Mass wasting and earthquakes – unexpected interrelations offshore Central Chile

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Submarine landslides are an important but underestimated geological hazard that can generate destructive tsunamis and devastate populated shorelines. Based on a unique bathymetric dataset that covers ~ 90% of the Chilean continental margin between 33°S and 42°S, more than 60 submarine landslides were identified. The obtained database encompasses a wide spectrum of events, different in terms of failure mechanism, shape and size. The largest failure occurred in Pleistocene and mobilized 472 km³ of slope material, enough to cover Schleswig-Holstein with ~30 meters of debris. Rock material was dumped in the Chile Trench, where it forms a body of 1-2 km thickness. A fraction of this material has been subducted and now is sandwiched between the down-going Nazca, and the overriding South American Plates. The inhomogeneous nature of the subducted slide material changes the frictional properties of the plate interface, apparently generating a mechanical barrier for the propagation of earthquake rupture. This is the first indication of how mass wasting processes affect the seismological behavior of a convergent margin. The reverse causal relation, the triggering of mass wasting by earthquakes is often suspected. The Maule Earthquake of 2010 gave us the opportunity to investigate the impact of a megathrust earthquake on continental slope stability. We re-mapped the rupture area to investigate changes in the slope morphology quantitatively. Contrary to our expectations, this large seismic trigger did not result in major submarine slope failure.

Detailed acoustic scans of the seafloor have been acquired during 16 successive cruises led by scientist from the IFM-Geomar. This effort resulted in one of the best high-resolution bathymetric datasets of a continental margin worldwide. We used the dataset to create seafllor maps, determine gradients and spatial extent of submarine landslides and calculate displaced rock volumes. One of the highlights of the dataset is the availability of bathymetric data acquired prior to and shortly after the Maule earthquake of the 27 February 2010, the sixth largest ever recorded earthquake (Magnitude 8.8), allowing to investigate seafloor deformation related to the event.

In total, 62 submarine landslides were mapped with extents between 1 and 1,285 km². Roughly, 5.7% of the continental slope is affected, but within certain slope sectors this value increases significantly; in particular the zone off Arauco Peninsula (between 37°S and 38°S) stands out with 31% of failed slope (Figure 1). Based on type of morphology and area of occurrence, we distinguish four basic

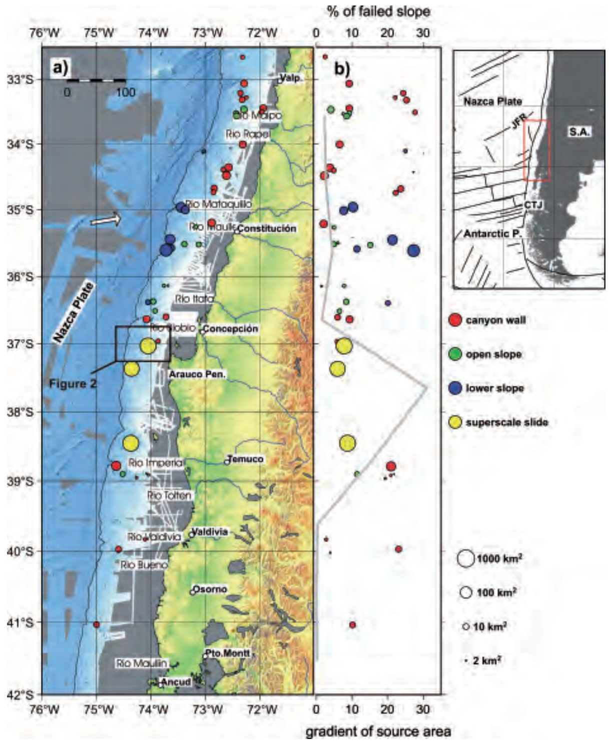

Figure 1: Bathymetric map of the working area, from a compilation of bathymetric cruises. The centers of submarine landslides are indicated as points (red = canyon wall collapses, blue = failures of lowermost slope, green = open slope failures, yellow = superscale failures) The outline of Fig. 2 is indicated as a box. (b) Spatial distribution of submarine landslides along the continental slope of Central Chile and distribution with slope gradient. Size of symbols is log-scaled to the total affected area. The percentage of areas affected by slides in latitudinal segments of 1° is given as curve

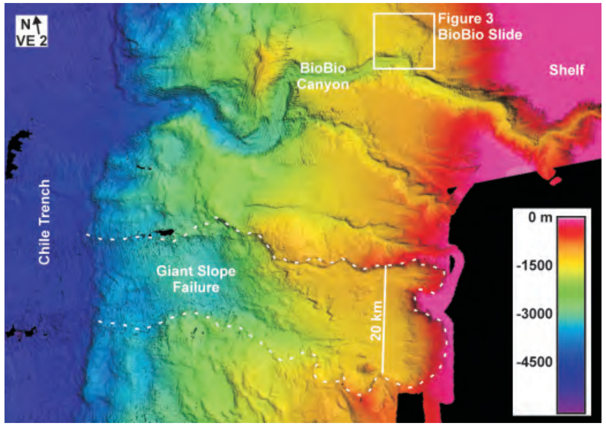

Figure 2: Giant submarine slide offshore Arauco Peninsula, stretching from the Chile Trench at 4800 m water depth to the shelf edge at 400 m water depth. Sidewalls are up to 500 m high. The BioBio Canyon, like all major submarine canyon systems is bordered by translational slides like the BioBio Slide, shown in Figure 3.

groups of sediment failure: (1) failure related to submarine canyons, (2) failure on open slopes, (3) failure affecting the lowermost continental margin and (4) failure at the scale of the entire slope (Völker et al., 2012). The spatial occurrence of lower slope collapses and failures that affect the entire slope are related to the tectonic segmentation of the forearc.

Half of the slope failures are related to seven major submarine canyons that incise the continental slope. Parasound data collected during R/V Sonne Cruise 210 in 2011 demonstrated that the canyon incision destabilizes large adjoining areas (Völker et al., 2012).

Among the lowermost slope collapse features, the Reloca Slide is the most noticeable because of its size and spectacular bathymetric expression. The displaced rocks are preserved as prominent blocks in the Chile Trench. The lower continental slope facing Reloca Slide is steep (20–30°), and forms a straight ramp of 2,000 m elevation. The blocks are angular, and together make up roughly 90% of the material that is missing at the slope scar. This completeness of the cohesive blocks as well as the drop height and the short runout distance are indicative of a fast event which makes Reloca Slide a tsunamogenic slide in spite of the large water depth (Völker et al., 2011).

Offshore Arauco Peninsula (Fig. 1), three very large slope indentations ranging in areal extent between 924 – 1285 km^2 shape the continental slope down to the abyssal plain and change the seismic reflection pattern of the sedimentary trench fill (Geersen et al. 2011a). Seismic images of the trench fill show chaotic deposits, commonly attributed to rapid deposition by mass wasting in front of the slope embayments. This is in marked contrast to the well-stratified trench fill elsewhere. Two of the failures define a significant landward retreat of the shelf break (Figure 2). The volume of material missing at the slope is in the order of 300–500 km^3 for each of the three slides.. Submarine mass wasting in this area is linked to the local tectonic regime, where continuous uplift of the forearc results in steep slope gradients. The recurrence time of the three giant slides is about 200,000 years.

Apart from their geohazard, the large submarine slides are interesting as they appear to affect the seismotectonic regime of Southern Chile. Deep underthrusting of the inhomogeneous slide deposits along with the downgoing Nazca Plate may play an instrumental role in arresting earthquake ruptures. One of the subducted giant slides is located at the boundary of the coseismic ruptures of the 1960 Great Chile and the 2010 Maule earthquakes (Geersen et al., 2011b). The slip zone of megathrust earthquakes must be thin and continuous to allow the fast propagation of coseismic slip over distances of hundreds of kilometers. This condition is likely given within the rupture areas of the 2010 Maule and the 1960 Great Chile earthquakes, because there the underthrust trench sediment is well stratified. In contrast, the underthrust slide material is highly inhomogeneous in terms of structure and physical properties. This results in the absence of continuous weak layers parallel to the plate boundary megathrust, and prevents development of a continuous slip zone that is required for earthquake rupture propagation.

No newly formed slides were found in the rupture area of the 2010 Maule Earthquake, the 6^{th} largest ever instrumentally recorded earthquake, although a number of older failures were identified (Völker et al., 2011, Figure 3). The absence of new mass wasting is particularly remarkable, as the slope gradient is steeper than 20°. Among the few cases, where mass wasting was studied after an earthquake, we find tsunamogenic landslides (like the Papua New-Guinea event of 1998), as well as the absence of landslides, just like in Chile. Obviously the impact of a

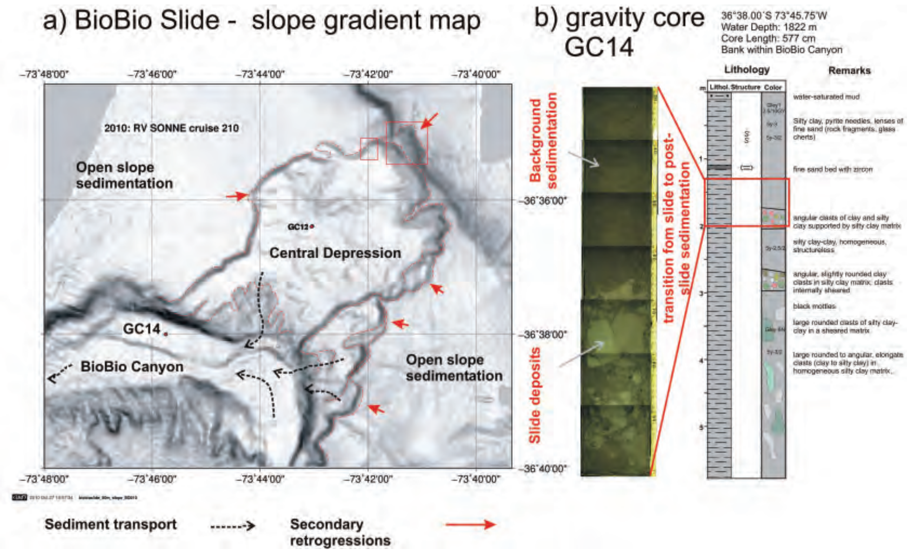

Figure 3: a) Detail gradient map of BioBio Slide and adjacent BioBio Canyon with coring locations of SONNE cruise SO210. BioBio Slide is a depression of 29 km² extent that is 55–160 m deep in relation to the surrounding sea floor, opening to the deeply incised BioBio Canyon.The steep head- and sidewalls indented by smaller and less deep, partly overlapping retrogressions. Within the canyon, a flat-topped terrace forms a depositional feature on top of which gravity core GC14 was taken. b) Core photo mosaic and description for GC14 , showing the transition from the youngest, ~7000 year old mass wasting deposit from the BioBio Slide area to background sedimentation.

seismic source on the slope stability is limited by factors such as sediment supply, distribution and rheology. In contrast to popular hypotheses, we contend that the frequent recurrence of earthquakes at convergent continental margins does not necessarily pose a particular risk of landslide-generated tsunamis. As landslides of much larger volume and tsunamogenic potential are observed at seismically more stable passive margins, it seems that the frequent shaking at active margins shifts the size spectrum of submarine slide events towards smaller scales.

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