

## RESEARCH LETTER

10.1002/2014GL059472

## Key Points:

- High-resolution 3-D thermo-mechanical models of slab detachment
- Along-strike variations strongly impact the evolution of the Earth's surface
- We investigate the role of slab age on the detachment and its consequences

## Supporting Information:

- Readme
- Figure S1
- Figure S2
- Figure S3

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## Citation:

Duretz, T., T. V. Gerya, and W. Spakman (2014), Slab detachment in laterally varying subduction zones: 3-D numerical modeling, *Geophys. Res. Lett.*, *41*, 1951–1956, doi:10.1002/2014GL059472.

Received 30 JAN 2014

Accepted 28 FEB 2014

Accepted article online 3 MAR 2014

Published online 25 MAR 2014

## Slab detachment in laterally varying subduction zones: 3-D numerical modeling

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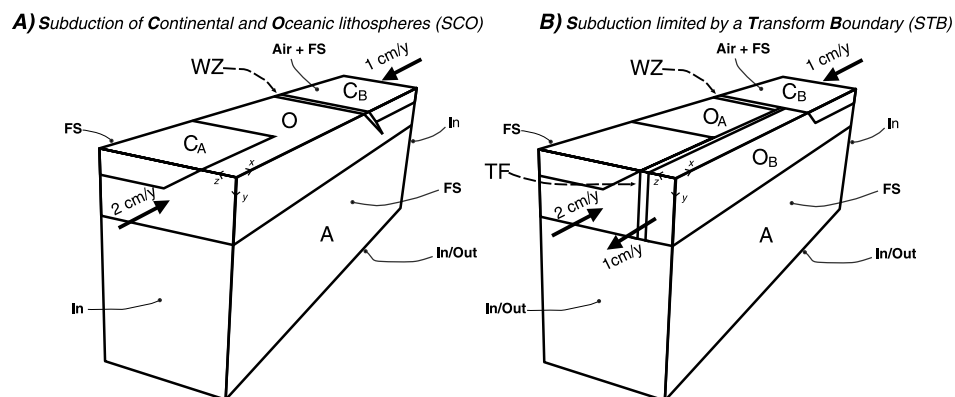
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**Abstract** Understanding the three-dimensional (3-D) dynamics of subduction-collision systems is a longstanding challenge in geodynamics. We investigate the impact of slab detachment in collision systems that are subjected to along-trench variations. High-resolution thermomechanical numerical models, encompassing experimentally derived flow laws and a pseudo free surface, are employed to unravel lithospheric and topographic evolutions. First, we consider coeval subduction of adjacent continental and oceanic lithospheres (SCO). This configuration yields to two-stage slab detachment during collision, topographic buildup and extrusion, variable along-trench convergence rates, and associated trench deformation. The second setting considers a convergent margin, which is laterally limited by a transform boundary (STB). Such collisional system is affected by a single slab detachment, little trench deformation, and moderately confined upper plate topography. The effect of initial thermal slab age on SCO and STB models are explored. Similarities with natural analogs along the Arabia-Eurasia collision are discussed.

### 1. Introduction

Slab detachment (or break off) is a popular model in continental collision geodynamics, which relates a strong transition in subduction dynamics to geological processes such as metamorphic rock exhumation [Andersen *et al.*, 1991], surface uplift rates [Fox, 2012], or plutonism [Davies and von Blanckenburg, 1995]. Besides numerous two-dimensional thermomechanical studies [e.g., Duretz *et al.*, 2012a], three-dimensional (3-D) slab detachment dynamics during continental collision remain largely unexplored. In van Hunen and Allen [2011], the role of an inclined margin on the propagation of slab detachment was highlighted, Capitanio and Replumaz [2013] have explored the impact of slab detachment on the curvature of orogenic belts and Li *et al.* [2013] investigated the role of the collision rate on slab detachment depth. Along-strike variations have a strong impact on subduction processes [Guillaume *et al.*, 2013], but the impact of slab detachment on the dynamics and topography evolution in such system remains however unclear. Lateral variations, which exist prior to collision, are a natural consequence of the finite extent of tectonic plates and their inherited internal structure. In this study, we consider two different types of along-strike variation: (1) coeval subduction of adjacent continental and oceanic lithospheres (SCO) and (2) subduction laterally limited by a transform boundary (STB). Such convergent plates' settings are not unusual on Earth and are common in the framework of Mediterranean tectonics (Calabrian arc [e.g., Wortel *et al.*, 2009] and Western Hellenic arc [e.g., Pearce *et al.*, 2012]), Tethyan tectonics (Zagros-Makran transition [e.g., Regard *et al.*, 2010]), or in the southeast Asian plate boundary system (Sunda trench-Timor trough [e.g., Spakman and Hall, 2010]). In addition, the plate tectonic history is characterized by multiple continental collisions unavoidably involving lithosphere entering the trench that was composed of both continental and oceanic lithosphere of which the subduction events leading to the formation of the Pangea continental landmass is a prime example.

Here we employ high-resolution (2 km for velocity and pressure fields, 1 km for lithology and material properties) numerical modeling to investigate the influence of SCOs and STBs on collisional slab detachment dynamics. We emphasize the role of along-strike variations and describe the subsequent pattern of surface deformation. Additionally, we investigate the role of the initial slab's thermal age as suggested in previous modeling studies [e.g., Duretz *et al.*, 2011].



**Figure 1.** Two model setups of laterally variable subduction/collision systems employed in this study (not to scale). Both settings comprise a limited width lower plate continent ( $C_A$ ) and an upper plate continent ( $C_B$ ), which are both overlying the asthenospheric mantle ( $A$ ). (a) The lower plate continent is coupled to adjacent oceanic lithosphere ( $O$ ). Subduction of continental and oceanic material will therefore take place coevally. The models are subjected to mixed types of boundary conditions such as Dirichlet (arrows), free slip (FS), inflow/outflow (In/Out), and the presence of a sticky air layer (SA). (b) A transform fault (TF) that separates two oceanic blocks ( $O_A$  and  $O_B$ ). The subduction is laterally limited by the fault and initially develops along a predefined weak zone (WZ).

## 2. Method and Setup

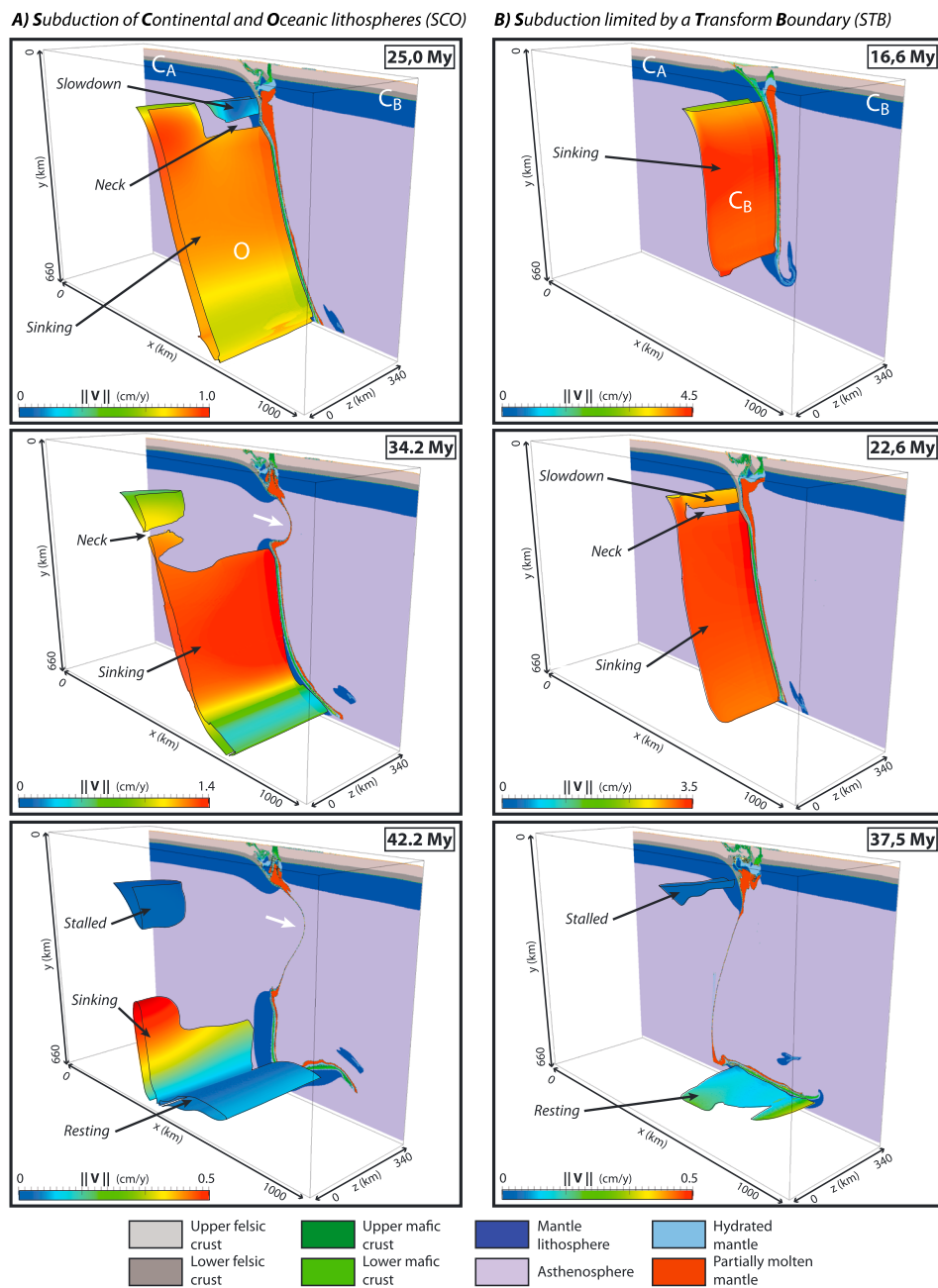
In order to model 3-D subduction/collision processes, we employ the Eulerian-Lagrangian method described in Gerya [2010]. The discrete equations resulting from the finite difference approximation of the energy, momentum, and mass balances are solved using a geometric multigrid approach. A sticky air layer [Cramer *et al.*, 2012] is employed to simulate a free surface and the evolution of topography. Water release from the slab is computed on the basis of metamorphic reactions using Gibbs free energy minimization [Li *et al.*, 2013]. A composite rheological model includes the effects of Mohr-Coulomb, diffusion-dislocation, and Peierls creep in the mantle lithosphere [Duretz *et al.*, 2012b]. Both SCO and STB setups have the same domain dimensions ( $1000 \times 680 \times 328$  km) and grid resolution ( $501 \times 341 \times 165$  nodes). Continents are characterized by a 35 km thick crust with an initially linear continental geotherm (with 1600 K defined at  $y = 100$  km). Oceans have a 7 km crust, and their initial geotherm is calculated from a half-space cooling model considering an age ( $\tau$ ) of 90 Myr for the reference models. The thermal and mechanical parameters of each of the material phases are similar to those employed in Duretz *et al.* [2011] and Li *et al.* [2013]. The passive margins are 50 km wide and are characterized by smooth (linear) geothermal transitions. Subduction is predefined by a  $27^\circ$  dipping hydrated mantle layer intersecting the upper plate's passive margin. Oceanic subduction and subduction slowdown related to continental collision are imposed via time-dependent compression velocity ( $V_{comp}$ ). A 15 Myr compressive period (at 3 cm/y) is followed by a 5 Myr period of linear velocity decrease to zero. Other boundary conditions are depicted in Figure 1. The difference between the SCO and STB setups resides in the presence of a transform boundary (at  $z = 100$  km) in the STB setup, which provides mechanical decoupling during subduction/collision and inhibits subduction of the adjacent oceanic domain ( $z < 100$  km).

## 3. Modeling Results

To illustrate slab behaviors, 3-D geometries at various stages are depicted in Figure 2 for both reference models ( $\tau = 90$  Myr), corresponding modeled topography is shown in Figure 3.

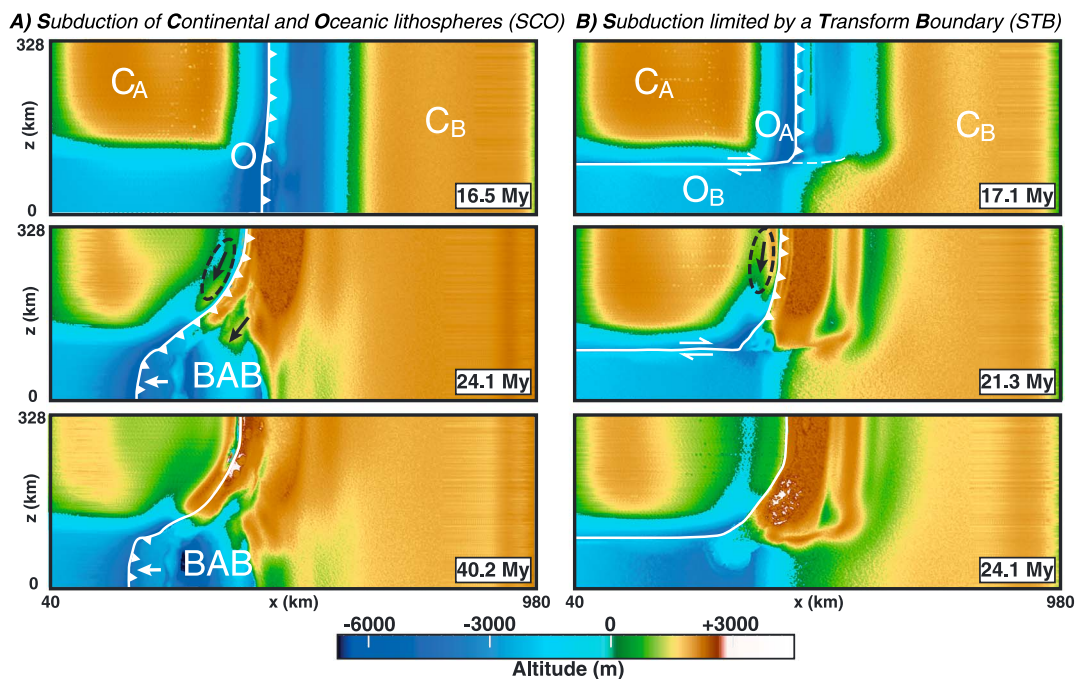
### 3.1. SCO: Coeval Subduction of Continental and Oceanic Material

During the first 15 Myr, there is no along-trench variation and subduction of the oceanic basin leads to a laterally homogeneous subduction zone as well as the subsidence and back-arc extension of the upper plate (Figure 3a;  $\sim 16$  Myr). After 18 Myr, contrasting subduction styles as the oceanic slab retreats triggering the opening of a back-arc basin (Figure 3a;  $\sim 24$  Myr). Subduction of continental material produces a subduction resistive force that will ultimately promote slab detachment. Continental collision takes place for  $z > 100$  km, and crustal thickening triggers lateral flow (Figure 3a;  $\sim 24$  Myr). This type of lateral extrusion internally affects the continental material but does not trigger rigid plate motion. The subducted margin



**Figure 2.** Time evolution of the reference simulations: (a) SCO: subduction of oceanic and continental lithospheres and (b) STB: subduction limited by a transform fault. The 3-D slab morphology is denoted by the viscosity contour  $5 \times 10^{23}$  Pa s and plotted for  $y > 100$  km depth. Slab shapes are colored by the magnitude of the velocity vector (notice the different color maps in each panel). Vertical compositional sections are shown for  $z = 335$  km and depicts the structure of the collision zone. Arrows indicate slab portions that are subjected to slowdown, necking, sinking, stalling, or resting on the bottom of the box (660 phase boundary). White characters refer to the labels used in Figure 1, the white arrows indicate return mantle flow through the slab gap.

starts detaching 8 Myr after the start of collision and takes place at 120 km depth (Figure 2a; ~24 Myr). Eventually the continental slab detaches after the necking of the continental slab, which takes place within 2 Myr (Figure 4). This event causes uplift of the lower plate at instantaneous rate of 2 mm/yr. After detachment, the slab pull is reduced beneath the collision and is transferred along the trench affecting the adjacent oceanic slab ( $z < 100$  km). The slab remains attached during, at least, the next 15 Myr (Figure 2a; ~ 40 Myr) and accommodated the deformation by stretching and steepening of its upper segment as the lower part sinks

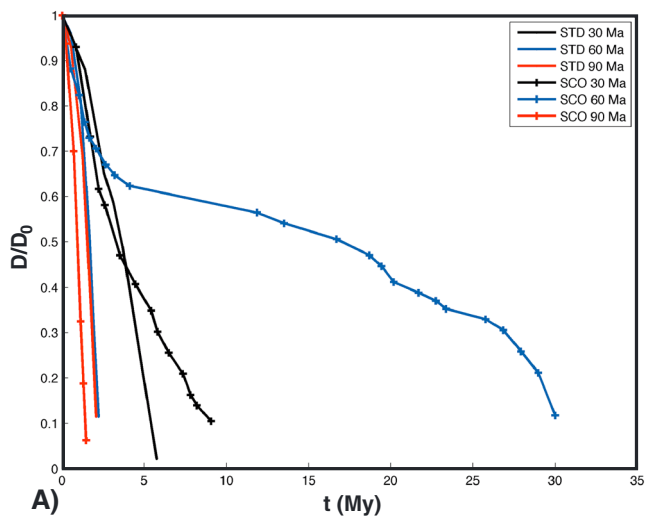


**Figure 3.** Topographic evolution of the two reference models. The plate boundaries (subduction, transform, and inactive) are indicated by solid white lines, where barbed lines indicate active subduction/collision. Dashed lines indicate the deformation front on the upper plate. Black and white arrows respectively represent the directions of topographic extrusion and slab rollback. Dashed ellipses delimit the areas affected by slab detachment. White labels correspond to those utilized in Figures 1 and 2, BAB indicates the location of back-arc basins.

toward the bottom of the domain ( $y = 660$  km). The slab deformation is accompanied by return mantle flow through the detached slab that promotes flattening of the continental slab (Figure 2a;  $\sim 40$  Myr).

**3.1.1. Impact of the Initial Slab Age**

In complement to the reference simulation, we have investigated the role of thermally younger slabs. For a 60 Myr slab, continental slab detachment takes place in two stages. The initiation of continental slab detachment is delayed and takes place at 19 Myr. During the next 5 Myr, the plate accommodates 30% thinning (Figure 4) at 135 km depth.



**Figure 4.** Evolution of slab thickness throughout detachment for the SCO and STB models with variable oceanic thermal age. Reported thicknesses correspond to the distances separating the  $1300^\circ$  isotherm in the necking zones.

It is then subjected to slow thinning until its detachment 25 Myr later. The slab detachment eventually propagates in the oceanic domain, which detaches at 47 Myr. A 30 Myr old slab results in a 10 Myr slab detachment duration (Figure 4). The detachment onsets at 19 Myr and localizes at 145 km depth. The younger thermal structure of the plate also facilitates the detachment of the adjacent oceanic segment that takes place at 42 Myr. More generally, variations in slab ages modify the pull of the oceanic subduction, which is laterally transmitted toward the collision zone. As a result, subduction of an old plate ( $\tau = 90$  Myr) results in a delayed uplift in the adjacent collision zone (see supporting information).

### 3.2. STB: Subduction/Collision Along a Transform Boundary

The initial stage of convergence triggers the development of subduction zone limited by the transform fault (Figure 2b; ~17 Myr). As oceanic subduction develops, the upper plate subsides and is affected by back-arc extension (Figure 3b; 10–17 Myr). Continental collision initiates after 15 Myr of convergence. After 7 Myr of compression, the subducted continental margin undergoes necking under slab's negative buoyancy eventually leading to detachment at 125 km depth. Slab thinning initiates at the slab's center and migrates toward its edge. The total detachment duration lasts up to 3 Myr (Figure 2b; ~21 Myr). In the first stage, the topography induced by the collision is laterally limited by the transform fault and the signal of detachment is seen on the lower plate. The topography grows from the center ( $z = 328$  km) to the edge of the collision, witnessing the evolution of the detachment ( $z < 100$  km; Figure 3b; ~21 Myr). Peak instantaneous surface uplift of 6 mm/yr is obtained at this location. In the second stage, extrusion of topography overcomes the transform boundary and the thickened crustal material flows out of the collision zone (Figure 3b; ~24 Myr). As slab pull is no more transmitted to the orogen and no kinematic push is prescribed, the lithospheric root becomes stalled and the slab sinks down to the 660 km boundary (Figure 2b; ~24 Myr). In contrast with the SCO model, no effect of the mantle flow on the continental collision zone was observed as most of the flow induced by the slab's descent occurred around its edge.

#### 3.2.1. Impact of the Initial Slab Age

For this STB setup, varying the slab age did not provide a strong influence on slab detachment and collision dynamics. Slab ages of 60 or 30 Myr both triggered detachment at ~19 Myr (similar to the reference case). A 30 Myr old slab leads to 10 Myr slab detachment duration (Figure 4), whereas detachment only lasted 2.5 Myr for older slabs. The main impact concerns the depth of slab detachment which increases together with younging slabs and reached 170 km for 30 Myr slab. In all cases, topographic uplift of lower plates takes place within ~1–2 Myr after detachment.

## 4. Discussion

We presented 3-D models of convergent systems subjected to slab detachment, with emphasis on collision dynamics and topographic evolution. Our models share a number of features with natural subduction-collision system and may, to some extent, apply to the Arabia-Eurasia collision. Whereas the Zagros-Makran region represents a prototype of SCO, the transition from Makran to the Indian plate may be regarded as an STB (see supporting information). Both transitions are characterized by the presence of transform fault systems, the Zendan-Minab fault to the west and the Chaman fault system to the east. These fault systems accommodate discontinuous convergence at the edges of the Makran accretionary wedge [Regard *et al.*, 2010; Lawrence *et al.*, 1981] and are marked by sharp lateral topographic gradients. These kinematic and morphological patterns reflect the lateral variability inherent to SCO and STB boundaries. In general, our models show that transform zones and related surface deformation can naturally emerge from laterally variable subduction-collision systems. Besides that, the Zagros orogen likely underwent slab detachment after the onset of continental collision [Agard *et al.*, 2011; McQuarrie and van Hinsbergen, 2013]. Despite detachment, oceanic subduction persisted in the adjacent Makran region. This particularity is well reproduced by our SCO model, which shows that oceanic subduction may continue at least 10 Myr after detachment in the adjacent collision zone when considering a sufficiently aged lithospheric slab ( $\tau \geq 90$  Myr).

In this study, the morphology of slab detachment compares well with previous studies [van Hunen and Allen, 2011; Burkett and Billen, 2011], which showed the tendency for slab to detach from their center toward their edges. In addition, we show that such detachments are accompanied by a characteristic upper plate topographic imprint, which progresses along strike with ongoing slab detachment. Our detachment durations correlate with previous results [Duretz *et al.*, 2012a] but are significantly shorter than those in van Hunen and Allen [2011]. This variation likely reflects differences in the employed rheological models, which was shown to control kinematics [Schmalholz, 2011]. Due to the confined boundaries, continued convergence after detachment [Capitanio and Replumaz, 2013] is limited and dynamic effects such as plate eduction [Duretz *et al.*, 2012b] are minimized. Further studies would benefit from the implementation of dynamic boundary conditions [e.g., Chertova *et al.*, 2012] to circumvent that aspect.

### 4.1. Conclusions

We designed 3-D thermomechanical models in order to investigate the 3-D complexities of slab detachment and topographic evolution in laterally variable subduction-collision systems. The two models, SCO and STB, differed by the presence of mechanical coupling with adjacent slabs and resulted in significantly

different time evolutions. We could show that the initial oceanic plate thermal age has a notable impact on the evolution SCO type margins, affecting the timing and duration of slab detachment. It also influences the propagation of detachment toward the adjacent oceanic domain, which may ultimately result in its detachment. After detachment we could observe that the descent of an adjacent slab can excite mantle flow beneath the collision zone. STB type margins exhibited less sensitivity to initial slab ages, which mostly modulated the detachment depth and magnitude of the uplift rate. In both experimental settings, slab detachment yielded to a systematic topographic pattern characterized by rapid uplift of the lower plate that propagates laterally with ongoing detachment. Topographic extrusion was promoted in SCO type models while, owing to this particular collision geometry, the initiated retreat of the adjacent oceanic slab accommodates the extrusion of thickened crust. Our experiments of fading subduction demonstrate that along-trench rheological and compositional variations have a strong impact on the subsequent dynamic slab evolution eventually leading to slab detachment. Apart from demonstrating distinctly different slab responses to two end-member models, our 3-D modeling particularly leads to novel predictions of topography evolution above such subduction systems. In spite of the early nature of such 3-D modeling results, we anticipate that rigorous applications to natural settings will improve this modeling and provide discriminating diagnostics for linking geological responses to transient subduction dynamics, eventually coupling surface evolution to deep driving processes.

#### Acknowledgments

We thank Fabio Capitanio and an anonymous reviewer for providing insightful reviews. This work was partly supported by the Research Council of Norway through its Centres of Excellence funding scheme, project number 223272. Numerical simulations were run on Brutus (ETH Zurich) and Ulysse clusters (UPMC Paris). We thank Dave May for his great help with postprocessing and visualization of 3-D simulations.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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