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► **To cite this version:**

Jonas B. Ruh. Submarine Landslides caused by Seamounts entering Accretionary Wedge Systems. Terra Nova, 2016, 28 (3), pp.163-170 10.1111/ter.12204 . hal-01289133

HAL Id: hal-01289133

<https://hal.sorbonne-universite.fr/hal-01289133>

Submitted on 16 Mar 2016

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1 Submarine Landslides caused by Seamounts entering Accretionary 2 Wedge Systems

3

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7

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

19

20 **INTRODUCTION**

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

24 Wessel et al., 2010). Seamounts differ in height and may exhibit either conical shapes (peaked),
25 multiple branches (star shaped), and some can be flat-topped (Schmidt and Schmincke, 2002). Along
26 active convergent margins, seamounts enter subduction zones and eventually collide with overriding
27 plates. Observations of seamount subduction at active margins are documented from the Tonga-
28 Kermadec trench (Timm et al., 2013), Nankai trench (Bangs et al., 2006), Japan and Kuril trench
29 (Lallemand et al., 1989; Nishizawa et al., 2009), Cascadia (Wells et al., 1998), New Hebrides (Collot
30 and Fisher, 1994), Hikurangi trench (Pedley et al., 2010), Middle America trench (von Huene, 2008),
31 Central Chile margin (Laursen et al., 2009), Central Mariana and Izu-Bonin trenches (Oakley et al.,
32 2008), Mediterranean ridge (von Huene et al., 1997), and Aleutian trench (Das and Watts, 2009).
33 Relatively large seamounts are truncated when reaching the fore arc at shallow levels and may
34 potentially be decapitated at larger depths, related to seismogenic deformation (Cloos, 1992). But
35 whether seamounts along subduction interfaces trigger large earthquakes, form natural barriers for
36 earthquake propagation, or even decrease seismic coupling between two plates is still a matter of
37 debate (Mochizuki et al., 1997; Scholtz and Small, 1997; Das and Watts, 2009; Watts et al., 2010;
38 Wang and Bilek, 2011).

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

46 Collision of seamounts into accretionary systems have been dynamically reconstructed with
47 analogue models that could reproduce main features of observed upper plate deformation (Lallemand et
48 al., 1992; Dominguez et al., 1998; 2000). However, there is no published numerical modelling study so

49 far investigating the effect of seamount subduction on deformation localization within the upper plate
50 in general and the occurrence of gravitational submarine landslides in particular.

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

57

58 **APPLIED GEOMETRICAL SETUP**

59 Numerical model and setup are similar to those documented in earlier studies (Ruh et al., 2013;
60 2014), and are based on a three-dimensional, high-resolution, fully-staggered grid, finite difference,
61 marker-in-cell code with a standard visco-brittle/plastic rheology and an efficient OpenMP-parallelized
62 multigrid solver (I3ELVIS; Gerya, 2010; Gerya and Yuen, 2007; see supplementary material). Eulerian
63 grid dimensions of presented simulations are $97.6 \cdot 97.6 \cdot 14.8$ km in x -, y -, z -directions with a nodal
64 resolution of $245 \cdot 245 \cdot 149$, respectively; resulting cell size is 400/400/100 m, each containing 8 La-
65 grangian markers. Accordingly, the code calculates for ~ 9 million nodes and ~ 70 million markers. The
66 geometrical setup resembles typical “sandbox”-type models. Initial marker distribution defines a 300 m
67 thick lowermost rigid plate, topped by a 500 m thick décollement and 3 km of sedimentary sequence.
68 Above, 11 km of “sticky-air” mimic a free surface allowing wedge to thicken. At the bottom, the rigid
69 plate moves with a velocity $v_x = -1$ cm/yr and is pulled out below the lateral boundary at $x = 0$, which
70 acts as a rigid backstop (no slip). On the opposite boundary, new stratigraphy is entering the Eulerian
71 grid with v_x . Lateral side and top boundaries are free slip. Seamounts root into the rigid bottom plate
72 and are introduced opposite of the backstop into undeformed stratigraphy after 4 Myr runtime.
73 Plastic/brittle failure is based on the Drucker-Prager formulation depending on pressure P , friction an-

74 gle φ , cohesion C , and fluid pressure ratio λ (Ruh et al., 2014). Décollement: $\varphi_b = 10^\circ$ and $C_b = 0.2$
75 MPa. Sedimentary sequence: $\varphi = 30^\circ$ and $C = 10$ MPa. Seamounts: $\varphi = 30^\circ$ and $C = 20$ MPa. A hydro-
76 static fluid pressure ratio $\lambda = 0.4$ is applied for décollement and sediments. Sediments and seamounts
77 are weakened by linearly lowering φ to 20° and C to 0.2 MPa according to plastic strain ε_{pl} between 0.5
78 $< \varepsilon_{pl} < 1.5$ (Ruh et al., 2013). A total of nine simulations are presented here: One model without
79 seamount implementation acts as reference, eight simulations were carried out to investigate effects of
80 size and shape of seamounts on upper plate deformation. Modeled seamounts rise 1.5, 3, 4.5, or 6 km
81 high (above the décollement level) with either conical or flat-topped shapes. Seamounts are round with
82 a lateral slope of 30° , which is on the upper level of naturally observed seamount slopes (Figure 1 in
83 Dominguez et al., 1998). Flat-topped seamounts exhibit a horizontal cap with a radius of 5 km.

84

85 **TOPOGRAPHIC EVOLUTION DURING SEAMOUNT SUBDUCTION**

86 Deformation of numerical accretionary wedges localizes along the backstop and the
87 deformation front migrates outward in-sequence with ongoing shortening (Gif 1 in supplementary
88 material). Frontal accretion and out-of-sequence thrusting assure wedge growth in width (x -direction)
89 and thickness, respectively, leading to a wedge body thickened at the rear ($x = 0$) thinning towards the
90 toe (Fig. 1a). The topographic evolution of compressive wedges varies strongly depending on size and
91 shape of entering seamounts. A conical seamount with a height of 1.5 km (above the décollement level)
92 leaves a trace only in the thrust sheet that was the frontal one at the time of seamount entrance into the
93 wedge (Fig. 1b). Simulations with higher conical seamounts exhibit topographic peaks spatially related
94 to the seamount location and several thrust sheets are deformed due to its entrance (Fig. 1c-e). The
95 topographic response of accretionary wedges to flat-topped seamount subduction is more prominent. A
96 1.5 km high seamount leaves a clear trace in the accreting thrust sheets (Fig. 1f). Higher flat-topped
97 seamounts form wide entrances into the wedge front and there are no cylindrical frontal thrust sheets

98 developing within 9 Myr (Fig. 1g-i). Topographic peaks induced by underthrusting seamounts are
99 always located at the rearward side of the seamount top (Fig. 1).

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

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

113

114 **SUBMARINE LANDSLIDES TRIGGERED BY SEAMOUNTS**

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

119 The collision of a seamount has a major impact on the mechanical evolution of accretionary
120 wedges, regardless whether submarine landslides appear or not (Gifs 2-9 in supplementary material).
121 Seamounts act as barriers for the migration of the deformation front as they interrupt the flat
122 décollement. The gravitational potential of sedimentary strata overthrusting seamounts activates the

123 décollement level on the toward side of the seamount and a normal fault along the seamount develops
124 (Gifs 2-9 in supplementary material). Experiments exhibiting seamounts that exceed the initial
125 sedimentary sequence build up large enough gravitational forces within the overthrust stratigraphy to
126 trigger gravitational collapses (Gifs 4,5,8,9 in supplementary material). In case of a 6 km high flat-
127 topped seamount, stacked material atop of the seamount fails along a listric-like normal fault and
128 emplaces an up to 1.5 km thick sequence in front of the seamount (Fig. 3a). Strain rates indicate that
129 the emplacement of the landslide activates the décollement towards from the seamount and puts the
130 undeformed sedimentary sequence at the verge of failure (Fig. 3b). A steep main scarp, a listric fault, a
131 thin rupture surface, and a partly undeformed landslide mass are very well constrained features of
132 observed submarine landslides (Hampton et al., 1996). Velocity field in x -direction indicates that the
133 material above the active listric fault moves away from the rear (Fig. 3c; such slow velocities result
134 from lower viscosity cutoff: 10^{18} Pa·s). Low velocities of displaced material patches along the wedge
135 toe indicate an earlier landslide.

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

144 Submarine landslides decrease surface slopes (Fig. 4a,b). Tapers move from the supercritical
145 into the stable field (below the maximum critical value) where they remain at 6-8°. This demonstrates
146 that modeled wedges are behaving critical and that landslides are triggered by brittle/plastic
147 gravitational collapses. Slope profiles along subduction zones where seamounts enter can therefore

148 give insight in the strength relationship between basal and wedge internal material, expecting that
149 tapers away from seamount occurrences represent the minimum analytical value, whereas profiles
150 along seamount scars are close to maximum critical tapers (Geersen et al., 2015).

151

152 **SIZE OF SUBMARINE LANDSLIDES**

153 The volume of the dislocated mass during submarine landslides triggered by seamount
154 subduction differs strongly for conical and flat-topped seamounts (Fig. 4c,d). A 4.5 km high conical
155 seamount triggers a short-living landslide with a volume of $\sim 20 \text{ km}^3$ (Fig. 4c). A 6 km conical
156 seamount launches an up to 60 km^3 large avalanche that is active over a longer period of time. Initial
157 activation of landslides are contemporaneous with the strong decrease of surface taper between 7 and 8
158 Myr of experiment evolution (Fig. 4a,c). Flat-topped seamounts cause much larger landslides. Peak
159 volumes reach $\sim 300 \text{ km}^3$ for 4.5 km high and up to 500 km^3 for 6 km high seamounts (Fig. 4d). The
160 landslide remains active from its initiation at 7.7 Myr to the leveling of surface taper within the stable
161 area at 9 Myr (Fig. 4b,d). On the basis of these results, a first-order estimation of landslide volume can
162 be inferred from the volume of entering seamounts overtopping the initial sedimentary sequence (Fig.
163 4c,d), which also agrees with the absence of landslides for seamounts shorter than the stratigraphic
164 thickness of 3km.

165 Numerical submarine landslides presented here can be compared to reported natural cases and
166 estimations for their tsunamigenic potential can furthermore be provided. In general, numerical
167 avalanches are volumetrically comparable to ordinary submarine landslides triggered by gravitational
168 instabilities ($< 800 \text{ km}^3$; Hampton et al., 1996; and references therein). An example of landsliding
169 caused by seamount collision is documented along the Hikurangi margin (Lewis et al., 2004). The
170 Giant Ruatoria avalanche off New Zealand has a volume of $\sim 2000 \text{ km}^3$ and is a result of collision of
171 the now subducted Ruatoria seamount into the Hikurangi accretionary wedge (Collot et al., 2001). The

172 size of Ruatoria seamount is interpreted to be similar to that of Gisborne seamount offshore Hikurangi,
173 whose overtop volume can roughly be compared to the reported avalanche volume.

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

179 A potential of tsunami generation is apparent from a fault scar volume larger than $\sim 10 \text{ km}^3$ (van
180 Huene et al., 2004), which includes all presented experiments with a seamount height greater than the
181 initial sedimentary sequence (Fig. 4c,d). Yet, also smaller volumes of landslides have been interpreted
182 to be potentially tsunamigenic (Borrero et al., 2001; Fisher et al., 2005). Mass movements similar to
183 here reported can generate up to 50 m high tsunamis (von Huene et al., 1989). Trench areas where
184 rough and seamount covered oceanic crust is entering a subduction zone are in a critical stress state and
185 the interplay between seismic events, submarine landslides, and tsunami waves was reported for the
186 1992 Central Nicaragua earthquake (von Huene et al., 2004). Reentrants and scars indicate seamount
187 collision and taper angles with a high potential of gravitational failure during earthquakes. Experiments
188 presented here show that potential landslide volumes can be directly correlated to the (overtop) volume
189 of seamount.

190

191 **ACKNOWLEDGMENTS**

192 I am very thankful to Taras Gerya, who provided the numerical code. Funding was received
193 from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework
194 Programme FP7/2007-2013/ under REA grant agreement n° 604713 (ZIP "Zooming In between
195 Plates").

196

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306

307 **FIGURE CAPTIONS**

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

313

314 **Figure 2** Surface topography peaks related to seamount subduction (Fig. 1) are plotted against the com-
315 plete volume of according implemented seamounts for an experiment time of 7, 8 and 9 Myr. Circles
316 and squares indicate conical and flat-topped seamounts, respectively. Seamount heights are 1.5, 3, 4.5,
317 6 km above décollement level, increasing towards right according to their volume.

318

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

322

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

330

331 **Figure 5** Comparison between natural and numerical cases. (a) Top view of an experiment with a 6 km
332 high flat-topped seamount after 9 Myr. Grey scale background: surface topography. Red lines:
333 numerical faults. Blue tones: different landslides. Rose: landslide detachment. Blue and rose stripes:
334 detachment buried by landslide. (b) Profiles in x -direction at $Ly = 0.5$ of the experiment presented in
335 (a) before and after landslide occurrence at 7.4 and 9 Myr. Lower panel: surface lines before (red) and
336 after (green) landsliding corrected for seamount passage (measured surface lines minus height of
337 seamounts exceeding the initial sedimentary strata). Colors as in (a). (c) Simplified map of the Ruatoria
338 indentation at the northeastern tip of Newzealand (after Collot et al., 2001; Lewis et al., 2004). Dark
339 grey: upper margin. Light grey: imbricated zone. Dotted area: debris flow and disturbed trench fill.
340 Lined area: post-avalanche turbidites. Red lines: main faults. Broken red line: pre-avalanche
341 deformation front. Arrow: direction of plate motion and location of seamount entrance. Blue and rose
342 as in (a). (d) Profiles through the Ruatoria indentation (after Collot et al., 2001). Profile A-A' indicates

- 343 imbricate margin lacking a recent accretionary wedge. Dark grey: Neogene and Quaternary deposits.
- 344 Light grey: imbricate zone. Profile B-B' shows cross section before (red) and after (green) avalanching.
- 345 Black line: base of landslide. Color code equal to (a).