Susceptibility of coastal landslides and related hazards in the Chilean Patagonia: The case of Hornopirén area (42ºS)

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ABSTRACT

Coastal landslides can be a significant source of risk in fjord environments, with the potential of causing direct damage to local settlements as well as indirect damage by generation of destructive local tsunamis. Different types of landslides can be triggered either by intense rainfall or seismic activity, as it happened in the Aysén fjord in Southern Chile during the 2007 earthquake in the Liquiñe-Ofqui Fault Zone (LOFZ). In this paper we analyze the fjordland around the coastal town of Hornopirén, located along the trace of the LOFZ, using a bivariate statistical method to assess the landslide susceptibility. The results show an important degree of susceptibility to landsliding in the fjordland area around Hornopirén. This is a matter of concern for the town, the largest in the area and key for the connectivity to the Patagonia, which is potentially vulnerable to tsunamis waves that can be induced by coastal landslides. A detailed landslide-induced tsunamis hazard and risk study is highly recommended to address this potentially disastrous issue.

Key Words: Landslide, fjord, hazard, geological risk, tsunami

Susceptibilidad de Remociones en Masa Costeras y Amenazas Asociadas en la Patagonia Chilena: El Caso del Área de Hornopirén (42ºS)

RESUMEN

Las remociones en masa costeras pueden ser una importante fuente de riesgo en ambientes de fiordos, con el potencial de causar daños directos a poblaciones locales, así como daños indirectos por la generación de tsunamis locales destructores. Distintos tipos de remoción en masa pueden ser desencadenados ya sea por lluvias intensas o actividad sísmica, como ocurrió en el fiordo Aysén en el sur de Chile durante el terremoto de 2007 en la Zona de Falla Liquiñe-Ofqui (LOFZ). En este trabajo se analiza el área de fiordos cercanos al poblado costero de Hornopirén, ubicado en la traza de la LOFZ, utilizando métodos estadísticos bivariados para evaluar la susceptibilidad a la generación de remociones en masa. Los resultados muestran un grado de susceptibilidad importante en el área. Esto es fuente de preocupación para el pueblo, el más grande de la zona y clave para la conectividad hacia la Patagonia, ya que es potencialmente vulnerable a olas de tsunami que pueden ser inducidas por deslizamientos costeros. Por ello, se recomienda un estudio de amenaza y riesgos de tsunamis generados por remociones en masa en la zona.

Palabras Clave: Remoción en masa, fiordo, amenaza, riesgo geológico, tsunami

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INTRODUCTION

In fjord environments, coastal landslides may be a major issue from the perspective of geological and geomorphological hazards. Rock slides and rock avalanches triggered in the usually high and steep fjord slopes are capable of induce local tsunamis that may have devastating consequences along the fjord shores. Moreover, slides and debris flows in tributary creeks may also produce further damage to settlements along the shoreline. Areas inhabited for long time such as the Norwegian fjordland have suffered historic landslide-induced tsunamis with catastrophic consequences (HERMANNS *et al*. 2006). In this case, landslide hazard assessment, modelling and state-of-the-art monitoring schemes have been implemented to deal with the risk (BLIKRA 2008; KVELDSVIK *et al*. 2009; NORDVIK *et al*. 2010). In the case of Chile, the fjordland has only recently been settled in the last few decades and there was no documented history of such hazards, until an earthquake in 2007 (NARANJO *et al*. 2009; SEPÚLVEDA & SEREY 2009) made evident that there is an increasingly important risk related to tsunamigenic landslides, which in this case can be instantly triggered by rainfall or seismic activity, instead of the result of slow slope deformation as is the usual case in Norway.

The fjordland of the northern Chilean Patagonia (41.5º - 47.0º S, Fig. 1) presents a strong relief caused by a combination of glacial activity and tectonics. The area is located in an active tectonic environment, where the oblique subduction of the Nazca plate beneath the South American plate is accommodated by a regional strike-slip structure, the Liquiñe-Ofqui Fault Zone (LOFZ, CEMBRANO & HERVÉ 1993). The area is affected by large magnitude earthquakes triggered either by plate subduction, such as the Mw 9.5 1960 earthquake, or by sporadic shallow crustal earthquakes along the LOFZ. The latter case was not accounted for until an Mw 6.2 earthquake occurred on the 21st of April 2007 in the Aysén Fjord (45.5ºS). The earthquake triggered hundreds of landslides in the epicentral area along the fjord coast and surroundings. The largest landslides induced a tsunami that together with debris flows in tributary creeks caused ten fatalities and severely damaged several salmon farms, the most important economic activity of the area (NARANJO *et al*. 2009; SEPÚLVEDA & SEREY 2009; SEPÚLVEDA *et al*. 2010). This seismic event has configured a new situation of seismic and landslide hazard in the fjordland region, where the presence of towns and increasing infrastructure such as roads, tourist lodges and salmon farms along the coasts of several fjords, constitute a potential risk that has not been considered before. In the last few years, moderate shallow seismicity (depth less than 10 km and magnitudes up to 5.4; NÁQUIRA *et al*. 2009) associated with the LOFZ has also been detected in the Hornopirén area (42ºS), where similar geomorphological and geological conditions of the fjord coasts suggest that an event comparable to the 2007 in Aysén may occur in case of a strong earthquake, as well as with heavy rains.

In this paper, we present landslide susceptibility analyses of the Hornopirén area, using bivariate statistic techniques. These studies allow the determination of the most important conditioning factors for slope instability susceptibility in the area and a better understanding of the hazards in these geomorphological environments.

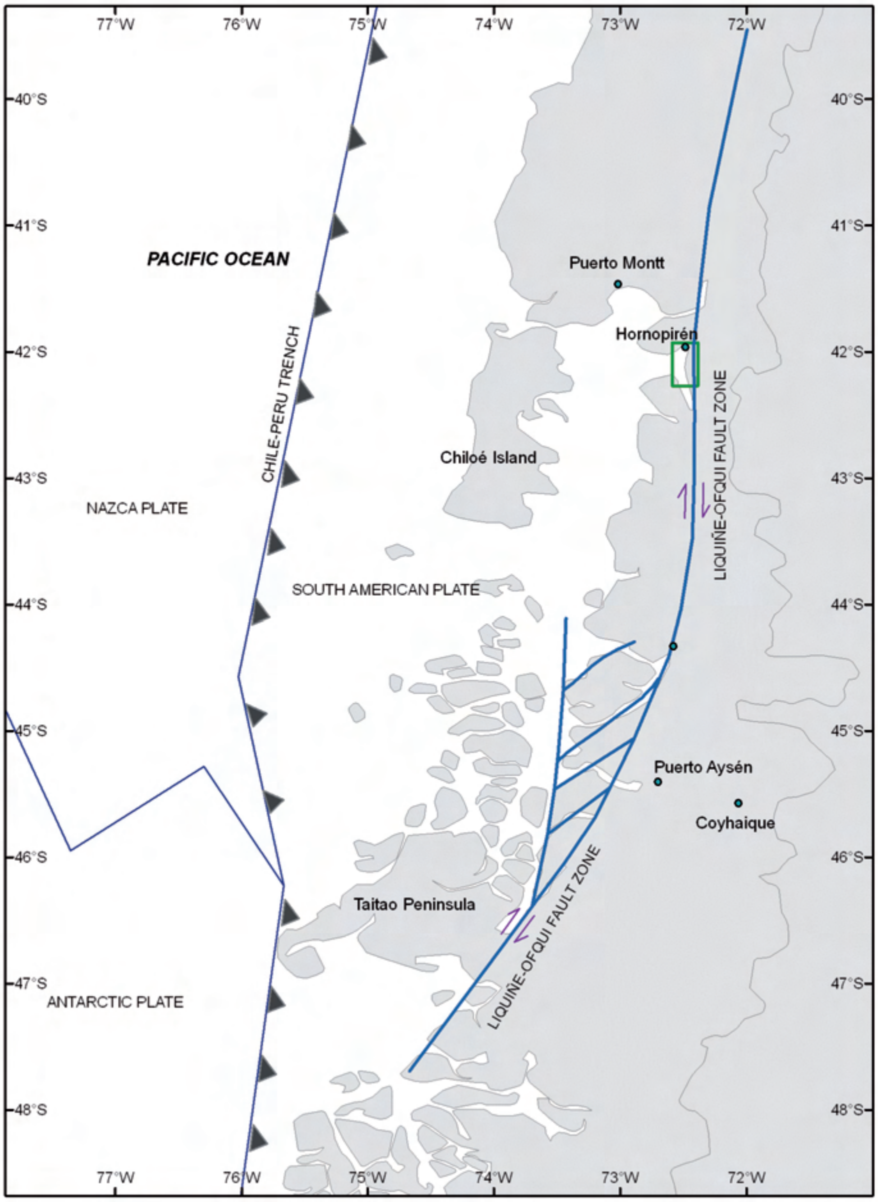

Fig. 1. Tectonic setting of southern Chile between 40º and 48º S, indicating the main trace of the Liquiñe-Ofqui Fault Zone and location of the area of study (rectangle).

Area of Study

Geological Setting

The geology of the northern Patagonia along the Andes main range is strongly dominated by the presence of the North Patagonian Batholith (NPB), composed by a series of intrusive bodies of granitoids, Jurassic to Miocene in age. Among the NPB there are outcrops of the Palaeozoic metamorphic basement, some marine Tertiary volcanosedimentary rocks and Quaternary volcanic centers with their associated deposits (SERNAGEOMIN 2003).

The most relevant tectonic structure of the region is the Liquiñe-Ofqui Fault Zone (LOFZ, Figure 1), a major NNE right-lateral strike-slip structure that accommodates the parallel component of the oblique subduction of the Nazca Plate beneath the South American Plate (CEMBRANO & HERVÉ 1993; LAVENU & CEMBRANO 1994; CEMBRANO *et al*. 2002). The coincidence of plutonic belts and recent volcanoes along the fault suggest that the structure has exerted a control on magma ascent and emplacement (CEMBRANO & HERVÉ 1993).

The climate in the region is cold and rainy, with an average annual rainfall ranging about 1,500 to 2,500 mm in the cities of Puerto Montt and Puerto Aysén, respectively (Fig. 1), although it can reach up to 4,000 mm in the fjordland west of the LOFZ. Given this large amount of rainfall, the soils are usually close to saturation and a dense rainforest covers most of the area.

Hornopirén and related fjords

The area of study is composed by a series of small fjords (locally called channels) separated by small islands. The main channels are Hornopirén and Cholgo, of NS to NNE trend, which are connected by the Llancahué channel (Fig. 2). The southern limit of the study area is the northern end of Comau channel, which continues further south with a north-south trend. A smaller east-west trending fjord called Quintumpeu is also included in the study area (Fig. 2). The Hornopirén, Cholgo and Comau fjords coincide with the regional trace of the LOFZ (Fig. 1). The town of Hornopirén is located on an alluvial plain at the northern shore of the Hornopirén channel.

The fjord slopes are steep (>30º) and rise over 1,000 m, while the islands in between the channels (Pelada and Llancahué) have a smoother relief. The geology of the coastline (Fig. 2) is mainly composed of intrusive rocks of the NPB and Palaeozoic metamorphic rocks (LEVI *et al*. 1966; NÁQUIRA 2009). The Cholgo channel and Quintumpeu fjord slopes and most of the Llancahué Island are mainly composed by monzodioritic granitoids and gneisses, while the western Hornopirén channel slope is composed of a dioritic to tonalitic porphyry. The western slopes of Pelada and Llancahué islands are dominated by schists of the metamorphic basement. North of the town is located the Hornopirén volcano, with no recent activity.

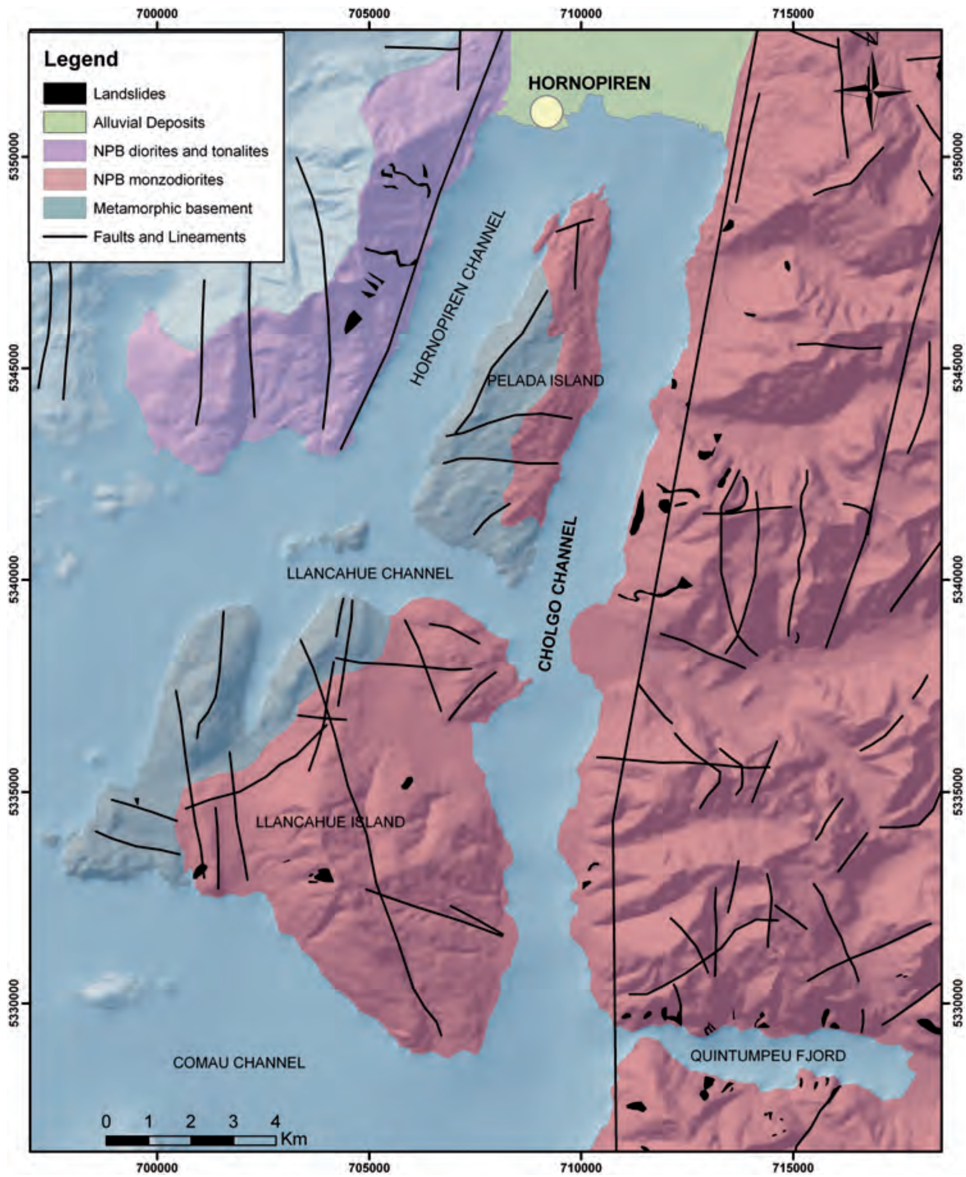

Fig. 2. Shaded relief map showing the geology and location of landslides in the Hornopirén study area.

The main trace of the LOFZ roughly coincides with the Cholgo channel east shoreline, following a NNE trend. Foliation planes on the granitoids have a NNW to NS strike and can be related with movement of the fault (Cembrano et al. 2002; LANGE *et al*. 2008; NÁQUIRA 2009). A series of NS-NNE, NW, NE and EW lineaments can be observed from photointerpretation of the local geomorphology (NÁQUIRA 2009; NÁQUIRA *et al*. 2009).

MATERIALS AND METHODS

Mass movements susceptibility analysis intends to predict terrain locations where future events will occur (SOETERS & VAN

WESTEN 1996). In general, it is based on the assumption that previous events are related and controlled by a certain number of conditioning factors. Thus, combination of selected terrain and land use parameters are commonly used in many different approaches, from heuristic to probabilistic, to assess terrain susceptibility to be affected by landslide processes (ALEOTTI & CHOWDHURY 1999).

In this study it was selected to use the bivariate statistical assessment technique (CASTRO & OJEDA 2001; ARENAS *et al*. 2008), as developed by NÁQUIRA (2009) and NÁQUIRA *et al*. (2009). Basically the method combines in various steps intrinsic terrain variables (factor maps) with the landslide inventory (evidence map). Controlling factor maps, previously divided into different "contribution classes", are combined separately with the landslide inventory. The results of each combination are finally added to obtain a weight map which is afterwards reclassified into three levels of susceptibility.

During the first step, terrain factors were selected according to their contribution to landslide susceptibility. These studied factors are lithology; slope gradient; slope aspect; mean curvature; drainage and lineament densities; distance to lineaments and faults; and normalized distance to slope ridge. The latter corresponds to the ratio between the distance from landslide crest to slope ridge and the total length of the slope, which is related to topographic amplification of seismic waves, a usual controlling factor of earthquake-induced landslides (MEUNIER *et al*. 2008; SEREY 2011). On the other hand, the evidence landslide map records all different types of mass movements, including rock falls and/or rock slides, shallow rock-soil slides, soil slides and debris flows, as classified by NÁQUIRA (2009).

During the second step a relative landslide density value is calculated for every class of each factor map. The process is developed separately for each factor map and each landslide type. Thus, density value corresponds to the contributing weight of a certain "class-factor" to landslide susceptibility. This calculation compares landslide density of each class with landslide density of the entire study area normalizing in this way the weight values.

During the next step a susceptibility map was generated by adding the weight values maps. Classification into three different susceptibility classes is the last step in the process. The classes are defined by analyzing the spatial correlation between the number of "landslide pixels" in the evidence map and higher susceptibility values. A success ratio is calculated by this mean, which gives information about how good, or bad, the method has recognized the evidence. The better the combination of factor maps the higher the matching of landslide pixels with highest susceptibility values.

RESULTS

Landslide inventory

A total of 72 mass movements were recognized in the Hornopirén area (Fig. 2). The landslides are significantly smaller than those observed in the Aysén fjord in 2007, with mapped surface areas ranging from 1,000 to 155,000 m^2. The failures are concentrated in high and steep slopes, with the highest landslide density in the Quintumpeu fjord, while smooth relief areas such as the Pelada and Llancahué islands have much less concentration. The failures were classified by NÁQUIRA (2009) as rock falls and slides (with a total of 39), rock-soil slides (17), soil slides (13) and debris flows (3). Some examples are shown in Figure 3.

Fig. 3. Examples of some of the largest rock slides and rock falls along the coastal slopes of Quintumpeu fjord (top) and Llancahué island (bottom).

Susceptibility map

The landslide susceptibility map prepared for the total of landslides is shown in figure 4. The flat alluvial plain where the town is located was not included in the analysis. Classification into three hazard classes was made using success ratio (Fig 5). In this case, the highest 25% of weight values were considered as high hazard, which includes 63% of landslide areas (equivalent to the number of “landslides” pixels in evidence map). Moderate and low hazard classes were defined in such a way that 22% and 15% of the observed landslides were included in each class respectively.

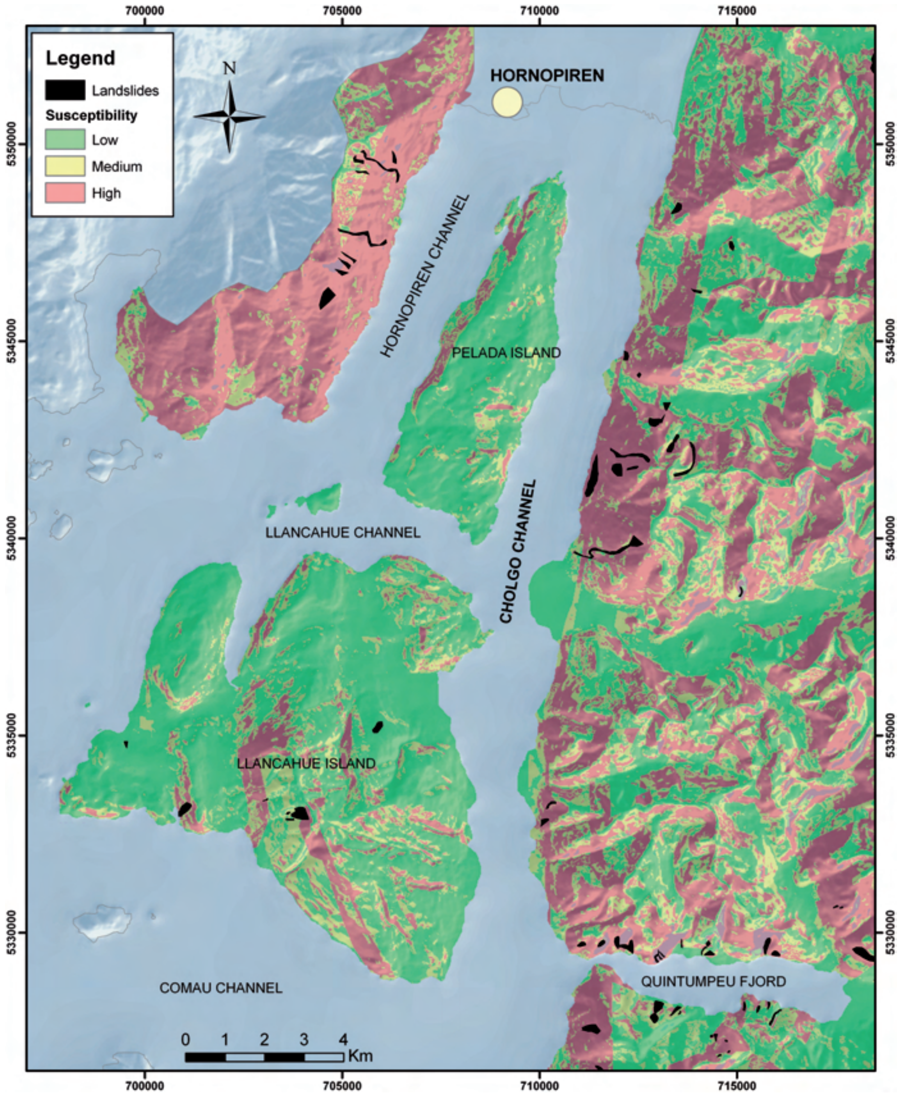

Fig. 4. Landslide susceptibility map of the study area.

High susceptibility values are found in the western slope of the Hornopirén channel; most of the eastern slopes of the Cholgo channel; the northern slope of Quintumpeu fjord; slopes of interior valleys; and, very locally, in the islands. Medium susceptibility zones generally surround the areas of high susceptibility. High susceptibility areas seem to be controlled by the influence of lithology (Hornopirén channel), distance to faults and lineaments, and slope (Cholgo channel and interior valleys). Fault density and slope aspect also contribute with relatively high weight values. On contrary, the normalized distance to slope crest was not found to be among the factors with highest weights. Preliminary maps made for individual landslide types (NÁQUIRA 2009) show that landslides susceptibility of the slopes at Hornopirén channel are mainly related to the occurrences of shallow soil and rock-soil slides, while the slopes at Cholgo channel are more prone to rock falls and slides. Slopes instabilities at Quintumpeu fjord are susceptible to all types of slides.

Fig. 5. Success ratio chart showing the predictive capacity of the statistical method when compared with the observed landslides (evidences). The high susceptibility (25% of higher values) areas correlate with 63% of the total mapped landslides.

DISCUSSION AND FINAL REMARKS

The results show an important degree of susceptibility to landsliding in the fjordland area around Hornopirén. The steep and high slopes, typical of a glacial morphology, in combination with the presence of geological faults are favourable to the triggering of landslides, induced either by rainfall or seismic activity. However, as many parameters can be considered for this kind of susceptibility analysis, the conclusions obtained from the results can only be applied to a specific area, and should not been extended to other regions, unless a rigorous previous analysis allows extrapolation (ALEOTTI & CHOWDHURY 1999). Furthermore, it must be emphasized that in many cases the analyzed factors are not truly independent and may have a low or high correlation between them (LEROI 1996).

In the studied case, the results show that the factor of normalized distance to slope crest has no major weight on landslide susceptibility, as it was found for the case of the Aysén fjord by different means (SEREY 2011; SEPÚLVEDA *et al*. 2010). Further, high weight values are found from the slope base to slope top depending on the type of slide (NÁQUIRA 2009), showing that the seismic factor is not well registered in the area. This coincides with the fact that only a couple of failures occurred during the last seismic swarm in 2008. We can conclude that most of the observed landslides in this area are most probably induced by rainfall. However, the high susceptibility found in the fjord coastal slopes imply anyway a hazard of landsliding in case of a major seismic event, which can be related to a close and local shallow earthquake in the Liquiñe-Ofqui fault, to major subduction earthquakes such as the 1960 event or even to volcanic activity in the nearby Yates and Hornopirén volcanoes, located north of the town (Fig. 6).

Fig. 6. Photograph of the town of Hornopirén, showing its vulnerable location for tsunami hazards. Behind the town is the Hornopirén volcano.

The high landslide susceptibility found around the study area is a matter of concern for the town of Hornopirén, which is potentially vulnerable to tsunami waves that can be induced by coastal landslides (Fig. 6), as happened in the Aysén fjord in 2007. The town has over 1,000 inhabitants and a floating tourist population, and is located on a key situation for land and sea transportation for the local fjordland community and to the Patagonia further south. The severity of such tsunami would largely depend on the landslide volume and location, as the islands may act as a shield in some cases. A detailed landslide-induced tsunami hazard and risk study is highly recommended to address this potentially disastrous issue.

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