A free plate surface and weak oceanic crust produce single-sided subduction on Earth

F. Crameri,[1] P. J. Tackley,[1] I. Meilick,[1] T. V. Gerya,[1] and B. J. P. Kaus[1,2]

[1] Earth's lithosphere is characterized by the relative movement of almost rigid plates as part of global mantle convection. Subduction zones on present-day Earth are strongly asymmetric features composed of an overriding plate above a subducting plate that sinks into the mantle. While global self-consistent numerical models of mantle convection have reproduced some aspects of plate tectonics, the assumptions behind these models do not allow for realistic single-sided subduction. Here we demonstrate that the asymmetry of subduction results from two major features of terrestrial plates: (1) the presence of a free deformable upper surface and (2) the presence of weak hydrated crust atop subducting slabs. We show that assuming a free surface, rather than the conventional free-slip surface, allows the dynamical behavior at convergent plate boundaries to change from double-sided to single-sided. A weak crustal layer further improves the behavior towards steady single-sided subduction by acting as lubricating layer between the sinking and the overriding plate. This is a first order finding of the causes of single-sided subduction, which by its own produces important features like the arcuate curvature of subduction trenches. Citation: Crameri, F., P. J. Tackley, I. Meilick, T. V. Gerya, and B. J. P. Kaus (2012), A free plate surface and weak oceanic crust produce single-sided subduction on Earth, *Geophys. Res. Lett.*, *39*, L03306, doi:10.1029/2011GL050046.

1. Introduction

[2] A first-order characteristic of the solid Earth is the existence of plate tectonics, which exists on no other terrestrial planet in our solar system [*Bercovici*, 2003]; understanding this remains a "grand challenge" of solid Earth geoscience. While there has been progress in self-consistently reproducing some aspects of plate-like behaviour in global models of mantle convection by the use of a visco-plastic rheology [*Foley and Becker*, 2009; *Moresi and Solomatov*, 1998; *Tackley*, 2000a, 2000b; *Trompert and Hansen*, 1998; *van Heck and Tackley*, 2008], such models fail to reproduce single-sided subduction; instead, convergent margins are always symmetric (double-sided), with both plates converging and merging to form a double-thickness "slab" (Figures 1a and 1b). One important assumption of such models is the definition of the top boundary: it is defined as a free slip surface, where the uppermost part of the model is free to

move horizontally (i.e., along the boundary) but not vertically (i.e., across the boundary). In contrast, on Earth, the upper surface of moving lithospheric plates is deformable thereby allowing for the development of topography, which is very large at subduction zones: oceanic trenches are the lowest places on our planet [*Smith and Sandwell*, 1997]. Also, a previous study of the transient subduction of a prescribed oceanic plate showed that a free surface has an important effect as it allows for a more natural bending of the slab during subduction [*Kaus et al.*, 2010]. Therefore, we here test the influence of the top boundary condition on the form of self-consistently-generated plate tectonics using a strongly temperature-dependent, visco-plastic rheology.

2. Method

[3] Calculations were performed using the finite difference/volume multi-grid code StagYY [*Tackley*, 2008] in either a 2 × 1 2-D Cartesian domain or a 3-D spherical shell. A Rayleigh number of 10^6 and internal heating rate of $5.44 \cdot 10^{-12}$ W/kg are used. The model assumes the Boussinesq approximation and its rheology is strongly temperature- and pressure- dependent:

$$\eta(T,p) = \eta_0 \cdot \exp\left[\frac{E_{act} + pV_{act}}{RT}\right] \quad (1)$$

where η is the viscosity, p is the pressure, $R = 8.314$ Jmol^{-1}K^{-1} is the gas constant, T is the temperature, $E_{act} = 240$ kJ/mol the activation energy, V_{act} the varied activation volume and η_0 is set such that η is the reference viscosity at $T = 1600$ K and $p = 0$ Pa. Additionally, plastic yielding is included using a Drucker-Prager yield criterion with the pressure-dependent yield stress σ_{yield} based on Byerlee's law

$$\sigma_{yield} = C + p\mu \quad (2)$$

with specified friction coefficient μ and a cohesion C of 0.6 MPa. The crustal layer has a two orders of magnitude lower viscosity and yield stress compared to mantle material and is assumed to become weak crust after it has resided in the top d_{crust} (see Table S1 in the auxiliary material) of the solid Earth for $t > 25$ ka.[1] It is converted to regular mantle again when subducted below a depth of $d > 900$ km into the mantle. Non-diffusive tracers track the composition. The model domain consists of the whole mantle depth plus (for free surface cases) a "sticky air" layer on top [*Schmeling*

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[1]Institute of Geophysics, ETH Zurich, Zurich, Switzerland.
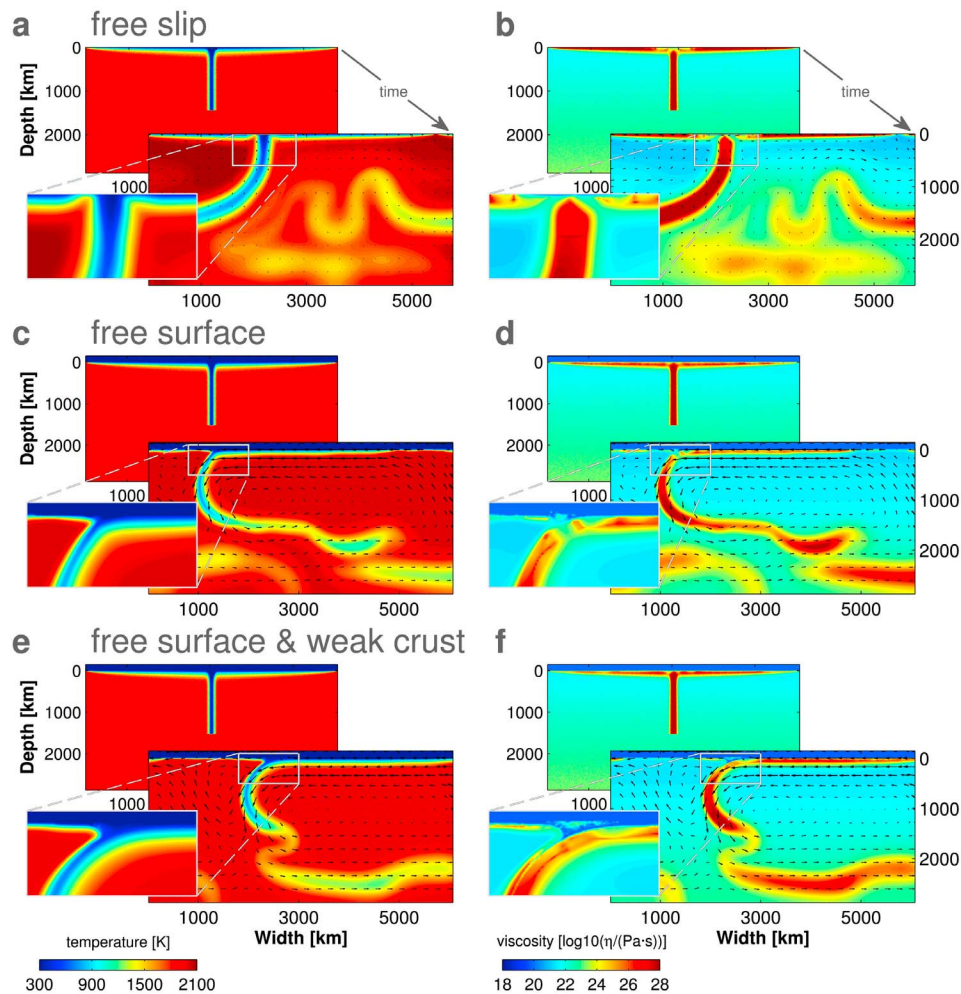[2]Institute of Geosciences, Johannes Gutenberg University Mainz, Mainz, Germany.

Figure 1. Influence of a free surface and a weak crust. Comparison of temperature and viscosity fields over time between calculations using (a, b) a free slip upper boundary condition (case 1) showing double-sided subduction, (c, d) a free surface condition (using a "sticky air" layer) (case 2) and (e, f) a free surface condition combined with a weak crustal layer (case 3), both resulting in single-sided subduction.

et al., 2008], which is a good approach for simulating a free surface with an Eulerian grid and consists of a low viscosity "air" layer of (nearly) zero density that decouples the surface of the lithosphere from the top of the model domain. For a good free-surface treatment this "air" layer has to (a) be sufficiently thick and (b) have sufficiently low viscosity [Crameri et al., 2012]. Using actual values of air or water viscosity are computationally unfeasible, but tests show that a viscosity of 10^{19} Pa·s with a thickness of 150 km is sufficient. Top and bottom boundaries are free slip and isothermal (300 K) on the top and zero heat flux at the bottom. Side boundaries are periodic.

[4] The inclusion of a thin weak crustal layer sets the minimum resolution, because it has to be resolved properly to a depth greater than the base of the lithosphere in order to guarantee lubrication between the converging plates. This requires a high number of vertical grid points. We performed resolution tests using up to 512 vertical grid points (nz). To ensure the fidelity of the dynamical processes that are of interest in this work, $nz > 64$ is needed if the grid is vertically refined at shallow depth (i.e., more than three grid points

covering the layer). In the 2-D cases we use 2 or 4 times as many points.

3. Results

3.1. Free Surface

[5] The snapshots in Figures 1a–1d show the time evolution of two numerical experiments of whole mantle convection that start from an identical symmetric setup that is chosen in order to prohibit straightforward development of asymmetric subduction. Both models have the same parameters (Table S1) except for a different upper boundary condition: free slip in Figures 1a and 1b and free surface in Figures 1c and 1d. Despite the initial symmetric setup, the difference is dramatic, with the free slip case displaying symmetric subduction in which both plates converge and subduct forming a double-thickness "slab", while in the free surface case, subduction soon becomes asymmetric, with only one plate subducting. Adding a free surface to the model allows the strong plate to bend in a more natural manner by developing a foreland bulge and more importantly, a deep trench at the collision zone. At the convergent zone, the two
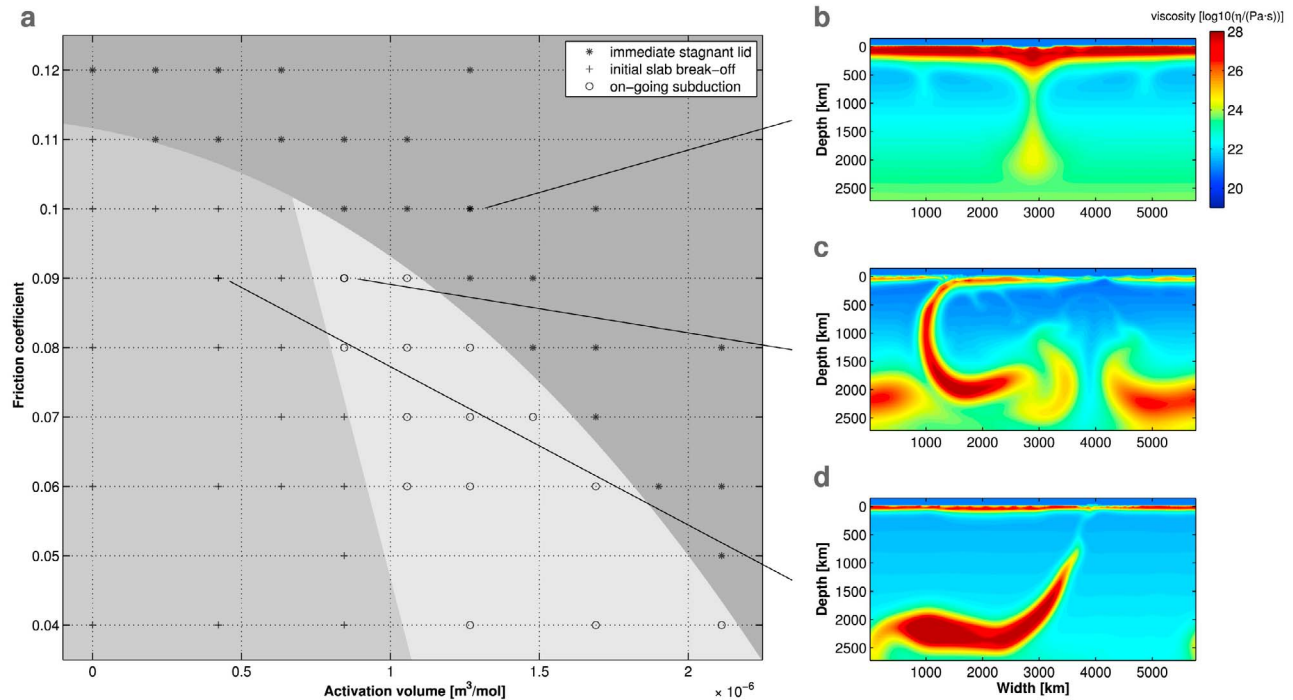
Figure 2. Regime diagram. Tectonic modes of mantle convection derived from 2-D Cartesian simulations in a 2:1 aspect ratio (case 4). (a) Distribution of tectonic modes as function of friction coefficient and activation volume, which are (b) immediate occurrence of a stagnant lid, (c) on-going subduction and (d) initial slab break-off.

converging plates are therefore no longer forced to move horizontally until reaching the very top of the downwelling. This previously forced both plates to bend by 90° over a very short distance and as a consequence undergo very high strain rates and become very weak (due to plastic failure). A free surface, on the contrary, allows the plate to bend more naturally (by forming a deep trench) and to remain sufficiently strong. As a consequence, this results in an asymmetric subduction of one plate under the other (Figures 1c and 1d).

3.2. Weak Hydrated Crust

[6] Despite this first-order change in behavior afforded by the free surface upper boundary, close examination of the velocity field for the simulations in Figures 1c and 1d reveals periods of double-sided subduction in which the subducting plate drags down small portions of material from the overlying plate due to viscous coupling between the plates. Previous studies showed that weak hydrated crust (sediments, hydrothermally altered basalts, serpentinites) present on top of the terrestrial oceanic plates have an important effect on the style of subduction by acting as a lubricating layer between two converging plates [*Lenardic and Kaula*, 1994; *Gerya et al.*, 2008; *Tagawa et al.*, 2007]. A common explanation of the weakness of deep faults (up to 200 km depth) is the presence of fluids (CO_2, H_2O) released by dehydration or decarbonatization reactions [*Peacock*, 1990; *Schmidt and Poli*, 1998]. The lithostatic pressure prohibiting slip along faults is consequently compensated by the fluid pressure. In addition, periodic shear-heating in pre-existing, fine-grained shear zones is thought to be the cause of intermediate depth ($\sim 30 - 50$ km) earthquakes and might therefore be another important mechanism in providing lubrication between two colliding plates [*Kelemen and Hirth*, 2007].

[7] Both, seismic and aseismic slip are, on the long-term average, well described by plasticity. We therefore test this here by adding weak crust. Material is assumed to become weak crust after it has resided near the surface for some time, and it is converted to regular mantle again when subducted below a specified depth into the mantle. We find here that adding such a weak crustal layer promotes thermally and mechanically single-sided subduction and improves the tendency towards continuous single-sided subduction (Figures 1e and 1f). The reason for both improvements is that the weak crust provides lubrication between the converging plates, allowing the subducting plate to be sufficiently strong during simultaneous on-going subduction. The weak crust accumulates at the subduction zone forming an accretionary wedge, some of which is entrained into the subduction channel.

3.3. Plate Strength and Mantle Viscosity

[8] We have performed a systematic suite of 2-D experiments with a free surface and a weak crustal layer, in order to understand how the tectonic regime depends on the yield strength of plates and the depth-dependence of viscosity. Three regimes have been identified (Figure 2). Introducing high plate strength by using a high friction coefficient prevents the initial slab from sinking into the mantle and results immediately in the stagnant lid regime (Figure 2b). When the viscosity increase with depth is small, the initial slab sinks rapidly and breaks off, also resulting in the stagnant lid regime (Figure 2d). In contrast, at higher values of activation volume (V_{act}) and for lower friction coefficients (μ) continuous subduction develops from the initial condition, including a trench that undergoes periods of both retreat and advance (Figure 2c). This shows that the requirements for
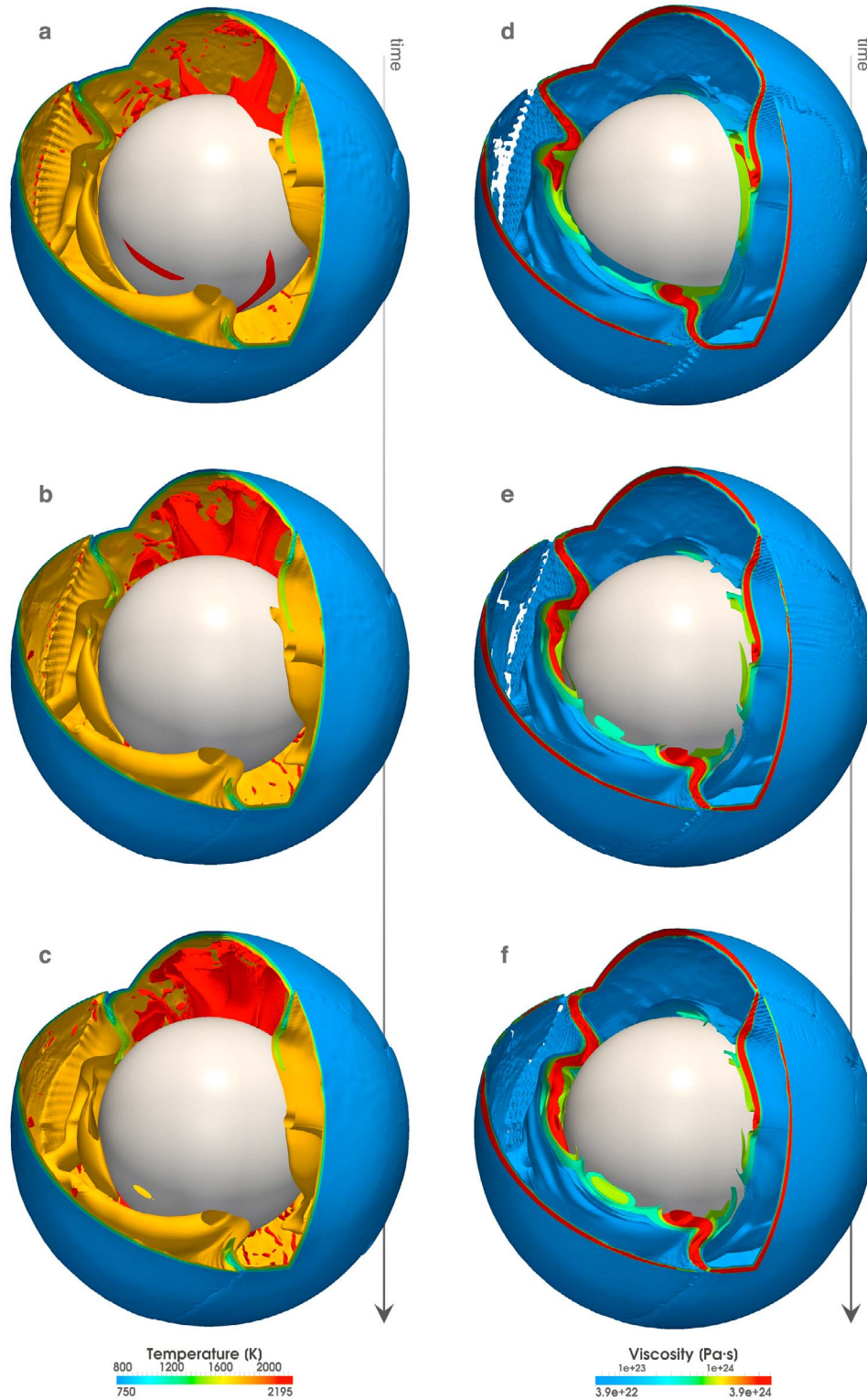
Figure 3. Three-dimensional spherical single-sided subduction. Time evolution of self-consistent plate tectonics in 3-D spherical mantle convection (case 5) with single-sided subduction. Plotted are (a–c) temperature and (d–f) viscosity isosurfaces.
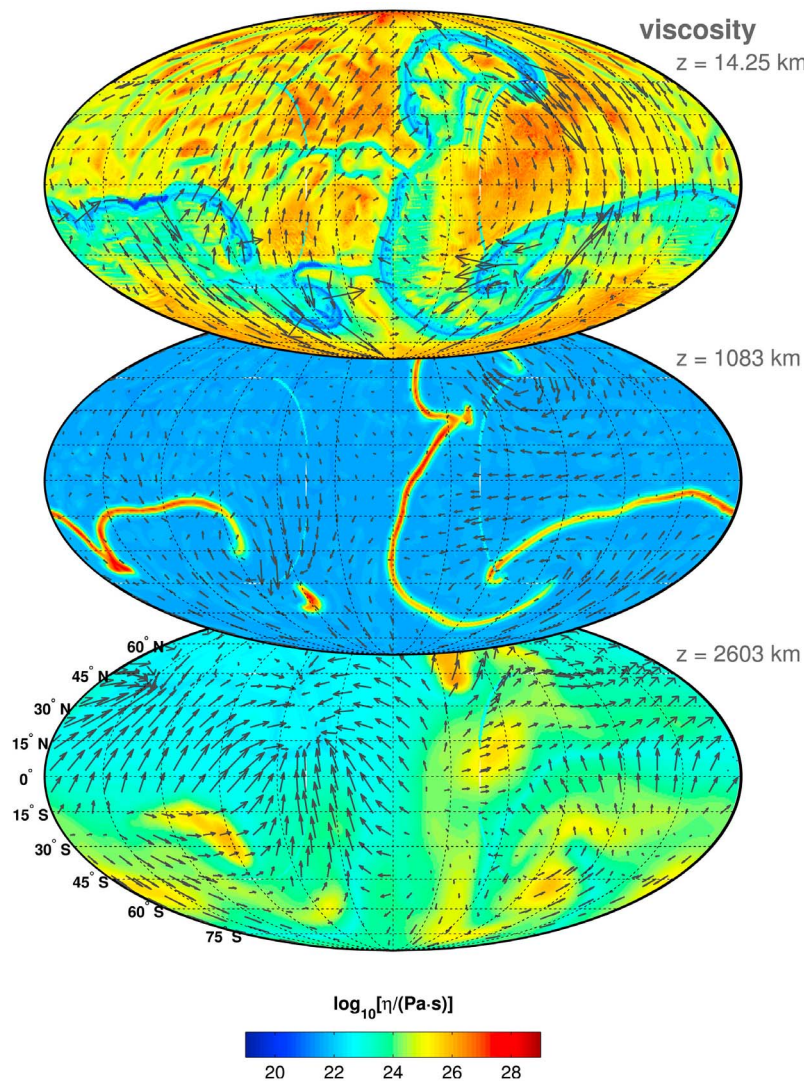
Figure 4. Mollweide projection of 3-D model. Viscosity fields at different depths showing characteristic arcuate trench and slab curvature induced by single-sided subduction (case 5).

steady subduction are a low enough yield strength (friction coefficient) and a moderate increase in viscosity with depth (i.e., at least 3 orders of magnitude with depth, with the upper cutoff depending strongly on friction coefficient) to provide some resistance to slab sinking and prevent break-off [*Mishin et al.*, 2008].

3.4. Sphericity and Three-Dimensionality

[9] Sphericity and three-dimensionality may play important roles in the circulation of Earth's mantle and plates. We therefore present an additional experiment in 3-D spherical geometry (Figure 3 and Animation S1). The inclusion of both a free surface and a weak crustal layer results in single-sided subduction at suitable parameters as determined by the two-dimensional experiments described above. Asymmetric single-sided subduction develops for all downwellings shortly after the symmetrically-configured beginning of the experiment. Retreating or stable trenches and, less commonly, advancing trenches characterize these convergent plate boundaries. Divergent boundaries (spreading ridges) often form close to trenches, resulting in back-arc basins. At

hotter regions further away from subducting slabs, a major region of upwelling forms with several narrow plumes reaching the base of the lithosphere, despite zero basal heat flux. Mantle currents originate from the sinking slabs and create the characteristic bending of wide trenches visible at the surface: wide, concave towards the mantle wedge geometries interrupted by narrow convex zones (Figure 4). Thus, besides promoting single-sided subduction, a free surface results in a more characteristic curvature of the subduction trenches along the surface [*Schellart et al.*, 2007]. This feature is formed due to toroidal mantle flow from the region of high pressure below the inclined sinking slab around its edges towards the region of low pressure above the slab, as has been shown by, e.g., analogue modeling [*Funiciello et al.*, 2006] and as found in nature [*Zandt and Humphreys*, 2008].

4. Discussion and Conclusion

[10] Single-sided subduction has typically been imposed in geodynamic convection models using a weak lubricating zone

or fault together with a prescribed subduction zone geometry [*Zhong and Gurnis*, 1997; *Tan et al.*, 2002; *Burkett and Billen*, 2009, 2010]. However, it has proved very difficult to produce realistic subduction geometry in a self-consistent manner. Here, independent of the domain geometry (2-D Cartesian or 3-D spherical), single-sided subduction is a robust finding. Long-lived single-sided subduction occurs for a range of friction coefficients and requires a moderate increase of viscosity with depth in order to avoid slab break-off. The lithospheric strength, here controlled by the friction coefficient, is a key parameter controlling subduction style. While weak plates result in unsteady 'blob-like' subduction, asymmetry and stable single-sided subduction are fostered by strong plates, although too-strong plates result in a stagnant lid. The values of friction coefficient required to obtain the mobile lid style of plate tectonics (Figure 2) are an order of magnitude smaller than laboratory values [*Kohlstedt et al.*, 1995], consistent with previous studies on yielding-induced plate tectonics [*Foley and Becker*, 2009; *Moresi and Solomatov*, 1998; *Tackley*, 2000a, 2000b; *Trompert and Hansen*, 1998; *van Heck and Tackley*, 2008]. This may be related to the presence of water in nature [*Regenauer-Lieb et al.*, 2001; *Tozer*, 1985]. In order to prevent the initial slab from immediately breaking off a certain viscosity increase with depth is needed to provide resistance to its sinking.

[11] In almost all experiments, a stagnant lid is eventually obtained, even if stable subduction first exists for a long time. Earth-like subduction is not re-initiated once the slab breaks off and plate tectonics reaches the stagnant lid mode. This behavior appears to be different from cases with a free slip upper boundary, in which (double-sided) subduction can reinitiate from a stagnant lid mode. The implementation of continents might help to solve this problem; the models presented here only contain oceanic lithosphere, neglecting the presence of continents. Continents would provide another source of asymmetry for the subduction process and they would also introduce additional lithospheric stresses. Another agent preventing strong plates from ending up in a stagnant lid is the weak crustal layer, which provides the necessary lubrication at the collision zones. In these models, the crustal layer is thicker than the 6–8 km oceanic crust thickness on Earth, but as the lithosphere is also thicker than on Earth due to the lower effective Ra-number assumed here, the ratio of crust to lithosphere thickness ($d_{crust}/d_{lithosphere}$) is reasonable.

[12] Earlier in Earth's history, tectonics may have been different: although there is some evidence for Archean plate tectonics involving subduction, the style of mantle convection on a hotter early Earth is still debated and the form of plate tectonics during that time is unclear [*Davies*, 1992; *de Wit*, 1998; *Sizova et al.*, 2010; *van Hunen and van den Berg*, 2008]. However in recent Earth history, plate tectonics is certainly characterized by single-sided subduction as observed nowadays by seismic tomography [*King*, 2001; *Wortel and Spakman*, 2000; *Zhao*, 2004].

[13] The use of numerical models (like the ones presented here) is central in the study of physical processes occurring in Earth's interior. Including two major features of terrestrial plates – a free upper surface and weak hydrated crust – in such models notably improve their dynamics by producing realistic asymmetric single-sided subduction, which again greatly affects the dynamics throughout the whole mantle. This leads to an improvement of many model tectonic features towards Earth-like physical behavior. Including a free surface will thus be essential in the understanding of global mantle convection present on Earth and on other rocky planets.

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F. Crameri, T. V. Gerya, B. J. P. Kaus, I. Meilick, and P. J. Tackley, Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich, Switzerland. (fabio.crameri@erdw.ethz.ch)