Submarine Landslides caused by Seamounts entering Accretionary Wedge Systems

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Seamounts entering active subduction zone trenches initially collide with the frontal sedimentary accretionary wedges resulting in severe deformation of the overriding plate. A typical feature of this deformation is the occurrence of submarine landslides due to gravitational instabilities. Such landslides have been reported from the Middle America and the Hikurangi trench and potentially generate tsunami waves. Yet, the dynamics of accretionary wedges during seamount indentation and landsliding as a mechanical response in particular have not been investigated quantitatively. Here, I apply 3D high-resolution numerical experiments to show that the topographical evolution of an accretionary wedge is mainly depending on the volume of the entering seamount and not on its height. Submarine landslides only occur if seamounts are not completely buried by the sedimentary sequence, where the volume of avalanches can be roughly correlated with the seamount volume overtopping the incoming sediments.

INTRODUCTION

Seamounts, or submarine volcanoes, are distributed among all oceanic plates around the globe (Hillier and Watts, 2007; Smith and Jordan, 1988). Although most of those are rather small, it has been suggested that around 12'000 large seamounts (> 1.5 km) cover the ocean floors (Watts et al., 2010;

Wessel et al., 2010). Seamounts differ in height and may exhibit either conical shapes (peaked), multiple branches (star shaped), and some can be flat-topped (Schmidt and Schmincke, 2002). Along active convergent margins, seamounts enter subduction zones and eventually collide with overriding plates. Observations of seamount subduction at active margins are documented from the Tonga-Kermandec trench (Timm et al., 2013), Nankai trench (Bangs et al., 2006), Japan and Kuril trench (Lallemand et al., 1989; Nishizawa et al., 2009), Cascadia (Wells et al., 1998), New Hebrides (Collot and Fisher, 1994), Hikurangi trench (Pedley et al., 2010), Middle America trench (von Huene, 2008), Central Chile margin (Laursen et al., 2009), Central Mariana and Izu-Bonin trenches (Oakley et al., 2008), Mediterranean ridge (von Huene et al., 1997), and Aleutian trench (Das and Watts, 2009). Relatively large seamounts are truncated when reaching the fore arc at shallow levels and may potentially be decapitated at larger depths, related to seismogenic deformation (Cloos, 1992). But whether seamounts along subduction interfaces trigger large earthquakes, form natural barriers for earthquake propagation, or even decrease seismic coupling between two plates is still a matter of debate (Mochizuki et al., 1997; Scholtz and Small, 1997; Das and Watts, 2009; Watts et al., 2010; Wang and Bilek, 2011).

Before a seamount reaches the fore arc, it traverses the frontal sedimentary accretionary wedge causing severe impact on the morphologic and tectonic evolution of the overriding plate. Topographic uplift above seamounts formes bulges (Park et al., 1999). Slope failure of such supercritical bulges (Lallemand and Le Pichon, 1987) occur that can trigger submarine avalanches (Lewis et al., 1998; Pedley et al., 2010). Such submarine avalanches (or landslides) can in turn cause major human and economic impact in the form of tsunamis (Fisher et al., 2005; Tappin et al., 2014), or demolition of offshore pipelines (Liu et al., 2015).

Collision of seamounts into accretionary systems have been dynamically reconstructed with analogue models that could reproduce main features of observed upper plate deformation (Lallemand et al., 1992; Dominguez et al., 1998; 2000). However, there is no published numerical modelling study so far investigating the effect of seamount subduction on deformation localization within the upper plate in general and the occurrence of gravitational submarine landslides in particular.

Due to the prevalent distribution of seamounts along subduction trenches and their geohazard potential, it is essential to understand the mechanics and dynamics of developing accretionary wedges during collision with a seamount. Therefore, I here test the influence of seamount size and shape on the tectonic and mechnical evolution of accretionary wedges with main focus on gravitational collapse and submarine landslides by applying a high-resolution three-dimensional numerical code. Results are discussed in the scope of the analytical critical wedge theory.

APPLIED GEOMETRICAL SETUP

Numerical model and setup are similar to those documented in earlier studies (Ruh et al., 2013; 2014), and are based on a three-dimensional, high-resolution, fully-staggered grid, finite difference, marker-in-cell code with a standard visco-brittle/plastic rheology and an efficient OpenMP-parallelized multigrid solver (I3ELVIS; Gerya, 2010; Gerya and Yuen, 2007; see supplementary material). Eulerian grid dimensions of presented simulations are 97.6 · 97.6 · 14.8 km in x-, y-, z-directions with a nodal resolution of 245 · 245 · 149, respectively; resulting cell size is 400/400/100 m, each containing 8 Lagrangian markers. Accordingly, the code calculates for ~9 million nodes and ~70 million markers. The geometrical setup resembles typical "sandbox"-type models. Initial marker distribution defines a 300 m thick lowermost rigid plate, topped by a 500 m thick décollement and 3 km of sedimentary sequence. Above, 11 km of "sticky-air" mimic a free surface allowing wedge to thicken. At the bottom, the rigid plate moves with a velocity $v_x = -1$ cm/yr and is pulled out below the lateral boundary at $x = 0$, which acts as a rigid backstop (no slip). On the opposite boundary, new stratigraphy is entering the Eulerian grid with v_x. Lateral side and top boundaries are free slip. Seamounts root into the rigid bottom plate and are introduced opposite of the backstop into undeformed stratigraphy after 4 Myr runtime. Plastic/brittle failure is based on the Drucker-Prager formulation depending on pressure P, friction angle φ, cohesion C, and fluid pressure ratio λ (Ruh et al., 2014). Décollement: φ_b = 10° and C_b = 0.2 MPa. Sedimentary sequence: φ = 30° and C = 10 MPa. Seamounts: φ = 30° and C = 20 MPa. A hydrostatic fluid pressure ratio λ = 0.4 is applied for décollement and sediments. Sediments and seamounts are weakened by linearly lowering φ to 20° and C to 0.2 MPa according to plastic strain ε_{pl} between $0.5 < \varepsilon_{pl} < 1.5$ (Ruh et al., 2013). A total of nine simulations are presented here: One model without seamount implementation acts as reference, eight simulations were carried out to investigate effects of size and shape of seamounts on upper plate deformation. Modeled seamounts rise 1.5, 3, 4.5, or 6 km high (above the décollement level) with either conical or flat-topped shapes. Seamounts are round with a lateral slope of 30°, which is on the upper level of naturally observed seamount slopes (Figure 1 in Dominguez et al., 1998). Flat-topped seamounts exhibit a horizontal cap with a radius of 5 km.

TOPOGRAPHIC EVOLUTION DURING SEAMOUNT SUBDUCTION

Deformation of numerical accretionary wedges localizes along the backstop and the deformation front migrates outward in-sequence with ongoing shortening (Gif 1 in supplementary material). Frontal accretion and out-of-sequence thrusting assure wedge growth in width (x-direction) and thickness, respectively, leading to a wedge body thickened at the rear (x = 0) thinning towards the toe (Fig. 1a). The topographic evolution of compressive wedges varies strongly depending on size and shape of entering seamounts. A conical seamount with a height of 1.5 km (above the décollement level) leaves a trace only in the thrust sheet that was the frontal one at the time of seamount entrance into the wedge (Fig. 1b). Simulations with higher conical seamounts exhibit topographic peaks spatially related to the seamount location and several thrust sheets are deformed due to its entrance (Fig. 1c-e). The topographic response of accretionary wedges to flat-topped seamount subduction is more prominent. A 1.5 km high semount leaves a clear trace in the accreting thrust sheets (Fig. 1f). Higher flat-topped seamounts form wide entrances into the wedge front and there are no cylindrical frontal thrust sheets developing within 9 Myr (Fig. 1g-i). Topographic peaks induced by underthrusting seamounts are always located at the rearward side of the seamount top (Fig. 1).

The elevation of these topographic peaks increases with increasing seamount height. Nonetheless, peak elevations of flat-topped seamount experiments are substantially higher than those with equally high conical seamounts. After 9 Myr, experiments of flat-topped seamounts with 1.5 and 3 km height (Fig. 1f,g) exhibit similar surface topographic reliefs as models with 4.5 and 6 km high conical seamounts (Fig. 1d,e), respectively: Only from the topographic map is not possible to determine whether the underthrusting seamount is flat-topped with 3 km height or conical with 6 km height (Fig. 1e,g).

Yet, peak elevations strongly dependent on the volume of seamounts entering an accretionary wedge (Fig. 2). This relation between the volume of a seamount and the peak elevation of overthrusting imbricate sheets is independent of the temporal evolution of seamount collision into an accretionary wedge. The similar differences of topographic peaks between 7 and 8 Myr and between 8 and 9 Myr, respectively, indicate a linear vertical thickening of accretonary wedges over time, independent of shape and height of subducting seamounts (Fig. 2).

SUBMARINE LANDSLIDES TRIGGERED BY SEAMOUNTS

It is widely accepted that seamounts entering subduction zones are a potential trigger of submarine landslides due to gravitational collapses (e.g., Lallemand and Le Pichon, 1987; Hühnerbach et al., 2005). Nevertheless, the dynamics of such avalanches and their volumetric and temporal relation to subducting seamounts have yet to be investigated.

The collision of a seamount has a major impact on the mechanical evolution of accretionary wedges, regardless whether submarine landslides appear or not (Gifs 2-9 in supplementary material). Seamounts act as barriers for the migration of the deformation front as they interrupt the flat décollement. The gravitational potential of sedimentary strata overthrusting seamounts activates the décollement level on the toeward side of the seamount and a normal fault along the seamount develops (Gifs 2-9 in supplementary material). Experiments exhibiting seamounts that exceed the initial sedimentary sequence build up large enough gravitational forces within the overthrust stratigraphy to trigger gravitational collapses (Gifs 4,5,8,9 in supplementary material). In case of a 6 km high flat-topped seamount, stacked material atop of the seamount fails along a listric-like normal fault and emplaces an up to 1.5 km thick sequence in front of the seamount (Fig. 3a). Strain rates indicate that the emplacement of the landslide activates the décollement toewards from the seamount and puts the undeformed sedimentary sequence at the verge of failure (Fig. 3b). A steep main scarp, a listric fault, a thin rupture surface, and a partly undeformed landslide mass are very well constrained features of observed submarine landslides (Hampton et al., 1996). Velocity field in *x*-direction indicates that the material above the active listric fault moves away from the rear (Fig. 3c; such slow velocities result from lower viscosity cutoff: 10^{18} Pa·s). Low velocities of displaced material patches along the wedge toe indicate an earlier landslide.

A topographic peak above the seamount and surpress frontal accretion due to the seamount interrupting the décollement level (Fig. 3) lead to a steepening of the surface taper along the profile where the seamount subduct (y = 48.8 km), as observed in seismic profiles through the Nankai accretionary wedge (Park et al., 1999). The temporal evolution of surface slope of a compressional wedge without seamount implementation (Gif 1 in supplementary material) indicates a taper leveling along the analytical minimum critical value within the stable regime (Fig. 4a). Dynamic surface tapers of seamount experiments are calculated from surface points located between the seamount top and the wedge toe, where a continuous décollement layer exists in between (Davis et al., 1983).

Submarine landslides decrease surface slopes (Fig. 4a,b). Tapers move from the supercritical into the stable field (below the maximum critical value) where they remain at 6-8°. This demonstrates that modeled wedges are behaving critical and that landslides are triggered by brittle/plastic gravitational collapses. Slope profiles along subduction zones where seamounts enter can therefore give insight in the strength relationship between basal and wedge internal material, expecting that tapers away from seamount occurrences represent the minimum analytical value, whereas profiles along seamount scars are close to maximum critical tapers (Geersen et al., 2015).

SIZE OF SUBMARINE LANDSLIDES

The volume of the dislocated mass during submarine landslides triggered by seamount subduction differs strongly for conical and flat-topped seamounts (Fig. 4c,d). A 4.5 km high conical seamount triggers a short-living landslide with a volume of ~20 km^3 (Fig. 4c). A 6 km conical seamount launches an up to 60 km^3 large avalanche that is active over a longer period of time. Initial activation of landslides are contemporaneous with the strong decrease of surface taper between 7 and 8 Myr of experiment evolution (Fig. 4a,c). Flat-topped seamounts cause much larger landslides. Peak volumes reach ~300 km^3 for 4.5 km high and up to 500 km^3 for 6 km high seamounts (Fig. 4d). The landslide remains active from its initiation at 7.7 Myr to the leveling of surface taper within the stable area at 9 Myr (Fig. 4b,d). On the basis of these results, a first-order estimation of landslide volume can be inferred from the volume of entering seamounts overtopping the initial sedimentary sequence (Fig. 4c,d), which also agrees with the absence of landslides for seamounts shorter than the stratigraphic thickness of 3km.

Numerical submarine landslides presented here can be compared to reported natural cases and estimations for their tsunamigenic potential can furthermore be provided. In general, numerical avalaches are volumetrically comparable to ordinary submarine landslides triggered by gravitational instabilities (<800 km^3; Hampton et al., 1996; and references therein). An example of landsliding caused by seamount collision is documented along the Hikurangi margin (Lewis et al., 2004). The Giant Ruartoria avalanche off New Zealand has a volume of ~2000 km^3 and is a result of collision of the now subducted Ruatoria seamount into the Hikurangi accretionary wedge (Collot et al., 2001). The size of Ruatoria seamount is interpreted to be similar to that of Gisborne seamount offshore Hikurangi, whose overtop volume can roughly be compared to the reported avalanche volume.

Figure 5 illustrates a comparison between the Ruatoria indentation and related avalanche and the numerical collision of a flat-topped 6 km high seamount into a developing accretionary wedge presented in this study (Fig. 3). In both cases, landsliding results from oversteepening and collapse of the wedge front due to seamount indentation (Fig. 5). In the natural as well as the numerical case, volumes of avalanches and exceeding seamounts are roughly similar.

A potential of tsunami generation is apparent from a fault scar volume larger than ~10 km^3 (van Huene et al., 2004), which includes all presented experiments with a seamount height greater than the initial sedimentary sequence (Fig. 4c,d). Yet, also smaller volumes of landslides have been interpreted to be potentially tsunamigenic (Borrero et al., 2001; Fisher et al., 2005). Mass movements similar to here reported can generate up to 50 m high tsunamis (von Huene et al., 1989). Trench areas where rough and seamount covered oceanic crust is entering a subduction zone are in a critical stress state and the interplay between seismic events, submarine landslides, and tsunami waves was reported for the 1992 Central Nicaragua earthquake (von Huene et al., 2004). Reentrants and scars indicate seamount collision and taper angles with a high potential of gravitational failure during earthquakes. Experiments presented here show that potential landslide volumes can be directly correlated to the (overtop) volume of seamount.

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FIGURE CAPTIONS

Figure 1 Surface topography of 3D accretionary wedges above initial sediment thickness in map view after 9 Myr experiment time. Backstop is located at $x = 0$ on the upper side of the plates. (a) No seamount implementation. (b-e**)** Conical seamount implementation. Dots indicate location of seamount peaks. (f-i) Flat-topped seamount implementation. Circles indicate location of flat area of seamount tops. Height of seamounts is indicated on top for all columns.

Figure 2 Surface topography peaks related to seamount subduction (Fig. 1) are plotted against the complete volume of according implemented seamounts for an experiment time of 7, 8 and 9 Myr. Circles and squares indicate conical and flat-topped seamounts, respectively. Seamount heights are 1.5, 3, 4.5, 6 km above décollement level, increasing towards right according to their volume.

Figure 3 (a) Compositional map, (b) strain rate, and (c) velocity in *x*-direction of an accretionary wedge indented by a 6 km high flat-topped seamount after 9 Myr shortening. Wedges are cut parallel to *x*-direction at $y = 44.8$ km. Seamounts are displayed by their composition.

Figure 4 Dynamics of numerical landslides. (a,b) Temporal surface taper evolution of reference and landslide-generating experiments. Dotted line: no seamount implementation. Grey line: 4.5 km high seamount. Black line: 6 km high seamount. Dashed lines: Minimum and maximum critical taper angles (Davis et al., 1983). (c,d) Volume of landslides triggered by conical and flat-topped seamounts, respectively. Filled areas indicate volumes between 0.5 cm/yr $< v_x <$ 1 cm/yr moving against shortening direction. Dashed lines indicate volume of seamounts overtopping the initial sedimentary stratigraphic thickness. Grey: 4.5 km high seamount. Black: 6 km high seamount.

Figure 5 Comparison between natural and numerical cases. (a) Top view of an experiment with a 6 km high flat-topped seamount after 9 Myr. Grey scale background: surface topography. Red lines: numerical faults. Blue tones: different landslides. Rose: landslide detachment. Blue and rose stripes: detachment burried by landslide. (b) Profiles in *x*-direction at $Ly = 0.5$ of the experiment presented in (a) before and after landslide occurrence at 7.4 and 9 Myr. Lower panel: surface lines before (red) and after (green) landsliding corrected for seamount passage (measured surface lines minus height of seamounts exceeding the initial sedimentary strata). Colors as in (a). (c) Simplified map of the Ruaroria indentation at the northeastern tip of Newzealand (after Collot et al., 2001; Lewis et al., 2004).Dark grey: upper margin. Light grey: imbricated zone. Dotted area: debris flow and disturbed trench fill. Lined area: post-avalanche turbidites. Red lines: main faults. Broken red line: pre-avalanche deformation front. Arrow: direction of plate motion and location of seamount entrance. Blue and rose as in (a). (d) Profiles through the Ruatoria indentation (after Collot et al., 2001). Profile A-A' indicates imbricate margin lacking a recent accretionary wedge. Dark grey: Neogene and Quaternary deposits. Light grey: imbricate zone. Profile B-B' shows cross section before (red) and after (green) avalanching. Black line: base of landslide. Color code equal to (a).