the 2007 Earthquake in Aysen Fjord (all in granitic rock masses of the Patagonian Batholith); C and E: Debris slides (2010 Maule earthquake); D: Rock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

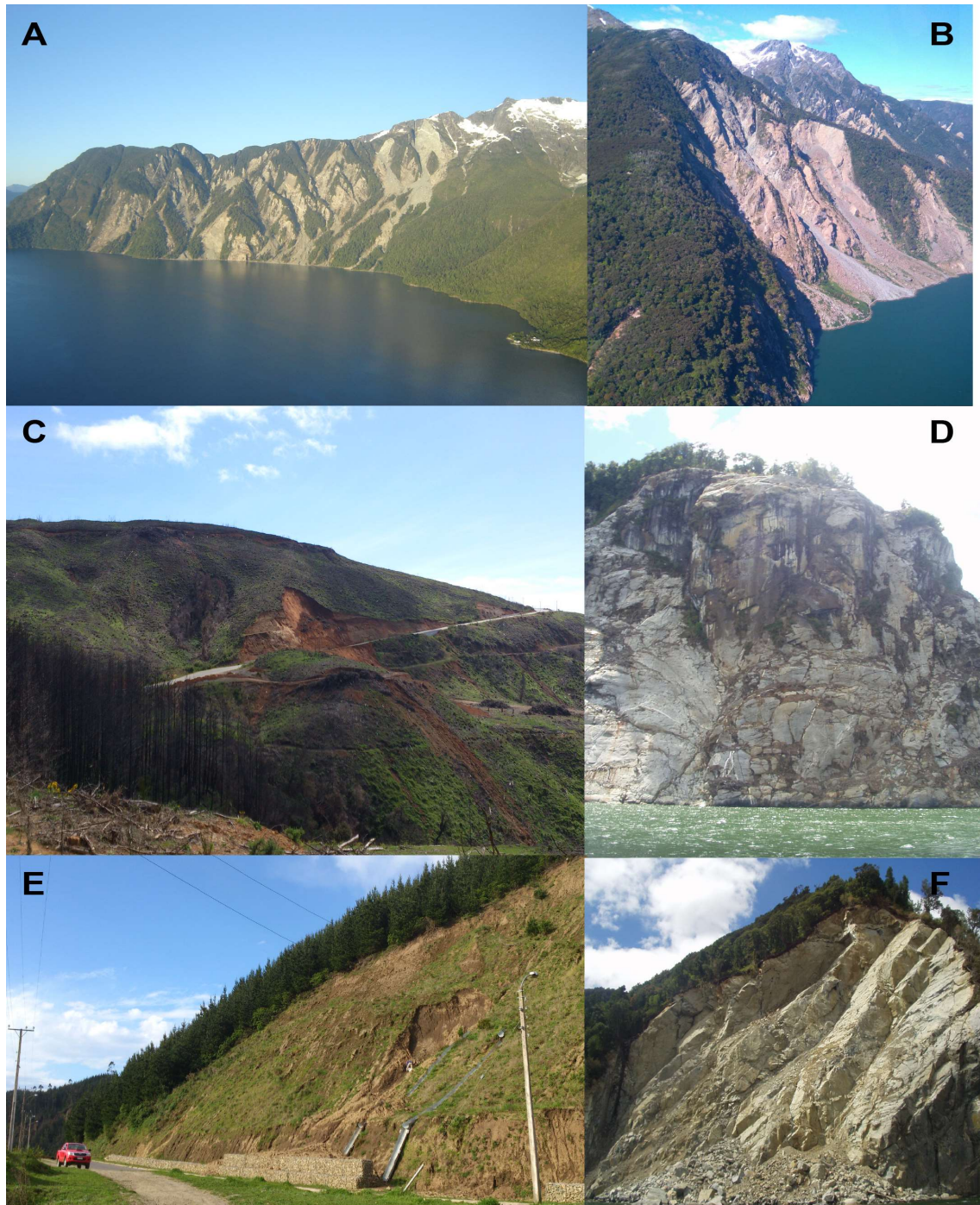


Figure 3. Glacial cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

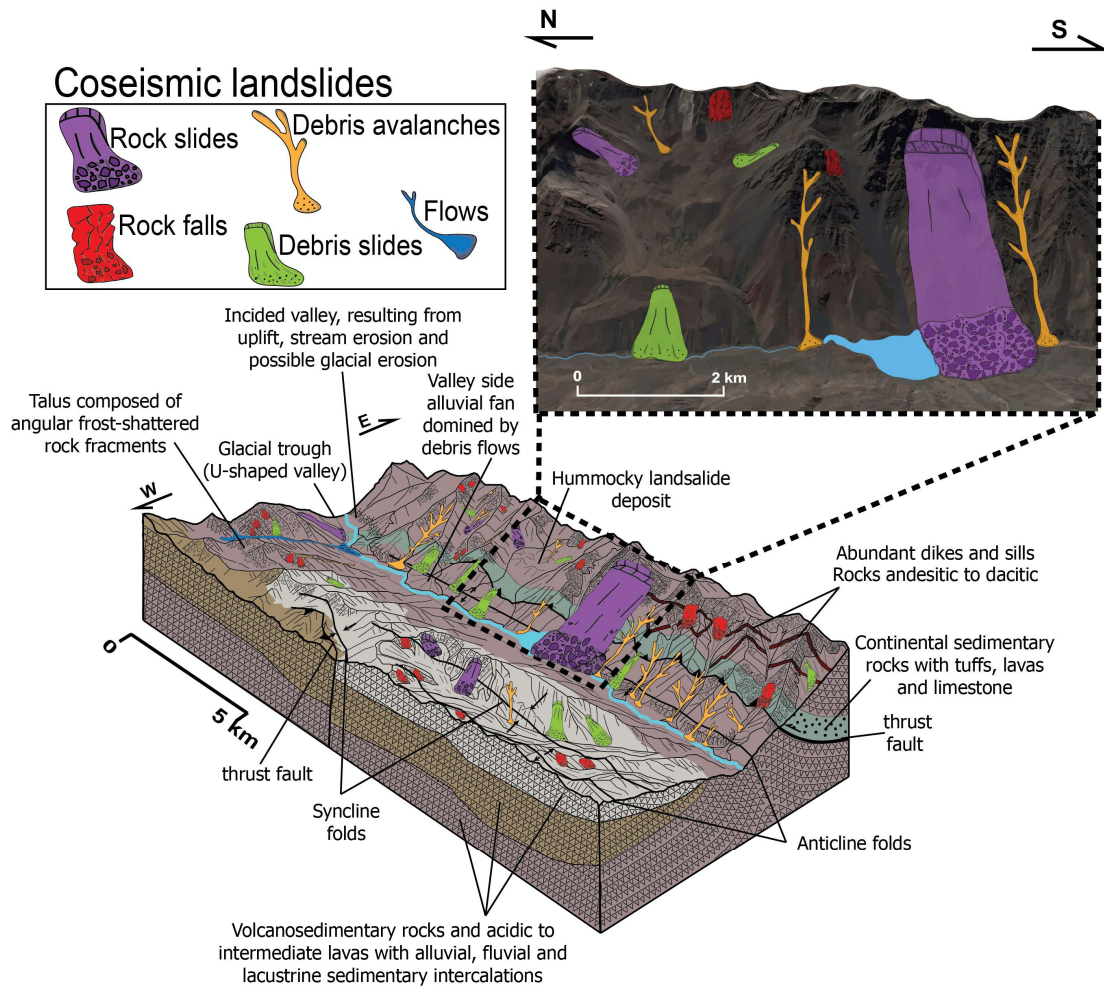


Figure 4. Glacial cordilleran environment. Conceptual geomodel of coseismic landslides induced by large interplate/subduction zone earthquake.

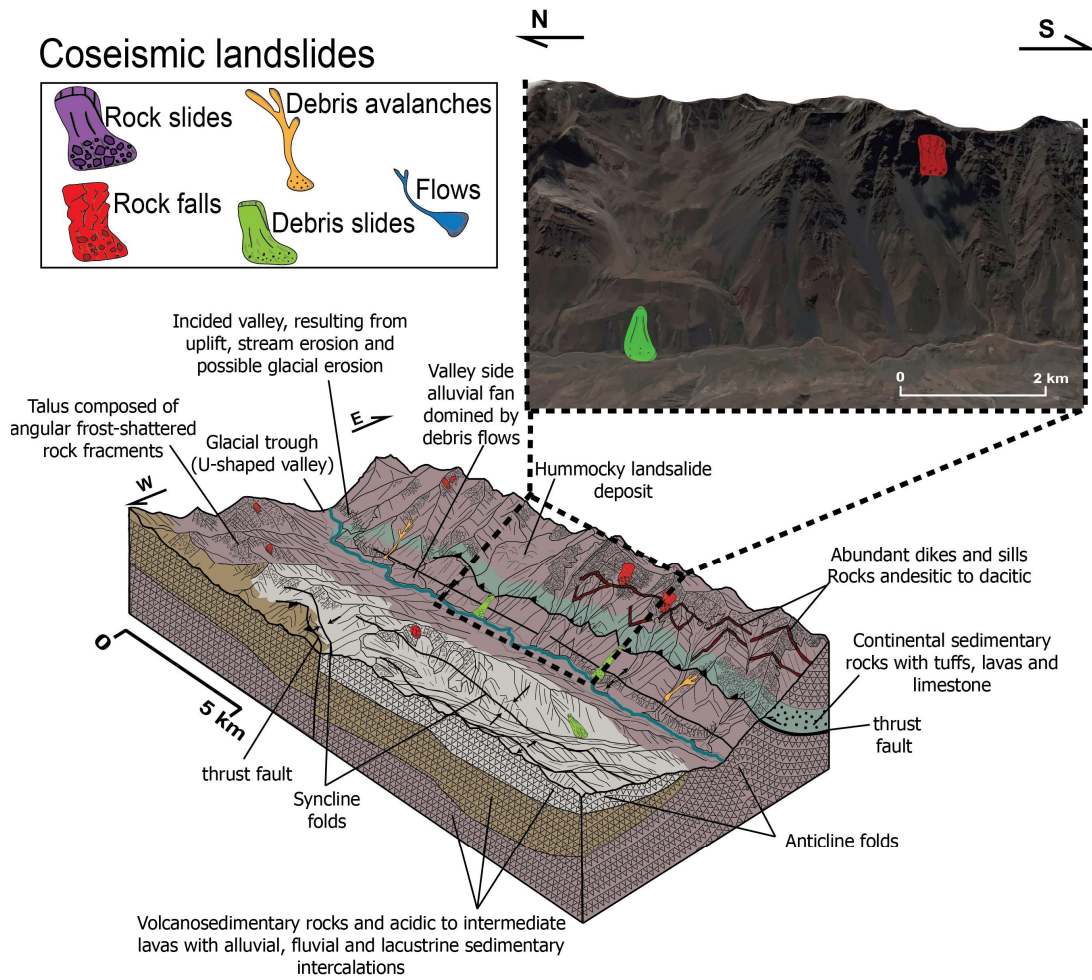


Figure 5. Fluvial cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

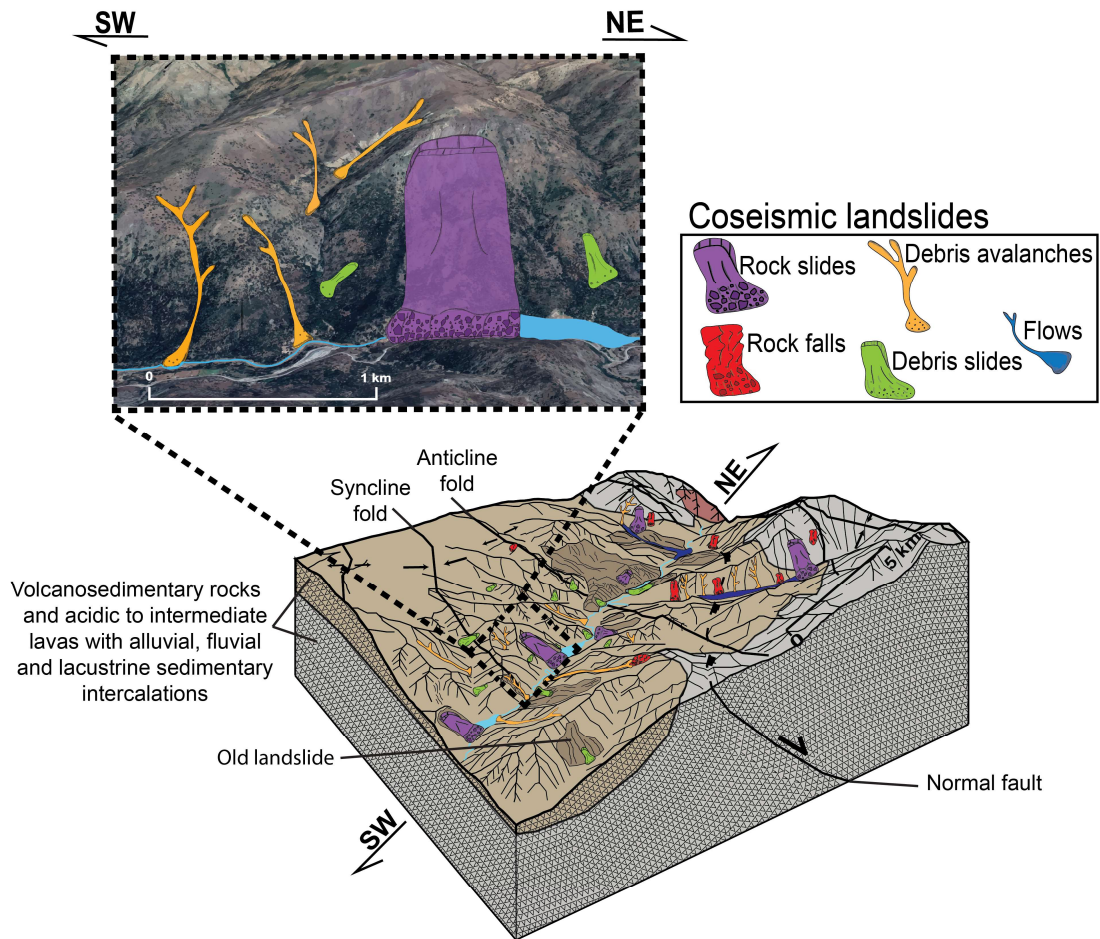


Figure 6. Fluvial cordilleran environment. Conceptual geomodel of coseismic landslides induced by large interplate/subduction zone earthquake.

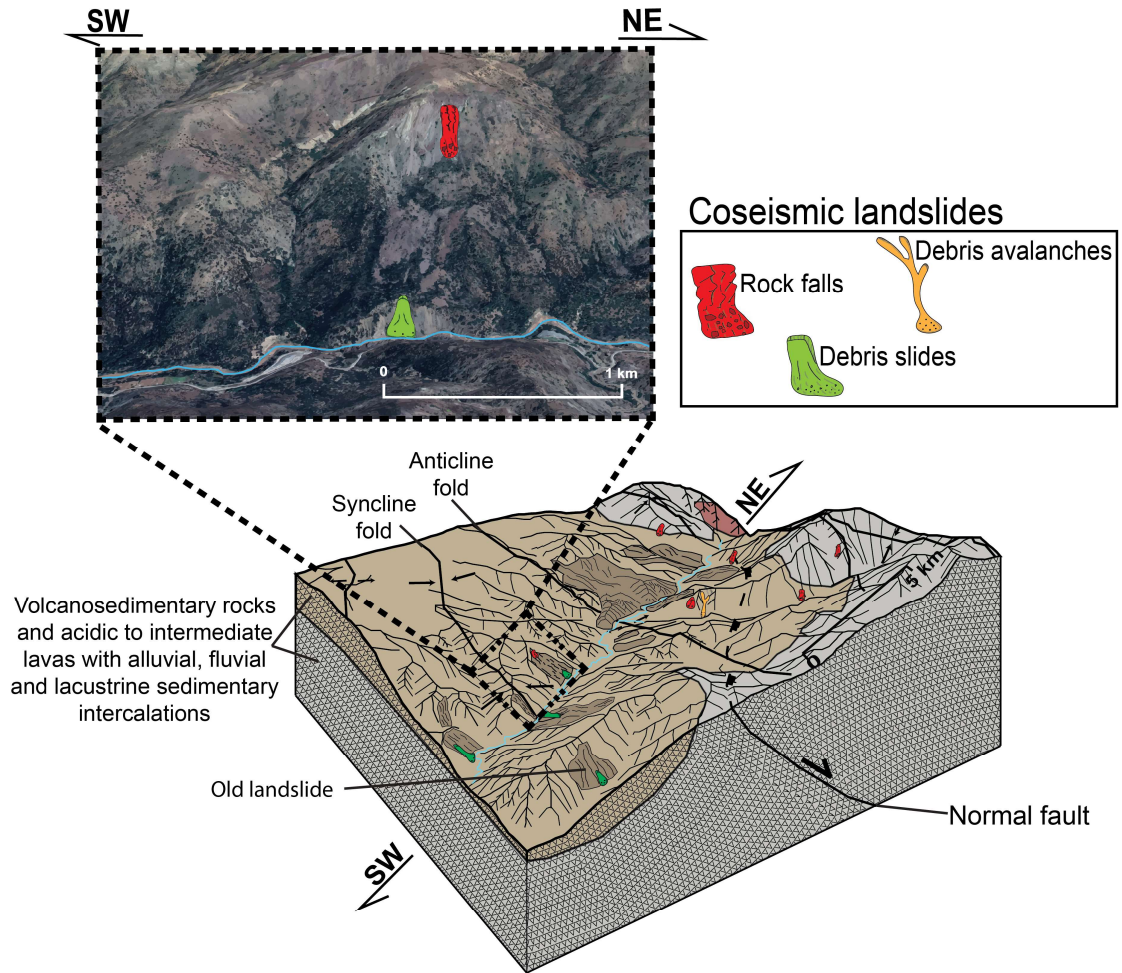


Figure 7. Plutonic cordilleran environment. Conceptual geomodel of coseismic landslides induced by shallow crustal earthquake.

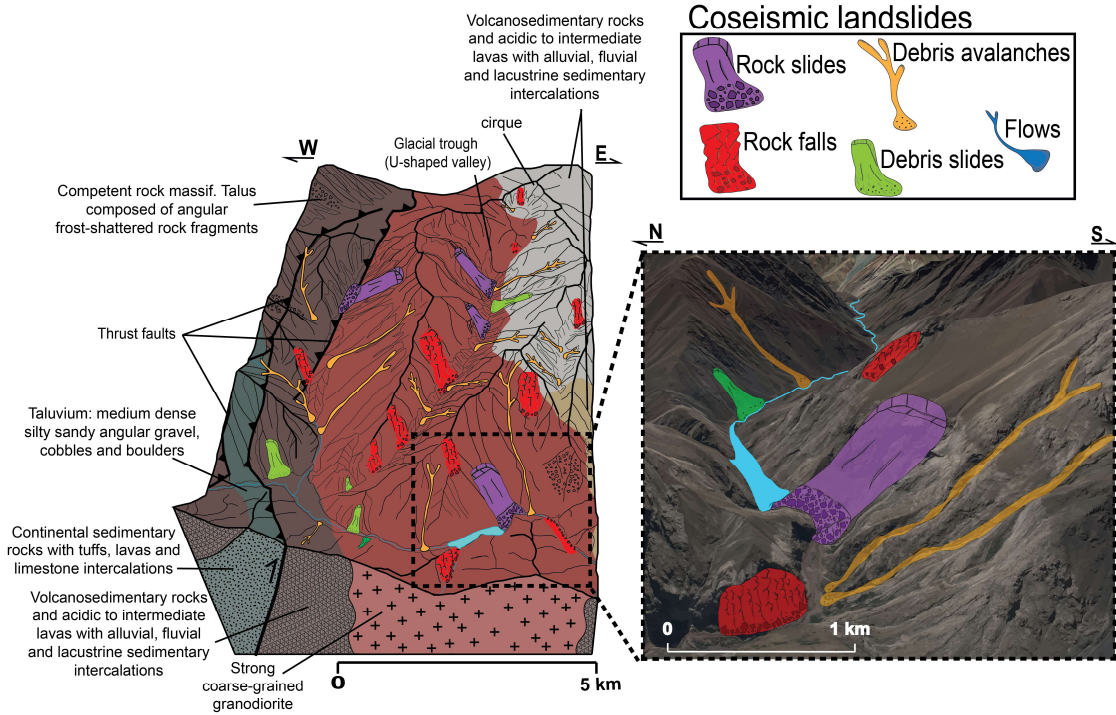


Figure 8. Plutonic cordilleran environment. Conceptual geomodel of coseismic landslides induced by subduction earthquake.

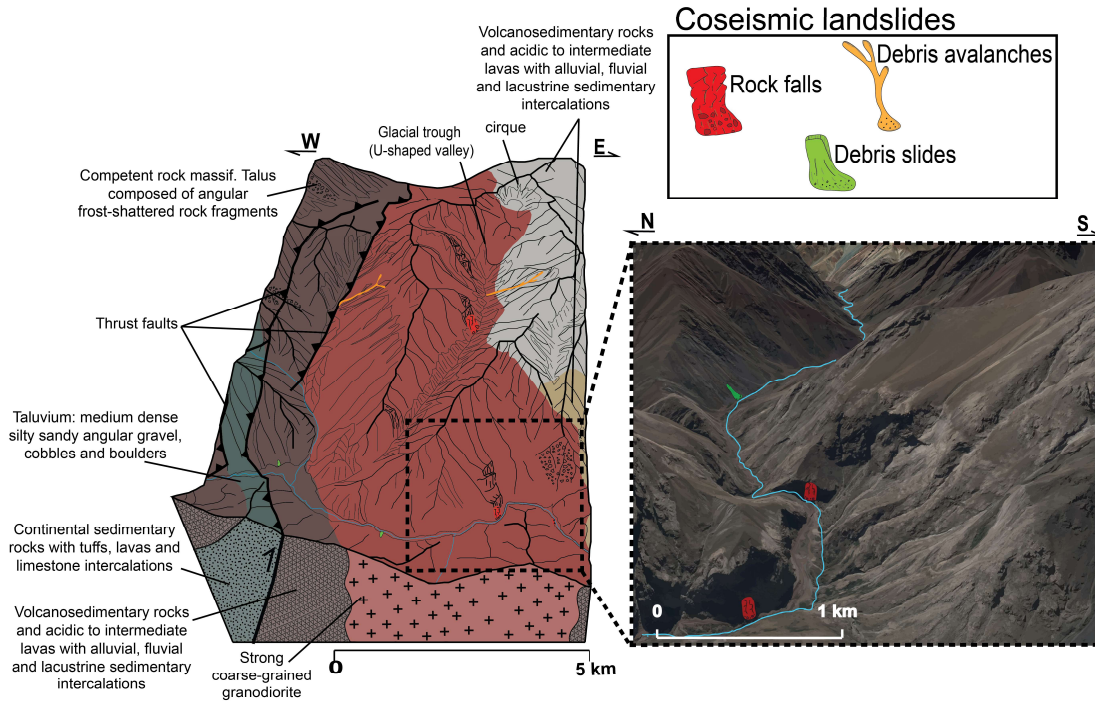


Figure 9. Mountain front bordering urban area environment. Conceptual geomodel of coseismic landslide induced by shallow crustal earthquake.

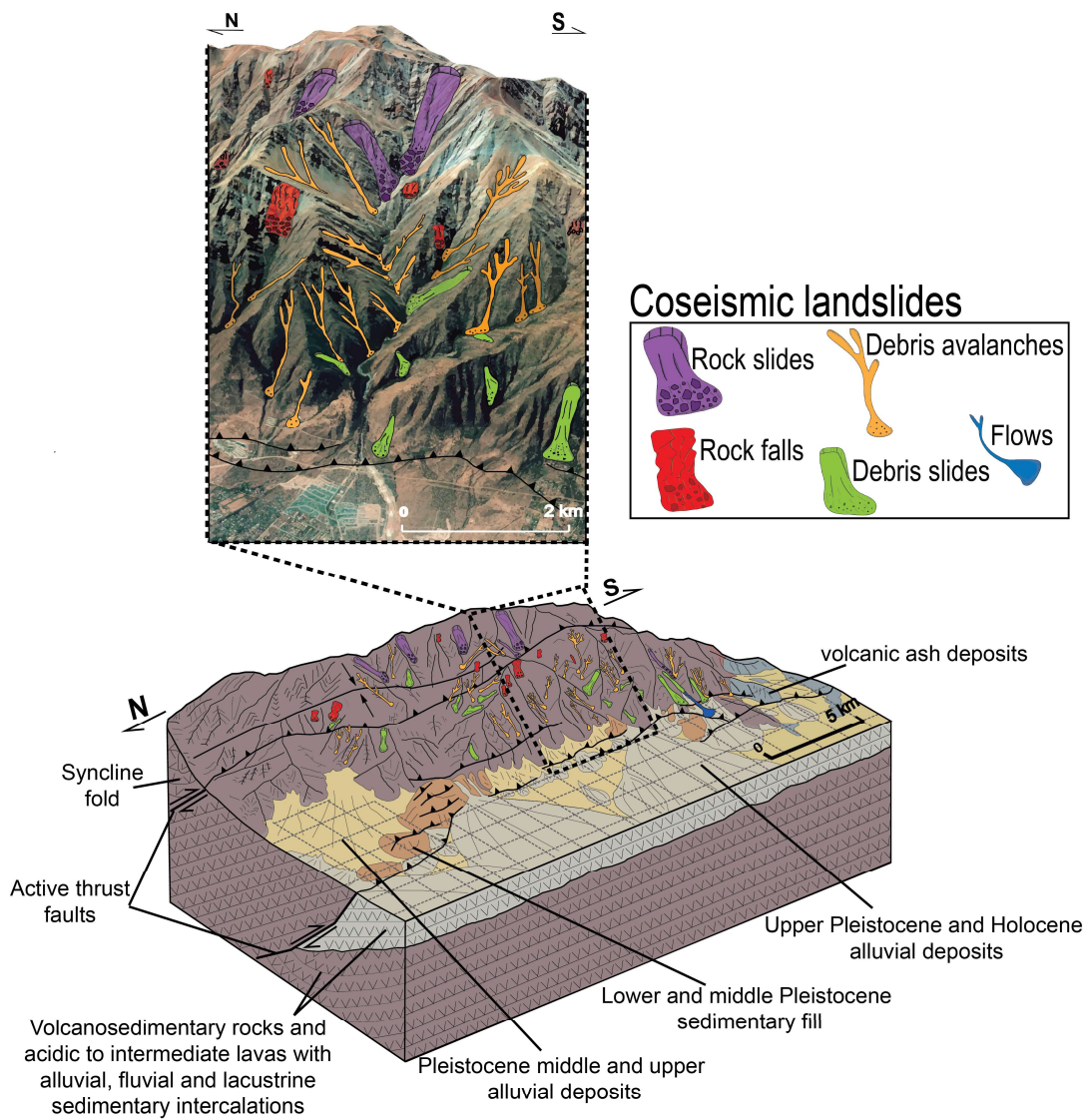


Figure 10. Mountain front bordering urban area environment. Conceptual geomodel of coseismic landslides induced by subduction earthquake.

