Chapter 34
Submarine Mass Wasting Off Southern Central Chile: Distribution and Possible Mechanisms of Slope Failure at an Active Continental Margin

David Völker, Jacob Geersen, Jan H. Behrmann, and Willhelm R. Weinrebe

Abstract Around 5–6% of the convergent continental margin of Southern Central Chile (33–42°S) is shaped by a variety of submarine mass wasting processes. We use swath bathymetric data covering >90% of the continental slope to map and investigate mass wasting-related seafloor features. In total, 62 submarine landslides are found that we separate into four categories (slides related to canyons, slides on open slopes, lower slope collapses and giant slope failures) with different failure mechanisms, preconditioning factors and time scales.

Keywords Submarine landslide • Mass-failure • Mass-transport • Slope failure Active continental margin

34.1 Introduction

With increasing coverage of submarine slopes by swath bathymetry echosounder data, the importance of downslope transport processes for shaping the seafloor becomes evident. Along with the increase in the number of described submarine slides, the knowledge of their variability in size, shape and internal deformation improves. The background relative to slope failure at convergent continental margins is fundamentally different from that of passive continental margins, because: (1) uplift and slope oversteepening are caused by frontal and basal sediment accretion, subduction erosion or seamount subduction; (2) megathrust earthquakes occur with a

D. Völker (✉) • J. Geersen • J.H. Behrmann • W.R. Weinrebe
SFB574, IFM-GEOMAR Leibniz Institute for Marine Sciences,
University of Kiel, Wischhofstr. 1-3, Kiel, Germany
e-mail: dvoelker@ifm-geomar.de

Y. Yamada et al. (eds.), *Submarine Mass Movements and Their Consequences*,
Advances in Natural and Technological Hazards Research 31,
DOI 10.1007/978-94-007-2162-3_34,

frequency in the range of centuries. In this study we present a dataset on mass-wasting related features affecting the continental slope of the Southern-Central Chile active margin (33–42°S, Fig. 34.1); the amount and detail of the data we analyze is comparable with that of datasets from passive margins (Hühnerbach and Masson 2004). The digital appendix to this article contains spreadsheet data on dimensions, properties and positions of these submarine landslides as well as mappable GIS data of detail features of the individual slides in the GRASS and ArcGIS format.

34.1.1 Geological Setting

The geological framework of the Southern Central Chilean continental margin is controlled by the subduction of the oceanic Nazca plate beneath South America at a present rate of 6.6 cm/year and an azimuth of about N78°W (Angermann et al. 1999). Until late Miocene, subduction erosion has controlled the marine forearc. Since then, sediment accretion resulted in the buildup of an accretionary prism between 33°S, where the Juan-Fernandez Ridge is subducting, and 46.5°S, where the Chile Triple Junction is located (e.g., Bangs and Cande 1997, Fig. 34.1). A common morphological feature of the study area is a lower continental slope with steep segments (up to 30°) alternating with trench-parallel belts of less steep and even landward verging seafloor. This morphology is caused by the continuous deformation of the accretionary prism (Contreras-Reyes et al. 2008). In contrast, the upper continental slope appears smoother and the seafloor here is only interrupted by ridges and escarpments that are surface expressions of faults (Geersen et al. 2011). Seismic studies (Contreras-Reyes et al. 2008) show that the transition coincides with a landward increase in seismic velocities. The rocks that underlie the upper slope are seen as part of a Mesozoic accretionary complex that serves as active backstop for the presently deforming prism (Bangs and Cande 1997). This general morphological pattern is interrupted offshore Arauco Peninsula (36.5–39°S). Here, uplift across transpressive upper plate faults, that are aligned oblique to the direction of plate motion controls the morphotectonic setting on the mainland (Melnick et al. 2009; Rehak et al. 2008) and likely also affects the marine forearc (Geersen et al. 2011).

Seven major submarine canyons incise the continental margin in the study area. From N to S these are San Antonio, Mataquito, Itata, BioBio, Paleo-Pellahuen, Imperial/Tolten and CalleCalle canyons (Fig. 34.1a). All major canyons are directly connected to river systems that drain the Andes and the Coastal Cordillera.

Plate convergence results in large subduction earthquakes (Mw > 8.5) by which the main seismogenic segments have been defined. The recurrence interval of megathrust earthquakes for the individual segments typically lies between 150 and 200 years (Lomnitz 1970). On 27 February 2010, the Central Chilean Maule Region between Constitución and Concepción was hit by such a megathrust earthquake of Mw 8.8. Strong earthquakes are considered potential triggers for slope failure and submarine landslides.

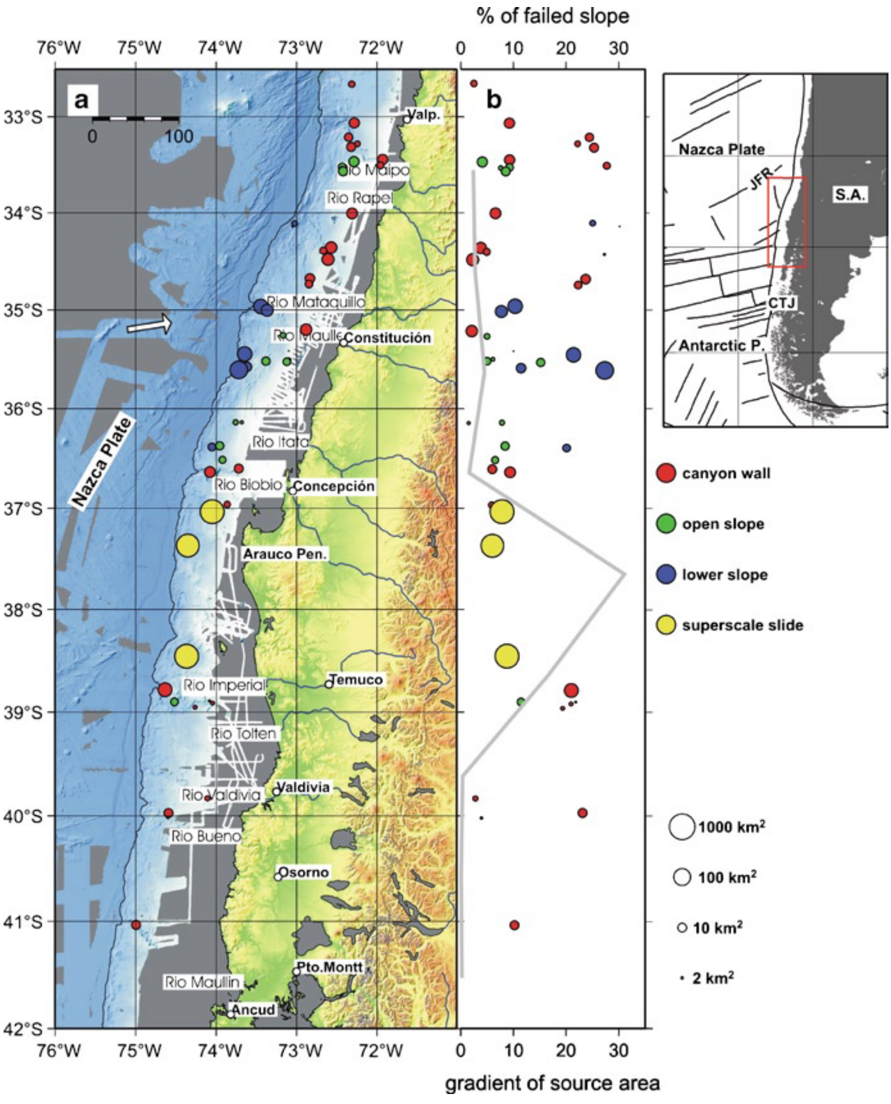

Fig. 34.1 (**a**) Bathymetric map of the working area, from a compilation of bathymetric cruises. The centers of submarine landslides are indicated as *points* (*red* = canyon wall collapses, *blue* = failures of lowermost slope, *green* = open slope failures, *yellow* = superscale failures) (**b**) 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*

34.1.2 Methods

Bathymetric datasets have been acquired during successive cruises on board RV SONNE, RV METEOR and RRS JAMES COOK using deep water echo sounders (SIMRAD EM-120 and 122); data cover ~90% of the continental slope off Central Chile. After post-processing, Digital Elevation Models (DEMs) were calculated to digitize details of the morphology and determine gradients and areal extent of related features. Bathymetric data acquired prior to and shortly after the 27 February 2010 Mw 8.8 Maule earthquake are available, allowing to image seafloor deformation related to the earthquake.

The volume of the material involved in the slides can be estimated from swath bathymetry data alone, if the resulting bathymetric features are well preserved and the background morphology is simple. In such cases, volumes are calculated by restoring a (hypothetical) original surface at either the slope scarp or at the place of redeposition and determining the volume difference between both. This is done with the numerical tool "the healer" (Völker 2009).

34.2 Results

In total, 62 submarine landslides were mapped with areal extent ranging between 1 and 1,285 km^2. Roughly, 5.7% of the continental slope between 33°S and 42°S is affected by mass wasting, 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 (Fig. 34.1b). Based on their different morphology, size and area of occurrence, we distinguish four basic 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. The latitudinal distribution, the size and the slope gradient for each of the slides herein documented is shown in Fig. 34.1b, together with the ratio of failed/unfailed slope area. The distinction coincides with fundamentally different failure mechanisms. In the following we present details for each of the four types of slides, providing the base for a discussion of preconditioning factors, possible triggers and frequency of slope failure.

34.2.1 Slides Related to Submarine Canyons

Half of the slope failures (33) are related to submarine canyons and all of the seven major canyons are bordered by slides. The slides are small in size (<30 km^2, with only three slides >30 and <90 km^2) and appear independent of the water depth (Fig. 34.1).

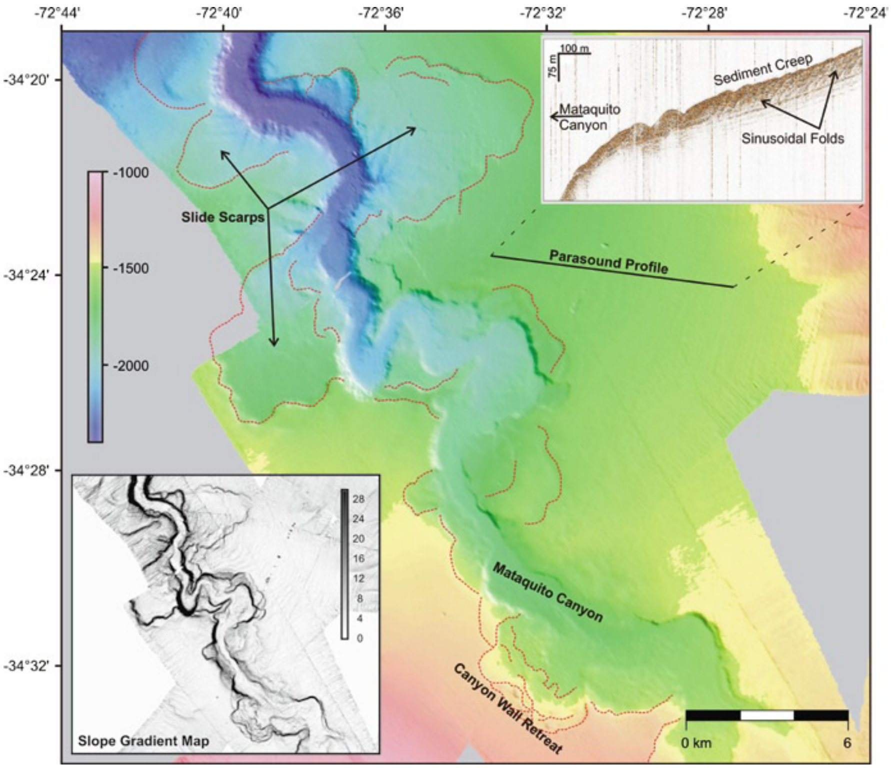

Fig. 34.2 Mass wasting at the sides of Mataquito Canyon. The map shows semicircular indentations of the canyon walls and multiple generations of flat-floored retrogressive failures that extend from the canyon wall collapses. The sediment echosounder profile shows creep deformation affecting sediment upslope of the failures

They are discernible as retreat of the canyon walls in the form of semicircular indentations that in places merge into elongate canyon wall collapses (Fig. 34.2). Often, there are secondary slides that extend from the canyon wall failures onto the open slope, forming pan-shaped depressions with steep walls (10–27°, Fig. 34.2) and a flat floor parallel to the undisturbed slope. The walls of secondary slides can be modified by further generations of semi-circular depressions. Upslope of some large failures, creep of sediment is obvious in the form of wavy deformations affecting otherwise parallel strata of hemipelagic sediment (Fig. 34.2).

In some cases, the collapsed material is still present as sagged and rotated sediment body within the canyons, but more often it is missing, likely because it is distributed within the canyons or transported into the trench. Within the BioBio Canyon, material of three consecutive failure events was found in a gravity core, whereas the San Antonio Canyon floor is devoid of unlithified sediments (Linke et al. 2011).

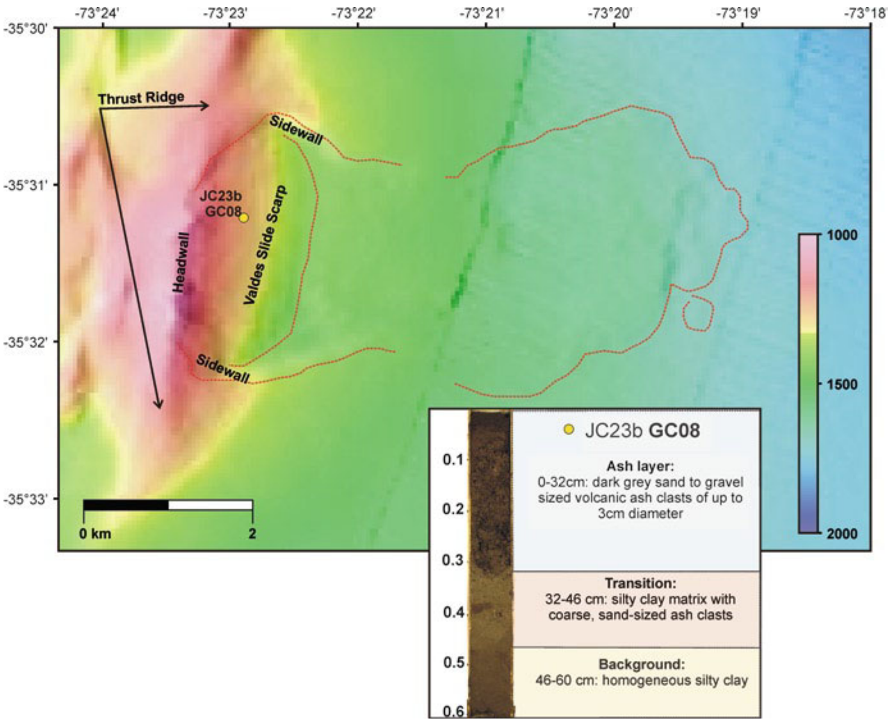

Fig. 34.3 Valdes Slide on the upper continental slope. This slide developed on the landward side of a prominent thrust ridge. Gravity core JC23b-GC08 from the exposed slide scar sampled a 30 cm thick ash clast layer

34.2.2 Slides on the Open Slope

Submarine slides on the open slopes have similar dimensions to those related to canyons (1–30 km^2). Seventeen slides of this category occur in water depths between 200 and 2,300 m where the slope gradient is less than 16° (Fig. 34.1b). The majority does not show any discernible relationship with the irregular topography and seems to have formed on gently inclined smooth slopes that are largely unfailed around them. The evacuation site typically has the form of isolated pan-shaped depressions with clearly defined lateral and head walls. In most cases, morphological features typical for displaced sediment are not clearly evidenced, perhaps being absent or buried.

Three slides fall out of this scheme as they are related to a trench-parallel thrust ridge on the middle slope which represents the surface expression of a deep-seated fault (Geersen et al. 2011) and produced differential uplift at the side of a slope basin (Contardo et al. 2008). Of those, the Valdes Slide formed at the landward side of this ridge and transported debris landward (Fig. 34.3). At the slide scar of Valdes Slide, a 30 cm thick volcanic ash clast layer was exposed (Anasetti et al. 2010).

34.2.3 Failure of the Lowermost Continental Slope

Steep (~30°) parts of the lowermost continental slope show a number of indentations, interrupting largely unfailed slopes between 34°S and 37°S (Fig. 34.1). Six slides of this kind are preserved in water depths between 2,100 and 5,000 m and two smaller slides lie on the flanks of sediment thrust ridges at the deformation front of the subduction zone. Lower slope collapses are significantly larger than slides related to canyons (15–217 km^2) and form irregular, steep, bowl-shaped depressions that end at the flat trench floor. In most cases, the displaced rock is either buried in the trench fill or absent.

Among this category, the Reloca Slide is the most noticeable because of its size and volume (217 km^2, 24 km^3, Völker et al. 2009) and because the displaced rocks are preserved as prominent features in the Chile Trench. The lower continental slope facing Reloca Slide is steep (20–30°) and with an arcuate shape reflecting the slide headscarp, which is characterized by a well-preserved crown at about 2,900–3,000 m water depth, thus forming a steep and straight ramp of 2,000 m elevation (Fig. 34.4).

The slide deposits consist of three blocks rising some 100 m and about 25 smaller blocks rising some 10 m above a cone of scattered debris (Fig. 34.4, outlines in yellow). The debris field has a run-out distance of 18 km and crosses (and partly buries) the 50–60 m deep axial channel of the Chile Trench. The larger blocks appear angular with steep flanks and lie directly at the foot of the continental slope. The blocks together make up roughly 90% of the material that is missing at the slope scar. The smaller blocks form clusters with a number of blocks aligned at the outer rim of the debris cone.

34.2.4 Giant Slope Failures

Offshore Arauco Peninsula (Fig. 34.1), three huge slope indentations ranging in areal extent 1,285, 924 and 1,145 km^2, respectively, shape the continental slope down to the abyssal plain and notably change the seismic reflection pattern of the sedimentary trench fill (Geersen et al. submitted, Fig. 34.5 insert). Two of these failures cause a landward retreat of the shelf break. The volume of material missing at the slope is in the order of 300–500 km^3 for each of the three slides.

The failure structures are discernible as elongate embayments with steep, up to 500 m high lateral and headwalls and chaotic seafloor morphology in the centers. The significant morphological differences between failed and unfailed slope suggests that huge rock volumes have been involved in the failure.

Seismic reflection profiles across the Chile Trench in front of these slope embayments show a chaotic interval embedded into well stratified undisturbed (turbiditic) sediments (Geersen et al. submitted). This is in marked contrast with the typical reflection pattern of the trench fill elsewhere, characterized by well-stratified sediment onlapping onto the subducting Nazca Plate (Fig. 34.5, inserts).

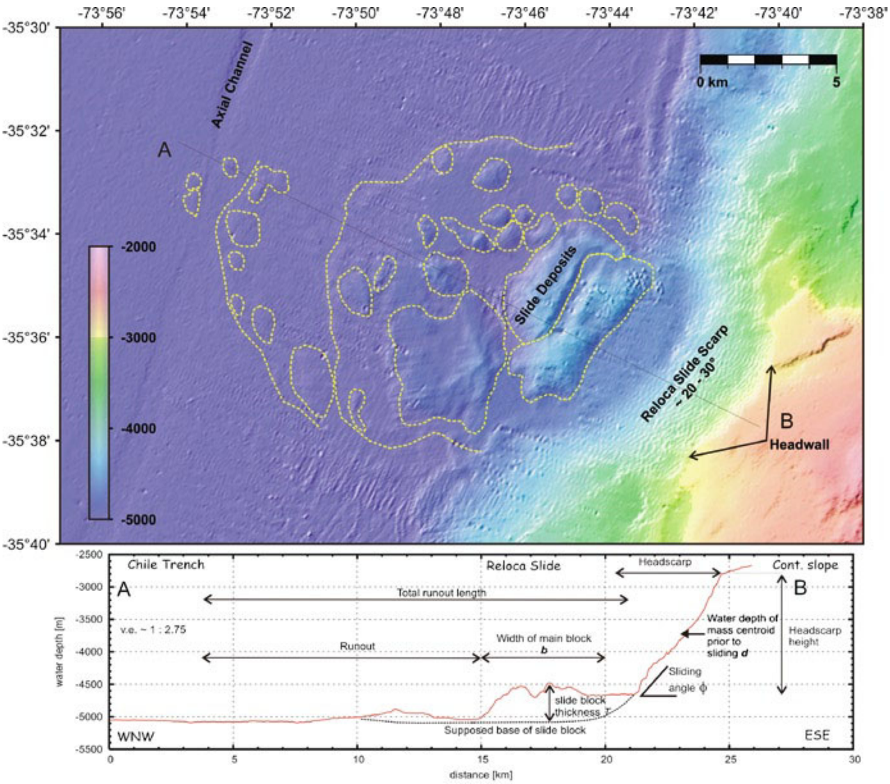

Fig. 34.4 Reloca Slide: Bathymetry and cross section along the slide complex. The depth profile runs from point *A* to *B*

34.3 Discussion and Conclusion

The flat slope-parallel floor of the evacuation areas of slides related to canyons and on open slopes suggests translational failure along lithologically defined weak layers some tens of meters below the seafloor. The most plausible cause for submarine canyon wall collapse is the destabilization by continuous or periodic canyon incision by sediment transport. The retrogression by secondary slides as well as the initiation of creep in slope sediments is a consequence of the removal of support with the initial collapse. As the canyons seem to have been more active during the last glacial (Völker et al. 2006), probably many of the features predate the Holocene. Retrogressions follow the initial wall collapses and often appear morphologically fresh. The youngest of a series of mass-wasting-related sediment units in the BioBio Canyon has a minimum age of 0.7–1 ka (Völker et al. submitted).

For slides on open slopes, failure mechanism is less evident. In the vicinity of tectonic features such as the thrust ridges where Valdes Slide is observed (Fig. 34.4), a

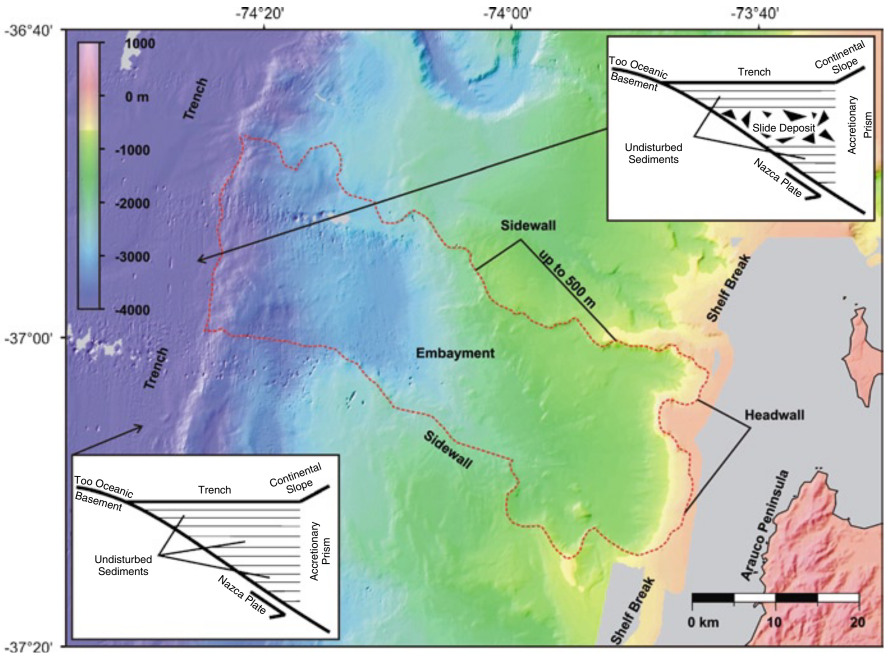

Fig. 34.5 Giant slide offshore Arauco Penisula. The slope indentation is bordered by steep walls, impinges on the course of the shelf break and reaches down to the sediment-filled Chile Trench. *Inserts* show simplified schemes of the seismic reflection pattern along the trench fill in front and south of the slope embayment

combination of continuous oversteepening and earthquake-induced vertical motion is possible. For a large number of slides, however, triggering and failure mechanisms are enigmatic, as the morphological conditions do not seem to differ from the surrounding unfailed slope. While Valdes Slide appears fresh in terms of morphology, Taza slide is covered by some 20 m of well-stratified sediment, as can be seen in sediment echosounder data.

The nature of the weak layers is unknown so far, but they seem to be present at discrete depth levels. Valdes slide appears to have failed along a thick, coarse layer of volcanic ash. Tephra layers of the Southern Volcanic Zone of Chile form huge sediment bodies on land and are found in cores offshore (Völker et al. 2006). They are considered potential weak layers because of their mechanical behaviour when subject to earthquake ground motion (Harders et al. 2010). However, neither new submarine landslides on the open slopes nor fresh failures of canyon or slide walls seem to have formed as a consequence of the Maule earthquake (Chadwell et al. 2010; Weinrebe et al. 2010; Völker et al. submitted).

Lower slope collapses and giant slope failures differ from the former groups by cutting deeper than 100 m into lithified rocks that lie beneath the slope sedimentary cover. At the lowermost slope this is material of the frontal prism that was accreted over the last 6 Ma, while in water depths less than 2,000 m this can be material of a Mesozoic accretionary complex, of Permian-Oligocene forearc basins as well as of the Paleozoic continental framework (Contreras-Reyes et al. 2008). The displaced rock bodies are some 100 m thick and the failure planes are slightly curved, indicating detachment planes that are not lithologically defined. Also, both types appear only within given latitudes where the continental margin is affected by particular tectonic lineaments that determine local to regional uplift of the marine forearc (Geersen et al. 2011).

The area where large lower slope collapses are present is characterized by localized uplift due to focussed basal sediment accretion. Here, the lowermost slope is particularly steep and may have reached a critical angle. Reloca Slide postdates the incision of the central axial channel of the Chile Trench (Fig. 34.3). The channel is believed to have been carved out about 10–12 ka BP (Völker et al. 2006).

Super-scale failures are restricted to offshore Arauco Peninsula which has been described as an anomalous stretch of forearc in terms of morphostructural setting, uplift history and occurrence of continental faults (Rehak et al. 2008; Melnick and Echtler 2006; Melnick et al. 2009). Uplift of the marine forearc seems to be the main agent leading to slope over-steepening, finally preconditioning the observed slope instabilities (Geersen et al. 2011). The thickness of the sediment cover of the slide-related debris corresponds to a minimum age of 200 ka for the youngest of these events. To our knowledge, the described slope failures are among the largest landslide deposits at active margins known to date.

Dating of a large number of the described slides is required to investigate possible links to climatic cycles as well as for a geohazard analysis. Geotechnical experiments aiming to understand the nature of weak layers will be carried out for Reloca and Valdes slide.

References

Anasetti A, Krastel S, Weinrebe W, Klaucke I, Bialas J (2010) Detailed analysis of the Valdes slide: a landward facing slope failure off Chile. In: Abstract EGU2010-13497 presented at 2010 general assembly of the EGU, Vienna, 02–07 May 2010

Angermann D, Klotz J, Reigber C (1999) Space-geodetic estimation of the Nazca-South America Euler vector. Earth Planet Sci Lett 171(3):329–334

Bangs NL, Cande SC (1997) Episodic development of a convergent margin inferred from structures and processes along the southern Chilean margin. Tectonics 16:489–503

Chadwell CD, Lonsdale P, Kluesner JW, Sweeney AD, Weinrebe W, Behrmann JH, Diaz-Naveas JL, Contreras Reyes E (2010) An examination of "before" and "after" bathymetry for uplift of the sea floor following the Feb. 27, 2010 Maule, Chile Earthquake. Abstract G33A-0851 presented at 2010 fall meeting, AGU, San Francisco, 13–17 Dec 2010

Contardo X, Cembrano J, Jensen A, Díaz-Naveas J (2008) Tectono-sedimentary evolution of marine slope basins in the Chilean forearc (33°30′–36°50′S): insights into their link with the subduction process. Tectonophysics 459(1–4):206–218

Contreras-Reyes E, Grevemeyer I, Flueh ER, Reichert C (2008) Upper lithospheric structure of the subduction zone offshore of southern Arauco Peninsula, Chile, at ~38°S. J Geophys Res 113:B07303

Geersen J, Behrmann JH, Völker D, Krastel S, Ranero CR, Diaz-Naveas J, Weinrebe RW (2011) Active tectonics of the South Chilean marine forearc (35°S–40°S). Tectonics. doi:10.1029/2010TC002777

Geersen J, Völker D, Behrmann JH, Reichert C, Krastel S (submitted) Pleistocene giant slope failures offshore Arauco Peninsula, Southern Chile. J Geol Soc

Harders R, Kutterolf S, Hensen C, Moerz T, Brueckmann W (2010) Tephra layers: a controlling factor on submarine translational sliding? Geochem Geophys Geosyst 11(5):Q05S23

Hühnerbach V, Masson DG (2004) Landslides in the North Atlantic and its adjacent seas: an analysis of their morphology, setting and behaviour. Mar Geol 213(1–4):343–362

Linke, P. and scientific cruise participants (2011). FS SONNE Fahrtbericht/Cruise Report SO210 ChiFlux - Identification and investigation of fluid flux, mass wasting and sediments in the forearc of the central Chile subduction zone, Valparaíso-Valparaíso, 23.09.-01.11.2010. IFM-GEOMAR Reports, 44, 112 pp., doi: 10.3289/ifm560geomar_rep_44_2011

Lomnitz C (1970) Major earthquakes and tsunamis in Chile during the period 1535 to 1955. Int J Earth Sci 59(3):938–960. doi:10.1007/BF02042278

Melnick D, Echtler HP (2006) Inversion of forearc basins in south-central Chile caused by rapid glacial age trench fill. Geology 34(9):709–712

Melnick D, Bookhagen B, Strecker MR, Echtler HP (2009) Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile. J Geophys Res 114:B01407. doi:10.1029/2008JB005788

Rehak K, Strecker MR, Echtler HP (2008) Morphotectonic segmentation of an active forearc, 37°–41°S, Chile. Geomorphology 94(1–2):98–116

Völker D (2009) A simple and efficient GIS tool for volume calculations of submarine landslides. Geo Mar Lett. doi:10.1007/s00367-009-0176-0

Völker D, Wiedicke M, Ladage S, Gaedicke C, Reichert C, Rauch K, Kramer W, Heubeck C (2006) Latitudinal variation in sedimentary processes in the Peru-Chile Trench off Central Chile. In: Oncken O et al (eds) The Andes – active subduction orogeny, Frontiers in earth sciences. Springer, Berlin/Heidelberg, pp 193–216

Völker D, Weinrebe W, Behrmann JH, Bialas J, Klaeschen D (2009) Mass wasting at the base of the south central Chilean continental margin: the Reloca Slide. Adv Geosci 22:155–167

Völker D, Scholz F, Geersen J (submitted) Recent submarine slide in the rupture area of the 27 February 2010 Maule earthquake offshore Chile. Mar Geo

Weinrebe W, Behrmann JH, Chadwell CD, Lonsdale P, Sweeney AD, Diaz-Naveas JL, Contreras Reyes E (2010) High-resolution seafloor bathymetry of the rupture area “before” and “after” the magnitude 8.8 Chilean earthquake of 2010. Abstract G33A-0852 presented at 2010 fall meeting, AGU, San Francisco, 13–17 Dec 2010