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On 21 April 2007, an M_w 6.2 earthquake produced an unforeseen chain of events in the Aysén fjord (Chilean Patagonia, 45.5°S). The earthquake triggered hundreds of subaerial landslides along the fjord flanks. Some of the landslides eventually involved a subaqueous component that, in turn, generated a series of displacement waves—tsunami-like waves produced by the fast entry of a subaerial landmass into a water body—within the fjord [Naranjo *et al.*, 2009; Sepúlveda and Serey, 2009; Hermanns *et al.*, 2013]. These waves, with run-ups several meters high along the shoreline, caused 10 fatalities. In addition, they severely damaged salmon farms, which constitute the main economic activity in the region, setting free millions of cultivated salmon with still unknown ecological consequences.

Since then, scientists with a number of research projects by different institutions have visited the fjord, aiming to understand the geological processes that favored and eventually triggered the slope failures and subsequent waves. The goals of this research effort have been to improve geohazard assessments in the fjord and to apply knowledge gained to other fjords as well as to landslide-prone semi-enclosed basins such as bays, lakes, and reservoirs, which often host large human populations and high-value assets. The most recent of the research projects in Aysén fjord is Tsunamigenic Landslides in Aysén Fjord (DETSUFA). The project, led by the University of Barcelona, included a cruise onboard *BIO Hespérides* in March 2013 that mapped with unprecedented detail the morphology of the impact structures created by the landslides in the fjord floor (Figure 1).

Early Studies: A Focus on Subaerial Landslides

Shortly after the 2007 earthquake and landslide crisis, which occurred in a seismically active region with modern faulting and volcanism [Legrand *et al.*, 2011], the first scientific efforts by Servicio Nacional de Geología y Minería and the University of Chile focused on its subaerial consequences [Naranjo *et al.*, 2009; Sepúlveda and Serey, 2009]. Field reconnaissance carried out a few days after the main shock and analyses of aerial photographs taken before and after the event led to the identification of a total of 538 landslides. These were mapped in greater

detail during new field surveys in 2008 and 2009 [Sepúlveda *et al.*, 2010].

Those studies found that landslides preferentially occurred on the glacially oversteepened granitic slopes of the North Patagonian Batholith facing Aysén fjord and nearby valleys. The landslides mainly affected the soil layer, which is volcanic in nature, although some also occurred in highly fractured basement rock. The highest displacement wave-generating landslides were a rockslide in front of Isla Mentirosa and a debris avalanche in Punta Cola, with volumes initially estimated at 8 and 12 million cubic meters, respectively [Sepúlveda *et al.*, 2010].

Subsequent subaerial studies focused on the Punta Cola debris avalanche [Yugsi-Molina *et al.*, 2012; Oppikofer *et al.*, 2012] (Figure 1). This complex, multi-phased landslide originated on a northwest-facing, 220- to 750-meter-high slope within the Punta Cola valley, less than 2 kilometers from the shoreline. Detailed studies conducted on land led by Norges geologiske undersøkelse (NGU) established that the initial rockslide had a volume of 20.9 million cubic meters. In addition, 7.3 million cubic meters of soil and rock from the valley fill were incorporated into the debris avalanche. Approximately half of the volume of this material was deposited onshore; the rest entered the fjord. The debris avalanche involved a shoreline retreat of

100 meters, probably indicating that it induced the destabilization of the deltaic deposits at the end of the Punta Cola valley and incorporated them into the landslide.

Research Cruises Examine Effects on Fjord Floor

Two research cruises explored the footprint of the 2007 events on the fjord floor. A cruise by the Renard Centre of Marine Geology (Ghent University) onboard *R/V Don Este* in December 2009 preceded the March 2013 DETSUFA cruise. During these two cruises, a variety of geophysical data (multibeam bathymetry, parametric sub-bottom profiles, and sparker and air gun seismic reflection data) and sediment cores were obtained.

These data demonstrate that subaerial landslides entering the fjord propagated offshore and triggered large-scale deformation of the fjord floor sediment and that the earthquake triggered other submarine mass movements that were previously undetected [Van Daele *et al.*, 2013]. The fjord floor deformation consists of proximal depressions surrounded by fold and thrust belts, as has also been observed in Lake Lucerne, Switzerland [Schnellmann *et al.*, 2005].

In addition, the observations suggest that subaerial and submarine debris descended and accelerated along well-identified 5° to 10° sloping ramps on the fjord flanks down to the fjord floor at 200 meters water depth. The impact of the debris generated large, 1- to 10-meter-deep depressions at the foot of the ramps. The sediment removed from these depressions moved radially and piled up,

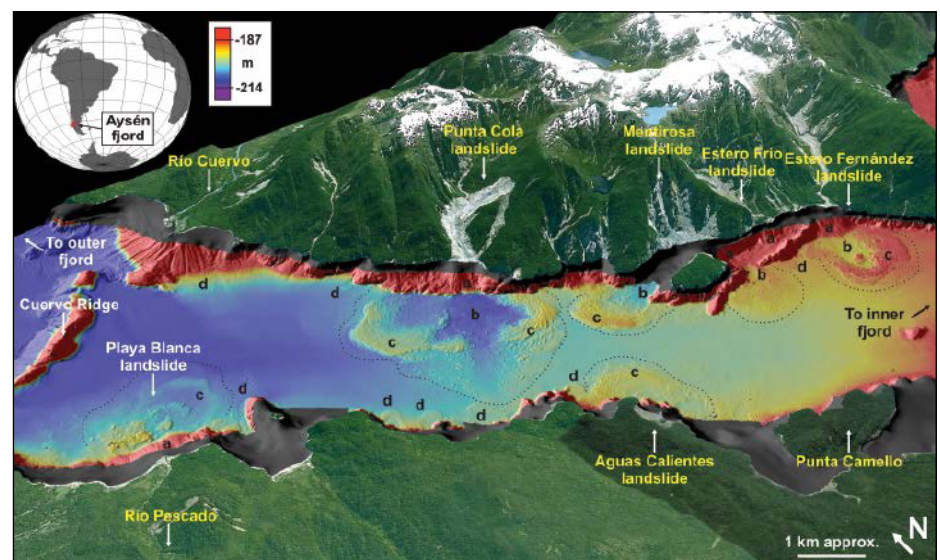


Fig. 1. Three-dimensional view of the Aysén fjord section affected by the 2007 earthquake-generated landslides. Bathymetric data obtained during the Tsunamigenic Landslides in Aysén Fjord (DETSUFA) survey show six large (Punta Cola, Mentirosa, Estero Fernández, Estero Frio, Aguas Calientes, and Playa Blanca) and several minor deformation structures formed by subaerial and submarine landslides: a, ramps; b, depressions at the foot of the ramp; c, compression ridge structures; d, minor landslides. Scale bar is approximate. Satellite data are from Google Earth™.

forming concentric compressional ridges up to 15 meters in height and a narrow frontal depression.

The DETSUFA cruise mapped with great detail the shape of six large and several minor impact and deformation structures along 15 kilometers of the middle fjord floor (Figure 1). In addition to the most apparent ones, created by the Punta Cola and Mentirosa landslides, data from the cruise show that large structures also appear off Aguas Calientes, Estero Fernández, Estero Frío, and Playa Blanca. The impact of the landslide in Punta Cola was energetic enough to break through the deformed sediment pile, producing large rock blocks likely coated with sediment, which extend to 3.5 kilometers from the shoreline (Figure 1). The Playa Blanca landslide was entirely submarine, like other minor landslides affecting the submerged fjord flanks.

Results Could Improve Modeling of Tsunami and Displacement Waves

The combined results from all of these studies show that the large destructive waves were likely generated by the concurrent effects of the entry of subaerial landslides into the water body, the subaqueous destabilization of the fjord flanks linked to coastline retreat, and the sudden generation of the compressional ridges, which implied a vertical displacement of the fjord floor of up to 15 meters. The subaerial and submarine observations made in Aysén fjord should

result in improved modeling of tsunami and displacement waves that could be applied to other fjords and semi-enclosed basins.

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