

The influence of ~~subducting slab~~ upper plate advance and erosion on overriding plate deformation in orogen syntaxes

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Abstract. Focused, rapid exhumation of rocks is observed at some ~~plate corners~~ orogen syntaxes, but the driving mechanisms remain poorly understood and contested. In this study, we use a fully coupled thermo-mechanical numerical model to investigate the effect of slab-~~upper plate~~ advance and different erosion scenarios on overriding plate deformation. The subducting slab in the model is curved in 3D, analogous to the indenter geometry observed in seismic studies. We find that the amount of slab advance dramatically changes the orientation of major shear zones in the upper plate and the location of rock uplift zones. Shear along the subduction interface facilitates the formation of a basal detachment situated above the indenter, causing localized rock uplift there. ~~Switching from flat (total erosion) to more realistic fluvial erosion leads to variation of rock uplift on the catchment scale. Here, deepest exhumation again occurred above the indenter apex.~~ We conclude that the change in orientation and dip angle set by the indenter geometry facilitates creation of localized uplift regions as long as subduction of the down-going plate is active. ~~Tectonic uplift~~ Switching from flat (total) erosion to more realistic fluvial erosion using a landscape evolution model leads to variations in rock uplift at the scale of large catchments. In this case, deepest exhumation again occurs above the indenter apex, but tectonic uplift is modulated on even smaller scales by lithostatic pressure from the overburden of the growing orogen, ~~and highest.~~ Highest rock uplift can occur when a strong tectonic uplift field spatially coincides with large erosion potential. This implies that both the geometry of the subducting plate and the geomorphic and climatic conditions are important for the creation of focused, rapid exhumation.

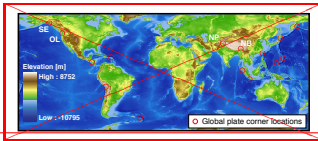
1 Introduction

~~Plate corners connect long curved plate boundary segments (Figure 1) in subduction settings observed around the world.~~ The deformation around ~~plate-plate corners, also referred to as orogen syntaxes~~, orogen syntaxes has been the subject of widespread attention over the last years due to the observed high, sustained, and spatially focused exhumation with rates in excess of 5 mm a^{-1} over million-year timescales. ~~Classic examples of focused rapid exhumation at syntaxes~~ Examples of focused exhumation have been documented for the Olympic mountains of the Cascadia subduction zone (e.g. Brandon et al., 1998; Michel et al., 2000), the Namche Barwa (e.g. Burg et al., 1998; Enkelmann et al., 2011; Stewart et al., 2008) and Nanga Parbat (Craw et al., 1994; Crowley et al., 2009) Himalayan Syntaxes, as well as for the Saint Elias Syntaxis (Berger et al., 2008; Enkelmann et al., 2010; Falkowski et al., 2014) in Alaska. Despite nearly two decades of work, the tectonic- and climate-driven erosional mechanisms

responsible for patterns and rates of upper plate deformation in these areas remain debated (Bendick and Ehlers, 2014; Lang et al., 2016; Wang et al., 2014; Whipp et al., 2014; Zeitler et al., 2001). Plate corners are characterized by a unique geometry (Bendick and Ehlers, 2014; Lang et al., 2016; Wang et al., 2014; Whipp et al., 2014; Zeitler et al., 2001).

The characteristic 3D indenter geometry of the subducting plate. The bending required by subduction on a sphere results in formation of long, slightly concave subduction segments connected by strongly bent, convex arcs, the plate corners. These are flexurally stiffened by the bending and associated with the formation of orogen syntaxes (Mahadevan et al., 2010). This specific at syntaxes can also be observed, to a lesser extent, at other locations. We use the term “plate corners” in this study to refer to all short, convex bends that separate the longer, straight to slightly concave plate boundary segments. This alternation between bends in the subducting plate and straight segments is a direct consequence of the slab bending that is required to accommodate subduction on a sphere (Frank, 1968; Mahadevan et al., 2010). Slab curvature and dip angles naturally vary widely across subduction settings observed around the world (Hayes et al., 2012), but common to all of them is their specific 3D shape can be clearly observed in seismic data from subduction zones, for example at the Cascadia subduction zone or the Alaskan plate corner (Hayes et al., 2012). geometry. The change in orientation of neighboring subducting slab segments effects flexural stiffening of the connecting region and thus creates a convex forward bend in the subducting slab (Mahadevan et al., 2010), referred to here as an indenter. Figure 1 shows the subducting slab geometry at the Cascadia subduction zone, which served as template to the plate geometry used in this study, although we note that the results presented here can provide insight into exhumation patterns other regions where similar plate geometries exist.

In many convergent plate settings, shortening is mostly accommodated by subduction of the down-going plate. However, an additional component of shortening can be taken up by slab advance, i. e. migration of the overriding plate toward the down-going plate (Heuret and Lallemand, 2005). The Nazca–South America subduction zone (Russo and Silver, 1994; Schellart et al., 2000), and the early stages of the India–Eurasia collision (Capitanio et al., 2010), provide examples of shortening with large amounts of slab advance. In previous studies, numerical modeling has played a central role towards understanding focused exhumation in orogen syntaxes. Work by Koons et al. (2002, 2013) simulated focused exhumation in syntaxes as a function of focused (climate driven) denudation. In their approach, they approximate the subsurface to be of homogeneous composition and define a straight S-line boundary between the subducting and the overriding plate, thus not accounting for the 3D geometry of subducting plates observed in many syntaxes. Although the link between erosion and uplift through isostasy is well established (Molnar and England, 1990; Montgomery, 1994; Simpson, 2004), their hypothesis of additional positive feedback by thermal weakening of the crust, causing accelerated deformation beneath deeply incised valleys (see also Zeitler et al., 2001), is controversial. Following this, work by Bendick and Ehlers (2014) considered the effect of the 3D subducting plate geometry, but with simplified upper plate rheology and erosion. In both of these previous approaches the kinematic boundary conditions were fixed, and However, it has been identified that rheological stratification of the effect of different slab advance scenarios not considered lithosphere (Ranalli and Murphy, 1987; Burov, 2011) is one of the key factors that determines deformation and rock exhumation in convergent orogens, by means of both numerical (e.g. Erdős et al., 2014; Vogt et al., 2017) and analog modeling (e.g. Willingshofer et al., 2013).



World map of plate corners. In these regions (red circles), changes in subduction orientation cause flexural buckling of the downgoing plate (Mahadevan et al., 2010). These plate corner span a large variety of geodynamical and climatic settings and provide test cases to identify relevant mechanisms for rapid and focused exhumation.

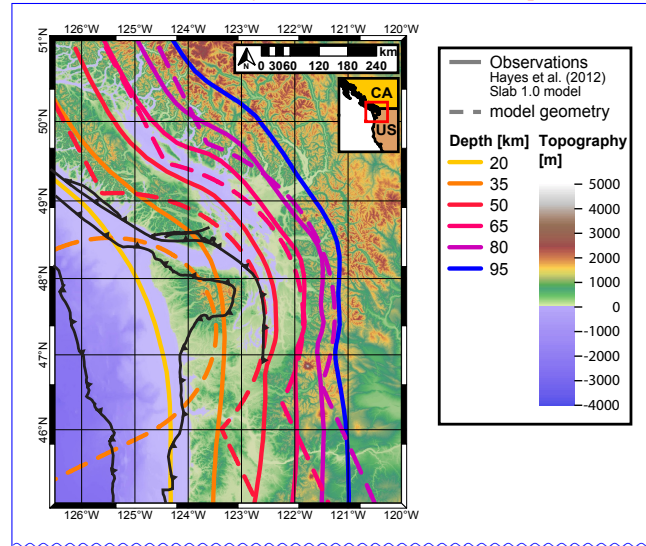


Figure 1. Observed subducting plate geometry and simplified model representation for the Cascadia subduction zone. Model geometry was chosen to best conform to the forward bulge of the downgoing plate. Their rotational shape and straight background slab allow consistent velocity boundary conditions and reduce edge effects. Slab contours from Hayes et al. (2012) Slab 1.0 global subduction zone geometry model, major structures in black from Brandon et al. (1998).

Depending on the direction of mantle flow, the amount of slab pull, and whether the subducting slab is anchored in the deep mantle, convergence of plates can be accommodated by both by subduction and by advance of the overriding plate towards the trench (e.g. Heuret and Lallemand, 2005; Faccenna et al., 2013). While subduction of the down-going plate commonly accounts for the larger part (e.g. Sumatra and Java (Chamot-Rooke and Le Pichon, 1999), or Aleutian (Gripp and Gordon, 2002) subduction zones), an additional component of shortening can be taken up by trench or upper plate advance, i.e. migration of the overriding upper plate toward the down-going plate (Heuret and Lallemand, 2005). The Nazca–South America subduction zone (Russo and Silver, 1994; Schellart et al., 2007), and the early stages of the India–Eurasia collision (Capitanio et al., 2010), provide examples of shortening with large amounts of upper plate advance. While Koons et al. (2002, 2013) used a stationary upper plate in their studies, Bendick and Ehlers (2014) considered solely the case of an advancing upper plate.

In this study, we complement previous work by ~~investigating how~~ Bendick and Ehlers (2014) and ~~investigate how a rheologically realistic upper plate and~~ slab advance and erosion ~~impacts impact~~ the pattern and rates of exhumation in a ~~rheologically realistic upper plate and in a~~ generalized plate corner setting ~~featuring a 3D-shaped, flexurally stiffened down-going plate~~. We do this

for regions featuring a subducting plate that is bent in 3D and flexurally stiffened at the plate corner. Our first aim in this study is the characterization of upper-plate deformation in ~~slab-advance-convergent~~ settings with a subducting 3D indenter geometry. Since Bendick and Ehlers (2014) employed an advancing upper plate, we additionally focus on possible effects caused by lower plate subduction and the degree to which the upper plate is advancing towards the subduction zone. Our second aim is to understand the effect of erosional efficiency on upper-plate deformation and exhumation by contrasting total erosion (i.e. a constant flat surface) with more realistic fluvial erosion ~~-determined from a surface process model.~~ It is important to note that we do not aim for exact representation of a specific region, which would require a more detailed and site-specific adjustment of material and thermal properties as well model geometry and boundary conditions, all of which may affect the style of deformation. Rather, we try to assess the impact of an indenter geometry in generic terms in order to understand the underlying mechanisms.

2 Methods

2.1 Numerical ~~model-details~~ modeling approach

~~Geodynamical-~~

We conduct geodynamical simulations of plate corner subduction ~~zones-are-performed~~ with the program DOUAR (Braun et al., 2008; Thieulot et al., 2008), a fully coupled three-dimensional thermomechanical numerical modeling program designed to solve visco-plastic creeping flow equations at the lithospheric scale. Models in DOUAR are defined by a set of velocity boundary conditions, material properties, and model geometry defining the material domains. Bulk velocities are the result of solving the quasi-steady state force balance equations for nearly incompressible fluids with a finite element approach on an octree mesh. Pressure values are derived indirectly from the velocity solution by the penalty method (e.g. Bathe, 1982) and local smoothing is applied to avoid small-scale pressure oscillations. Finally, temperature is computed, incorporating the effects of material velocities and thermal properties. Material interfaces and bulk volume properties are stored on a self-adapting cloud of particles advected within the model domain. Additional details of the model and governing equations are given in the appendix.

For this study, we developed a new module that makes use of DOUAR's particle-in-cell approach and permits extraction of the pressure and temperature history (p - T - t paths) of particles exhumed at the free surface. Following the methods detailed in Braun (2003), Ehlers (2005), and Whipp et al. (2009), and using the parameters given therein, thermochronometric cooling ages can be calculated from these paths to quantify upper plate exhumation patterns and rates over time.

2.2 Model setup

2.2.1 Geometry

The model domain is 800×800 km in planform and 81 km deep. The element size is $6.25 \times 6.25 \times 1.56$ km, corresponding to $128 \times 128 \times 52$ elements for the entire domain. The direction of subduction is parallel to the ~~x-axis~~ x-axis and the entire setup is symmetric with respect to the $y = 400$ km plane. Therefore, we refer to the $x = 0$ km and $x = 800$ km model boundaries as

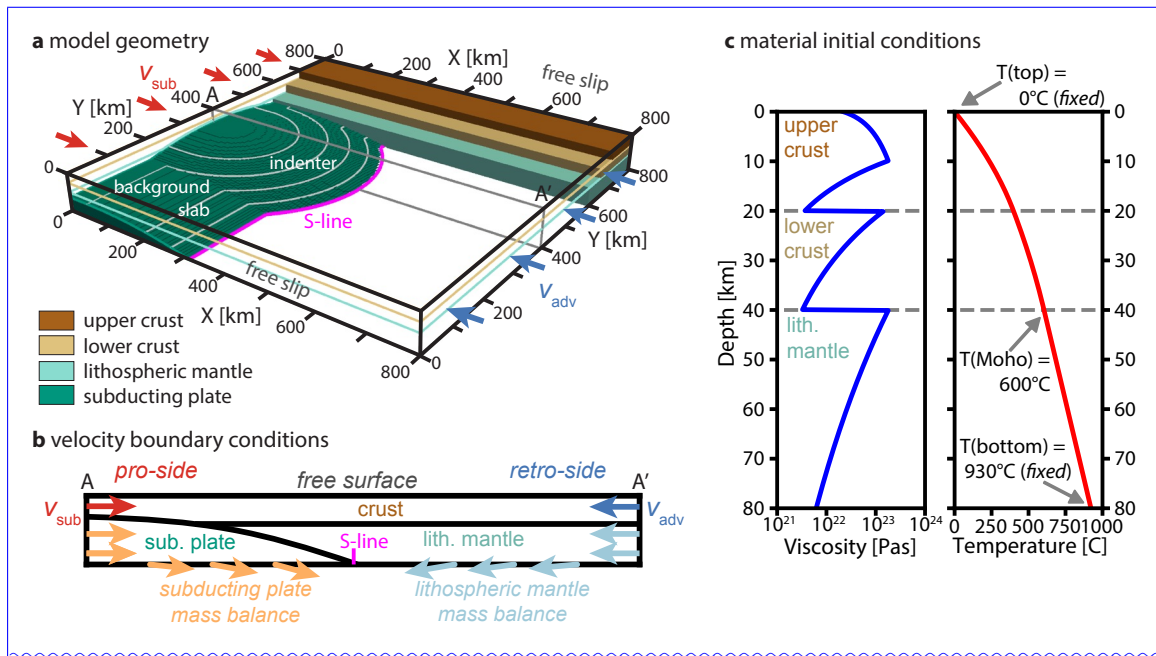


Figure 2. Model setup and properties. **a)** Cut-out oblique view of the model domain illustrating the geometry and material layers: The overriding plate is divided into an upper and lower crust and lithospheric mantle. The down-going plate is a of uniform viscous-rigid material. **b)** Velocity boundary conditions. Downward rotation of Horizontal material influx with v_{sub} from the subducting plate and accretion at left ($x = 0$ km with v_{sub}), as well as influx and v_{adv} from the right ($x = 800$ km with v_{adv}), and continued transport towards the S-line along the bottom boundary. Material influx of subducting plate and lithospheric mantle is compensated up to the Moho depth by rotational motion of the subducting plate and outflux at of the bottom lithospheric mantle increasing towards the center, i.e. only crustal influx is added to the domain. Additionally, vertical velocities can be modified by isostasy. Velocity boundary conditions along front and back ($y = 0$ and $y = 800$ km) are free slip, top is free surface. **c** Vertical profiles of the overriding plate effective viscosity and temperature initial conditions. Material Temperature boundary conditions are fixed temperatures at bottom and top, and zero-flux at all horizontal sides. Detailed material parameters given in supplement table ????

left and right, respectively, and to both $y = 0$ km and $y = 800$ km boundaries as model sides front and back. The model consists of a layered overriding plate, which is divided into upper and lower crust and lithospheric mantle. The subducting plate on the left has a central bulge, referred to here as the indenter. We use different geometries for the subducting plate in this study to investigate its effect on overriding plate deformation. The quasi-2D reference geometry is a downward curved straight slab. It is 30 km high and terminates at $x = 320$ km. The standard indenter is modeled after the Cascadia subduction zone (see Figure 1) and is 50 km high, 350 km wide and terminates at $x = 400$ km along dip. In contrast, the sides of the subducting plate are only 30. Additionally, we show a narrower and wider indenter (200 and 570 km high and terminate at $x = 320$ (see Fig. 2 wide, respectively).

We simplify the model setup to approximate the effect of a flexurally stiffened indenter by prescribing the shape of the indenter and subducting plate shape as fixed through time. ~~This approach minimizes internal deformation of the lower plate and ensures mass balance of the ingoing and outgoing subducted plate. This is achieved by assuming the~~ Furthermore, we set the shape and motion of the down-going plate to be rotational. ~~The, i.e. the~~ curved indenter and along-strike continuation of the plate (referred to as the ~~"background slab"~~ background slab) are spheroidal and cylindrical in cross-section, respectively (Fig. 2). This approach minimizes internal deformation of the lower plate and ensures mass balance of the in- and outgoing subducted plate.

Additionally, a thin, weak layer on top of the down-going plate is added to ensure partial decoupling, which also reduces indenter deformation (cf. Willingshofer and Sokoutis, 2009). The thickness of this weak layer is ~~varied along strike~~ 3.0 km above the indenter and 4.0 km above the lower slab in order to compensate for the changing depth to the slab, such that material inflow along the left domain edge is well-nigh horizontal.

2.2.2 Material parameters

Corresponding to the focus of this study, we use different material properties for the down-going and the overriding plate. In order to approximate the flexural stiffening of the buckled slab, we use a constant viscosity of 10^{25} Pa s and no plasticity for the rigid subducting plate. For the overriding plate, we adopt a layered, visco-plastic rheology. The ductile properties of the upper crust, lower crust, and lithospheric mantle are based on wet granite, dry diabase, and olivine viscous flow laws, respectively (Carter and Tsenn, 1987; Hirth and Kohlstedt, 2003; Jadamec and Billen, 2012). The lithospheric mantle viscosity was designed to conform to the known deformation of olivine aggregates (Hirth and Kohlstedt, 2003). Its pressure dependence was eliminated by using parameters from Jadamec and Billen (2012) and recalculation of the remaining parameters (i.e. stress exponent and activation energy) under lithostatic pressure conditions. Brittle parameters are uniform in the crust with a 10 MPa cohesion and an initial friction angle of 15° . Strain softening reduces the friction angle to 5° at a strain value of 0.55. In the lithospheric mantle, the friction angle is constant 10° . ~~All material parameters are summarized~~ An overview of all material parameters is given in table ~~???~~.

~~Upper Crust Lower Crust Lithospheric Mantle Wet Granite^a Dry Diabase^a Olivine aggregates^b Density ρ 2750 2900 3300 Thermal Diffusivity $k/\rho c$ 1.0 1.0 1.0 Heat Production 1.8 0.6 0.0 Viscosity Prefactor B 4.431.241.21 Activation Energy Q 140.6 276.0 324.3 Stress Exponent n 11.9 3.05 3.5 Cohesion C_0 10 10 2 Friction Angle ϕ 15 \rightarrow 5 15 \rightarrow 5 10 Strain Weakening Interval 10.05 \rightarrow 0.55 0.05 \rightarrow 0.55~~ Overriding plate material parameters

2.2.3 Temperature setup

Model temperatures are set by constant temperature boundary conditions of 0°C at the surface and 930°C at the bottom. Along all vertical sides, zero flux Neumann boundary conditions are applied. Heat production in the upper and lower crust is chosen to reproduce the thermal structure of Bendick and Ehlers (2014). At startup, temperatures are run to conductive steady state, resulting in a Moho temperature of ~~604~~ 600 $^\circ\text{C}$ and heat flux of ~~2425~~ 2425 mW m^{-2} and ~~6870~~ 6870 mW m^{-2} at the model bottom and

surface, respectively. ~~Since the indenter viscosity is temperature-independent, this temperature setup can be applied to the entire model domain.~~

2.2.4 ~~Boundary~~ Velocity boundary conditions

~~In the first part of this study, we investigate the effect of different slab advance scenarios. In the case of~~ We model the two
5 end-member cases, where convergence is completely accommodated either by overriding plate advance (*no-slab full advance*;
all shortening is taken up), or by subduction and accretion, i. e. material inflow into the domain only from left side ($v_{\text{sub}} =$ (*no*
advance), as well as the intermediate case (*half advance*). In order to keep these scenarios comparable, we choose a constant
overall convergence rate of 30 mm a^{-1} , $v_{\text{adv}} =$ in all cases (except for model 7 with doubled convergence rate for comparison).

10 These three scenarios translate into different sets of velocity boundary conditions in our models. Subduction and accretion
correspond to horizontal influx on the left boundary ($x = 0$). *Full-slab advance* corresponds to inflow only from the right side
($v_{\text{sub}} = 0$, $v_{\text{adv}} = 30$) km), while overriding plate advance translates to horizontal influx on the right boundary ($x = 800$ km)
with velocity v_{sub} and v_{adv} , respectively. Boundary conditions at the front and back ($y = 0$ and ~~in the case of *half advance* both~~
velocities are equal ($v_{\text{sub}} = v_{\text{adv}} = 15800$) km). This means the km) are free slip. The bottom is set up to ensure the same mass
15 added to the domain in all scenarios. It is separated into two regimes by the S-line, ~~intersection of overriding and down-going~~
(the kinematic boundary between upper and lower plate at the ~~bottom boundary of the model domain (see Figure 2), is kept at~~
a constant position. To allow better comparison between model scenarios, the overall shortening rate $v_{\text{short}} = v_{\text{adv}} + v_{\text{sub}}$ is kept
constant at 30, so that the model mass balance is the same for all cases. Additionally, outflux at the bottom of the lithospheric
20 mantle increases from zero at the right boundary toward the center in order to compensate material influx from the right. This
ensures all ratios of model bottom): to the left, velocities match a downward rotation of the subducting plate, which translates to
an increasingly downward direction of motion with velocity v_{sub} and up to the S-line; to the right, horizontal velocity is directed
along x with velocity v_{adv} ~~effect the same mass added to the model domain and an additional linearly increasing material outflux~~
that compensates the influx of material from the right up to the height of the background slab. Finally, material flux through
the bottom boundary is also governed by isostasy, which is calculated for an elastic plate thickness of 25 km.

25 2.2.5 Erosion

The ~~second part of this study contrasts two erosion scenarios of flat and fluvial erosion. Flat (or total) erosion removes all~~
~~material uplifted above the initial surface elevation instantly. In this special case top surface is free, with surface stabilization~~
~~algorithm based on Kaus et al. (2010) applied. In models 1 through 9, all topography created is immediately removed down~~
~~to baselevel (*flat or total erosion*), which lies 81.0 km above the model bottom. Under total erosion, rock uplift rate is equal~~
30 ~~to the exhumation rate (England and Molnar, 1990). ~~For~~ The last part of this study contrasts flat erosion with more realistic~~
~~fluvial and diffusive erosion (models 10–12). For this,~~ the landscape evolution model *FastScape* (Braun and Willett, 2013) was
coupled to DOUAR.

~~Fluvial erosion~~ Erosion in FastScape is computed on a regular grid of 0.78 km resolution with uniform precipitation of 1 mm a^{-1} . Erosion constants were $8.0 \cdot 10^{-5} \text{ m}^{-2}$ for fluvial and $4.0 \text{ m}^2 \text{ a}^{-1}$ for hillslope erosion with a stream power exponent of 0.4. The edges at $x = 0 \text{ km}$ and $x = 800 \text{ km}$ are fixed to baselevel and local minima are filled so that each catchment drains to one of those edgesides.

5 2.2.6 Thermochronometric cooling ages

~~Thermochronometric cooling~~ Thermochronometry determines the time since a mineral has cooled below a characteristic temperature, referred to as the closure temperature (Dodson, 1973). This is achieved by the measurement of accumulated decay products in relation to the abundance of radioactive mother nuclides. The loss of decay products – He atoms for the (U-Th)/He method and crystal lattice damage for the fission track method – is thermally activated and specific to each system. At high enough temperatures, all products are lost by diffusion or annealing, respectively. The depth at which temperatures mandate the transition from an open to a closed system is called the partial retention or annealing zone. Above that zone, decay products are accumulated, so their total amount observed at the surface indicates the time since cooling. In order to convert cooling rates into exhumation rates, the geothermal gradient must be known (see Reiners et al. (2005) for a more in-depth description).

In our numerical models, thermochronometric cooling ages are calculated using tracer particles within the domain, and assuming no deformation for 30 Myr prior to the model start. Each predicted age represents an integration of deformation from its respective partial annealing or retention zone to the surface (Dodson, 1973; Reiners et al., 2005). Consequently, exhumation of material from the respective zone to the surface is required before the predicted cooling age can be interpreted in a meaningful way. As thermochronometric ages are sensitive to both changes in particle trajectory and thermal gradients, thermochronometric ages will ~~continue to continuously~~ adjust to the evolving geodynamic conditions ~~after the initial phase~~.

20 3 Results

2.0.1 Modeling strategy

~~We~~ In this study, we investigate the effects of ~~crustal shortening by both~~ subduction and frontal accretion ($v_{\text{sub}} > 0$) and ~~slab upper plate~~ advance ($v_{\text{adv}} > 0$) on upper ~~crust deformation in a subduction zone with a rigid indenter in the central part of the model domain~~ plate deformation. To study the effect of subduction zone geometry, we first compare straight slab-models with ~~indenter-type models under different velocity boundary conditions. Furthermore, we model different indenter geometries. In the last step, we use a landscape evolution model to study the effect of erosion.~~ We evaluate ~~those all~~ models with respect to the resulting rock uplift and strain rates ~~due to the variation in boundary inflow velocities~~. Additionally, we discuss the models' temporal evolution and the predicted thermochronometric ages ~~. In total, we present four models. The first three (no, half, and full advance) are run with flat erosion, the fourth (fluvial erosion) uses the half advance velocity boundary conditions with fluvial instead of flat erosion. An overview is presented in table 1.~~ at the surface.

Table 1. Controlling Parameters Overview

Model Number	Subducting Plate Geometry	v_{sub} [mm a ⁻¹]	v_{adv} [mm a ⁻¹]	Upper Plate Advance	Erosion Type	in Figures
1	straight slab	30	0	No	Flat	4, ??
2	straight slab	15	15	Half	Flat	3, 4, ??
3	straight slab	0	30	Full	Flat	4, ??
4	indenter	30	0	No	Flat	4, 5, 7, ??
5	indenter	15	15	Half	Flat	3, 4, 5, 6, 7, 8, 10, ??, ??
6	indenter	0	30	Full	Flat	4, 5, 7, ??
7	indenter	30	30	Half	Flat	??
8	narrow indenter	15	15	Half	Flat	8
9	wide indenter	15	15	Half	Flat	8
10	indenter	30	0	No	Fluvial	??
11	indenter	15	15	Half	Fluvial	9, 10
12	indenter	0	320	Full	Fluvial	??

3 Results

3.1 Effect of slab advance on strain rate distribution

3.1 Effect of indenter presence and upper plate advance

3.1.1 Overview

5 Figure ??

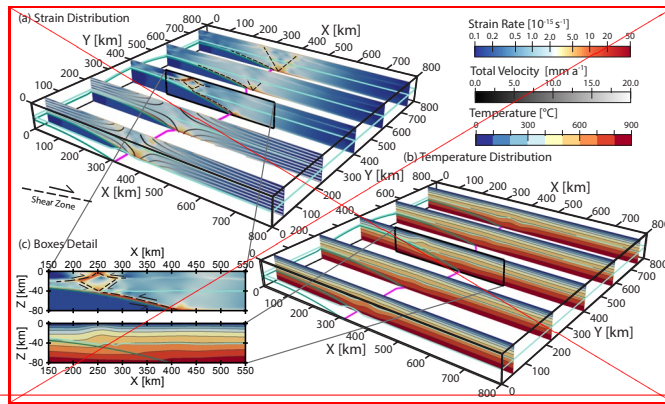
Figure 3 illustrates the key features of the half advance model in a snapshot taken indenter geometry effect on upper plate deformation. Snapshots are shown after 4 Myr modeling time. Strain rates (background colors in panel a) indicate two main systems of localized deformation (simulation time of the straight-slab reference and an indenter-type model under half advance boundary conditions (models 2 and 5; $v_{\text{sub}} = 50\%$ and $v_{\text{adv}} = 50\%$).

- 10 In the straight slab model 2 (Fig. 3a), shortening is accommodated by a lithospheric scale pop-up structure formed by two broad shear zones, indicated by strain rates above $5.0 \cdot 10^{-15} \text{ s}^{-1}$. In the first system, two broad, steeply dipping shear bands rooting
 $\cdot 10^{-15} \text{ s}^{-1}$. These are referred to hereafter as *pro* and *retro shear zone* to the left and right of the S-line and labeled (P) and (R), respectively. The two shear zones root to the S-line at an angle of $\sim 60^\circ$ form a lithospheric scale pop-up structure. Due to the and comprise shallow dipping detachments and steeply dipping reverse faults. However, due to mostly viscous deformation
15 (cf. see Fig. 2), the shear bands are poorly not as strongly localized in the lower crust and lithospheric mantle. Laterally towards the model center and the indenter ($y = 400$, those shear bands attenuate. Here, deformation is accommodated by the second

type of structure, a basal detachment located above the indenter. The particle trajectories shown on the slices at $y = 50$ and 225 km show that material is transported horizontally towards the S-line, where near which paths for crustal material turn upward. In contrast, the lithospheric mantle is gradually subducted. The temperatures shown in panel b) indicate two anomalies that correspond with the two major shear zones. Towards the model sides, temperatures undulate following the bent Moho. Likewise, temperatures above the indenter apex are elevated. With the addition of a curved indenter (model 5, Fig. 3b), the active structures change in the central part of the model, whereas the deformation pattern at the model front and back ($y < 200$ km and $y > 600$ km), beyond the indenter, remains similar to the straight-slab reference model 2. Above the indenter, deformation is mostly localized in a retro-dipping, upper-crustal detachment (referred to as *indenter detachment*, labeled ①), while the pro and retro shear zones are attenuated. The indenter detachment is better localized (strain rates $> 25 \cdot 10^{-15} \text{ s}^{-1}$) and is separate from the two previously discussed shear zones, it originates above the subduction interface rather than rooting to the S-line. The material layer boundaries illustrate cumulative deformation by the deviation from the initial horizontal layout. The straight slab model shows uniform and symmetrical upper crustal thinning, whereas material uplift in the indenter model is much stronger and focused at the location of the basal indenter detachment.

Different amounts of slab advance change the distribution of strain rates significantly, as can be seen from Figure ?? . In the no slab advance. The differences between the straight trench and indenter models are shown in more detail for all boundary condition scenarios in Figure 4. Since changes in deformation are confined to the indenter's vicinity, this figure shows strain rates and rock uplift rates along a central slice along dip. Comparing the straight slab models (left-hand panels) shows that deformation and thus rock uplift are always strongest toward the direction of main material inflow. The half advance scenario discussed above show a nearly symmetrical pattern of shear zones and rock uplift (Fig. ??a), the structures to the left of the S-line, the pro-shear band and the basal detachment, are expressed even more strongly than in the half advancing scenario, whereas the retro-shear band is weaker. The case of full slab advance (3b1 and 3b2), but in the case of no ($v_{\text{sub}} = 100\%$, $v_{\text{adv}} = 0\%$, panels Fig. 3a1 and 3a2) or full advance ($v_{\text{sub}} = 0\%$, $v_{\text{adv}} = 100\%$, panels Fig. ??b) exhibits the opposite behavior: The retro-shear zone to the 3c1 and 3c2), deformation shifts to the left or right of the S-line is more active, while the structures on the left are expressed more weakly. In both end-member cases, a shallow basal detachment forms in the upper crust above the more active of the steeply dipping shear bands, which is not observed in the half advance case., respectively.

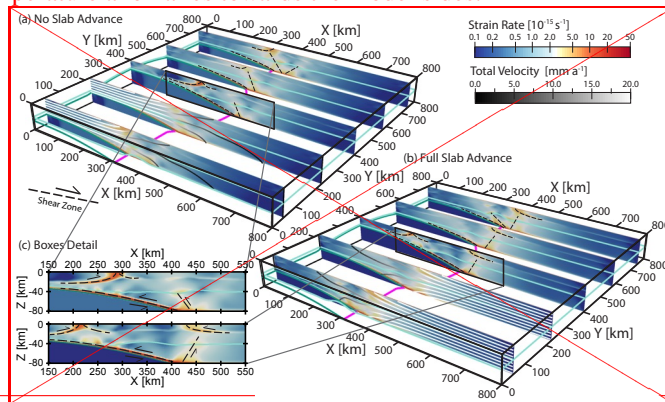
In all models with an indenter geometry, a basal detachment, situated centrally above the indenter, forms the third major structure. It accommodates shortening in the central part of the model and concurrently reduces deformation in the pro and retro shear zone (Fig. 3a5–c5). It is and its position shifts trenchward with increasing upper plate advance. It is strongest directly above the model center and decreases laterally as the height and dip of the subducting plate transition from indenter to the background slab.



Vertical slices along dip after 4.0 modeling time showing

the second invariant of the strain rate tensor, particle trajectories, and the temperature distribution for the half advance scenario. Outlines of the Moho (light green), subducting plate interface (dark green), and S-line (magenta) are added for orientation. Note that results and slices are symmetrical about the $y = 400$ plane. **a)** The strain rate outlines the major shear zones: Two broad, poorly localized shear zones nucleate at the S-line, while the pro-shear zone weakens towards the model center. This shear is accommodated by a basal detachment that is situated on top of the indenter. **b)** Temperatures follow crustal deformation. Significant upward heat advection can be seen in the vicinity of the basal detachment, while Moho deformation dominates the temperature anomalies towards the model sides.

5



Vertical slices after 4.0 modeling time showing the second

invariant of the strain rate tensor and particle trajectories for **a)** no and **b)** full slab advance scenarios. Outlines of the Moho (light green), subducting plate interface (dark green), and S-line (magenta) are added for orientation. The main shear zone rooting to the S-line is oriented towards the direction of influx. At shallow depths, that shear zone forms a basal detachment in the respective orientation. The basal detachment above the indenter exists for both cases, but is pronounced more strongly in the no slab advance scenario.

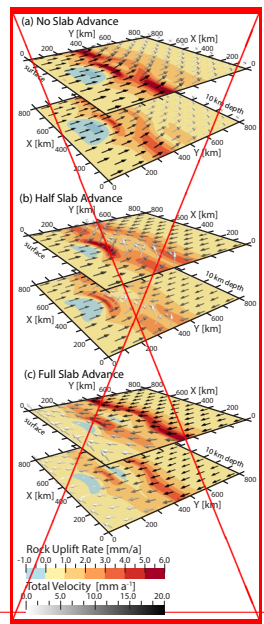
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15 3.2 Effect of slab advance on the spatial distribution of rock uplift

Figure ?? shows two horizontal slices of the rock uplift rate at the surface and 10 depth for the three scenarios. In general, three From these three structures, three corresponding zones of rock uplift, corresponding to the detachments described in

the previous section, can be identified. Two bands of uplift to the left and right of the S-line, associated to the steeply dipping pro- and retro-shear zones, respectively, and a curved ellipsis located above the indenter basal detachment. In all scenarios gives rise to the third region, an elliptical region of rock uplift (Fig. 4a3-c3).

In all models shown in Figure 4, the mean uplift rate is about 1.3 mm a^{-1} , but the distribution of rock uplift strongly depends on slab advance velocity boundary conditions. For no slab advance ($v_{\text{sub}} = 100, v_{\text{adv}} = 0$), deformation is strongest on the pro-side shear zones, i. e. those above the background slab and the indenter ellipsis, show the highest rock uplift rates (6.4 mm a^{-1} vs. 6.4 mm a^{-1}). Uplift rates above the indenter are 30% higher than in the straight-slab reference model (8.3 mm a^{-1} vs. 6.4 mm a^{-1}). In the half advance scenario ($v_{\text{sub}} = 50, v_{\text{adv}} = 0$), rock uplift in the straight slab model is evenly distributed between the pro- and retro-side uplift band (3.8 and 4.3 mm a^{-1}), while the indenter detachment creates a prominent ellipsis-shaped zone reaching almost twice as fast uplift rates of 7.8 mm a^{-1} . Finally, the full advance scenario ($v_{\text{sub}} = 0, v_{\text{adv}} = 100$) exhibits only a comparatively small increase of rock uplift exhibits lowest peak uplift rates above the indenter of all models (5.4 mm a^{-1}), whereas the right-side uplift band is well pronounced with rates reaching 6.3 mm a^{-1} , yet twice as fast as the surrounding area. However, retro-side uplift also reaches equally high rates in both the straight slab and indenter model (5.8 and 5.0 mm a^{-1} , respectively). To summarize, all models with indenter geometry exhibit a region of focused and increased rock uplift above the indenter. This effect is small in the full advance model, but much stronger for the no and half upper plate advance scenarios. For all scenarios, the horizontal distribution of rock uplift rates at 10 km depth mimics the pattern at the surface, but uplift rates are attenuated by roughly 50, indicating that upward motion is concentrated at shallow depths mm a^{-1} . It is shown in comparison to the standard half advance model in Figure ???. There is little difference in the relative distribution of strain and rock uplift between the two models, except at the front and back, where uplift between the pro and retro shear zones is increased in the fast convergence model.



3.2 Relative slab motion effects on temporal evolution

3.1.1 Temporal evolution under different plate motion scenarios

As simulation time progresses, the deformation patterns and rock uplift change differently for the three scenarios. The central region depicted in Figure 5 shows that ~~both for in both~~ the no and half advancing slab scenario, the ~~uplift peak~~ peak in uplift above the indenter increases and reaches a quasi-steady state. In ~~the~~ case of full slab advance, it ~~uplift~~ uplift decreases after reaching a maximum at ~ 4 Myr. Here, the strong and lasting increase can be observed in the right uplift band instead. These changes in uplift are also reflected in the position and modes of shear zones (compare ~~figs. ?? and ??~~ Figs. 3 and 4 showing strain rates at 4 Myr ~~modeling simulation~~ time with strain rates at 8 Myr in Fig. 5). Without slab advance, the indenter basal detachment slowly shifts to the right over time, while keeping its general shape. In contrast, additional shear zones develop alongside the basal detachment for the half advance scenario. In the case of full slab advance, however, motion across the ~~basal indenter~~ detachment almost ceases in favor of a ~~newly formed normal fault~~ reverse fault dipping in the pro-direction.

3.2 Prediction of thermochronometric ages

3.1.1 Prediction of thermochronometric ages

15 Figure 6 shows ~~thermochronometric age predictions and physical parameters~~ predicted thermochronometric ages and maximum depth, pressure, and temperature of exhumed material for ~~the half advancing slab model 5~~ (half advance with indenter geometry) after 8 Myr ~~modeling time and illustrate the possibilities of the newly added particle tracing module. The relative of simulation time.~~ modeling time and illustrate the possibilities of the newly added particle tracing module. The relative of simulation time. The distribution of predicted cooling ages is similar for all ~~systems and the relative increase in age~~ thermochronometric

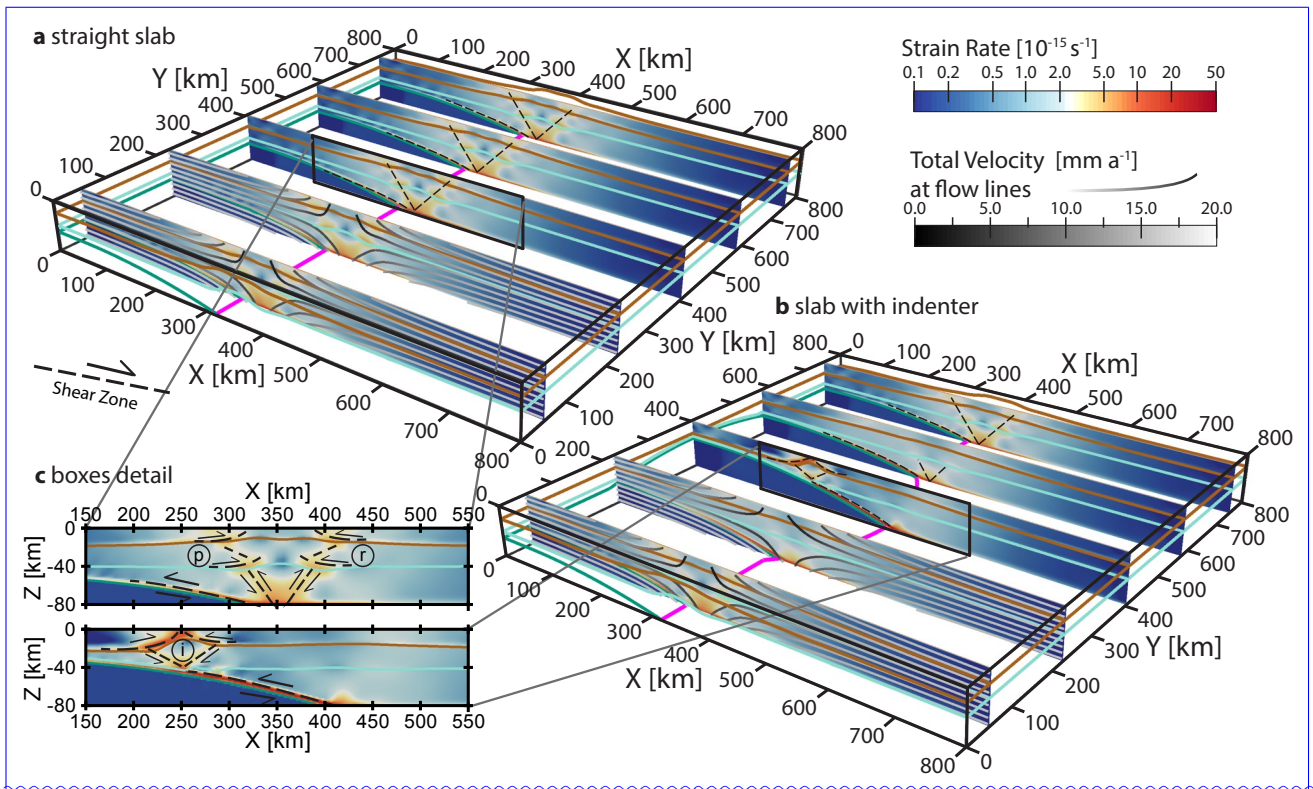


Figure 3. Rock velocity field and uplift rates—Vertical slices along dip after 2.54 Myr modeling simulation time .—Each panel shows two horizontal slices at showing the surface—second invariant of the strain rate tensor and 10 depth—particle trajectories for the three scenarios discussed, **a** straight slab and standard indenter geometries under half advance boundary conditions. **e.** **a**) noBrown, **b**) half, light green and **c**) full-advancing slab. Background colors show rock uplift rate—dark green lines denote the material layer boundaries between upper, with red tones indicating uplift—lower crust and blues—subsidence. Arrows illustrate lithospheric mantle, respectively; magenta marks the full 3-dimensional velocity field—S-line. Pro and retro shear zone are colored by total velocity—labeled \textcircled{P} and \textcircled{R} , indenter detachment \textcircled{I} . Rock uplift occurs in two bands along the S-line—Note that results and in an ellipsoid region above slices are symmetrical about the indenter $y = 400$ km plane. The relative uplift rate in **a** Straight slab geometry; strain rates outline the two bands depends on major shear zones: Two symmetrical and poorly localized shear zones rooting to the inflow velocity ratio—S-line forming a lithospheric-scale pop-up structure. For both **b** Indenter geometry; Deformation at the front and half-advancing slab—back remains unchanged, uplift but above the indenter is equally strong, but more distinguished—shortening is accommodated by a newly formed basal detachment replacing the steeply dipping shear zones. **c** Detail inset shows the stronger localization of strain and thus increased crustal deformation by the basal detachment in the half-advancing scenario—indenter model.

systems shown and the increase in ages between panels corresponds to the respective increase in closure temperature for each thermochronometric system. Likewise, all physical parameters—the maximum depth, pressure and temperature of exhumed rocks show the same pattern, which resembles that of as the cooling ages, which reflect the rock uplift rates at the surface

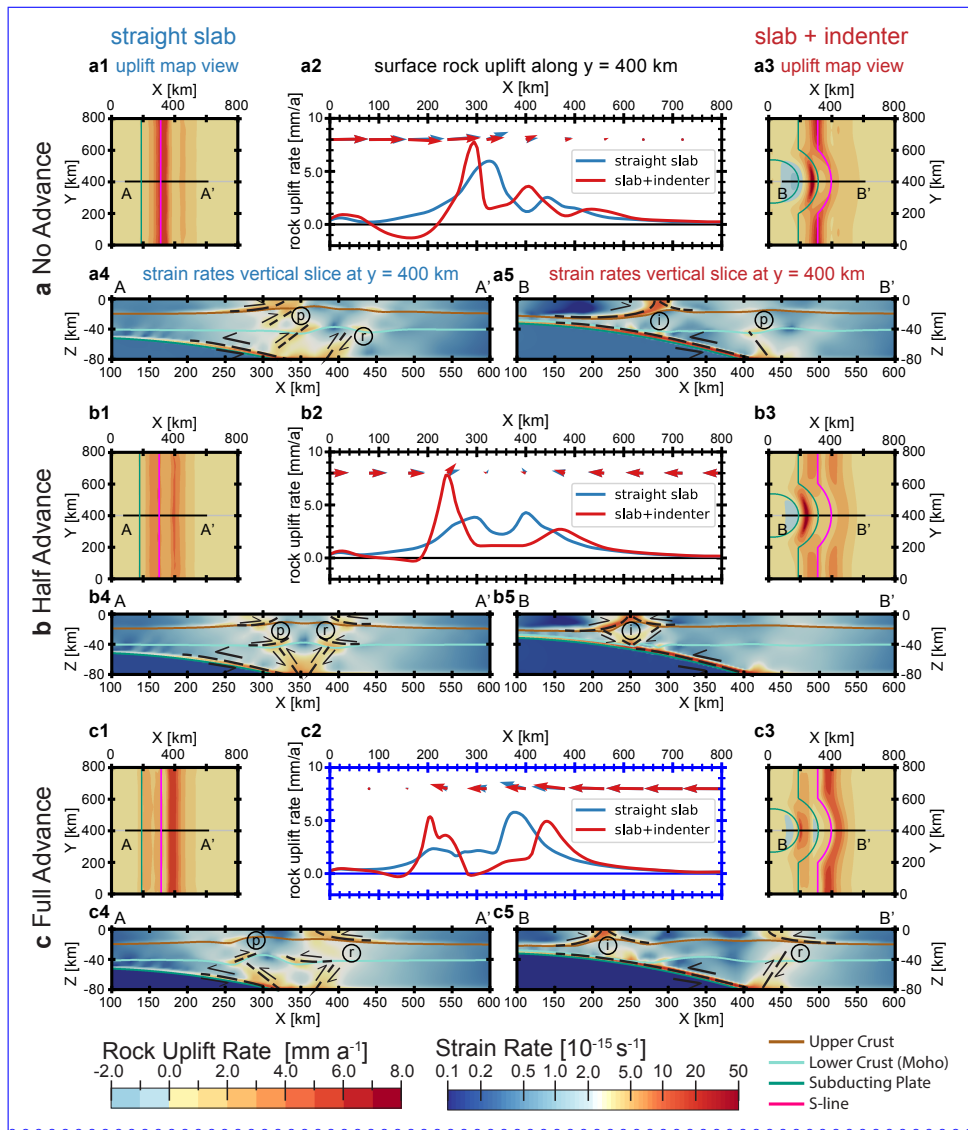


Figure 4. Effect of indenter geometry on rock uplift and strain rates for models 1–6. For each of the three upper plate motion scenarios, panels 1 and 3 show the distribution of rock uplift rates (vertical component of velocity) for the straight slab and indenter geometry, respectively. Magenta lines mark the position of the S-line and dark green are indenter contours at 40 and 60 km for orientation. Panels 2: rock uplift rates at the surface along dip at $y=400$ km (grey line in panels 1 and 3). Arrows indicate orientation of total velocity. Panels 4 and 5 show strain rates for vertical slice along dip at $y=400$ km (grey line in panels 1 and 3). Brown, light green and dark green indicate the material boundaries between upper plate, lower plate, and lithospheric mantle, respectively. Pro and retro shear zone are labeled \textcircled{P} and \textcircled{R} , indenter detachment \textcircled{I} . In all scenarios, the indenter gives rise to an ellipsoidal region of increased uplift above its apex, caused by the newly formed indenter detachment that accommodates shortening in the indenter's vicinity.

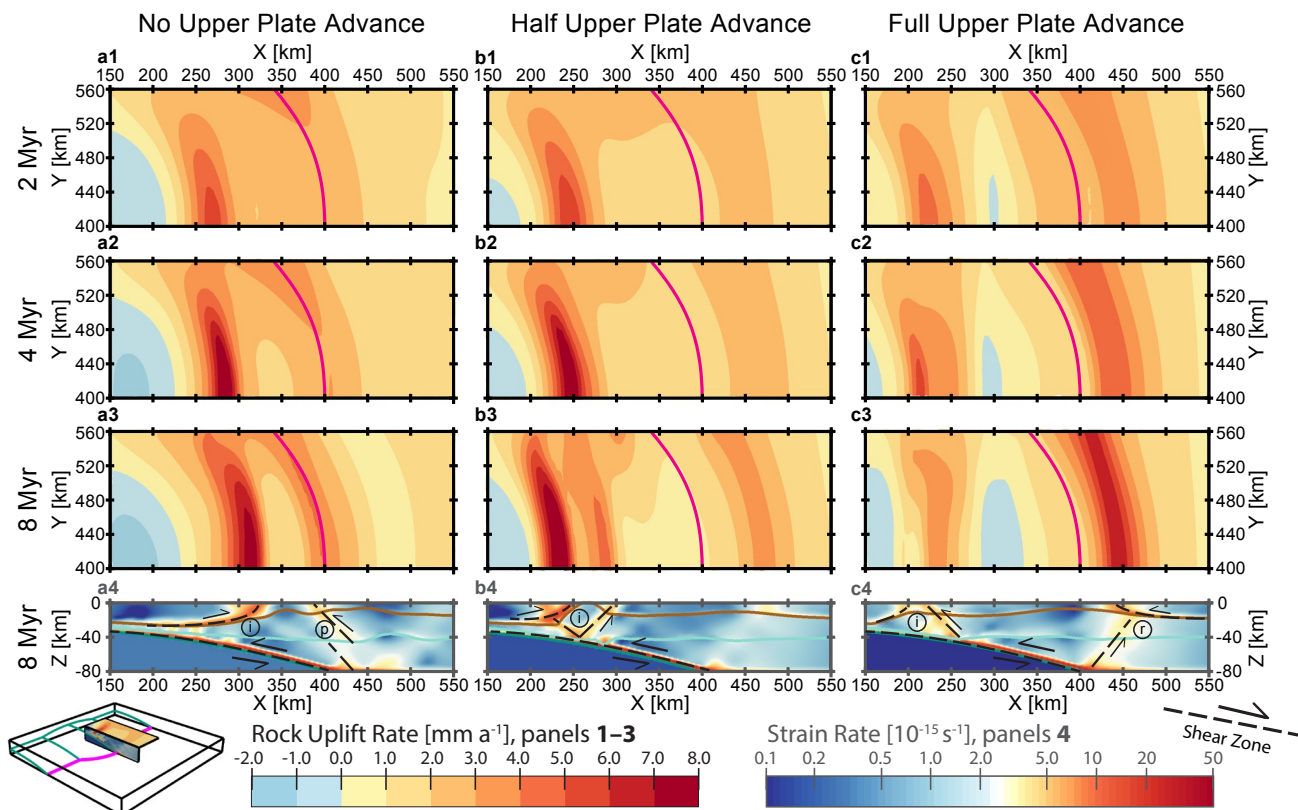


Figure 5. Rock uplift rates for the no, half, and fully-advancing slab scenarios full upper plate advance (models 4-6) at 2, 4, and 8 Myr modeling simulation time (panels a1–c3), and strain rates on the $y = 400$ km cross-section at 8 Myr (panels a4–c4). The panels are cropped to the region of interest of $x = 150\text{--}550$ km and $y = 400\text{--}560$ km. No upper plate advance slab (model 3; left panels) scenario shows a basal an indenter detachment in dynamic steady state that, which slowly migrates to the right. In the half advancing advance scenario (model 4; central panels), uplift above the indenter likewise reaches a plateau saturates, but its position is stable and additional shear zones form in the last stage. Lastly, the full advance case (model 6; right panels) exhibits most uplift at the right uplift band, which continuously increases, whereas the indenter uplift ceases again after reaching a peak at 4 Myr modeling simulation time.

(cf. Fig. ??). Although of similar range, see Figs. 4b3 and 5b). The cooling ages above the indenter are systematically younger in the area above the indenter compared to those from the uplift band slightly but consistently younger than those related to the pro and retro shear zone at the model sides front and back ($y < 200$ km and $y > 600$ km, respectively).

Figure 7 shows a comparison of resulting zircon (U–Th)/He cooling ages and rock uplift rates for the three flat erosion scenarios models 5 4–6 (indenter geometry with flat erosion). In all cases, the distribution of cooling ages again matches that of rock uplift rates (see corresponding plots in Figures 4 and 5). The shift in deformation towards the direction of inflow from pro to retro shear zone with increasing upper plate advance is clearly visible. Additionally, the concentration of young ages above the indenter

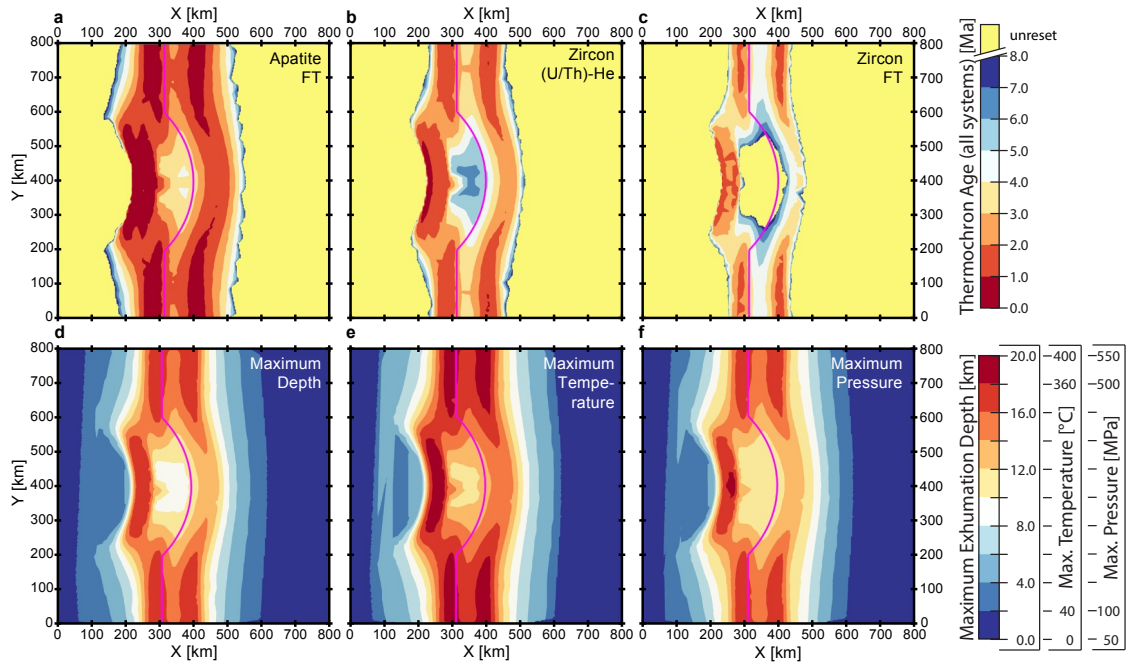


Figure 6. Thermochronometric cooling ages (apatite-Apatite fission track ($T_c \approx 120^\circ\text{C}$), zircon-Zircon (U-Th)/He ($T_c \approx 180^\circ\text{C}$), and zircon-Zircon fission track ($T_c \approx 240^\circ\text{C}$ and), as well as physical exhumation parameters (maximum depth, temperature, and pressure) after 8 Myr simulation time. All observables clearly follow the pattern set by rock uplift rates of two bands at to the model edge front and back, as well as a localized-region of localized uplift above the indenter. Thermochronometric age is increasingly older with a higher closing temperature of the respective system (from left to right).

can be seen in all scenarios. Even in the case of a fully advancing slab full upper plate advance (Fig. 7c), where most deformation is accommodated by the right steeply dipping shear shallow detachment of the retro-shear zone, this increase towards the center decrease in ages towards the area above the indenter is visible in the zircon (U-Th)/He ages.

3.2 Effect of variable erosion on exhumation indenter geometry

- 5 For the half advance velocity boundary conditions, an additional simulation In addition to comparing a straight slab to an indenter-type subducting slab, we investigate the indenter's effect on upper plate deformation by modeling different geometries. Figure 8 shows the distribution of rock uplift rates for both a narrower and wider indenter geometry compared to the standard/reference geometry previously discussed. For all models, the basic effect of the indenter is the same in that an ellipsoidal region of increased rock uplift is generated above its apex around $x \approx 225$ km, $y \approx 400$ km. The maximum uplift rates, however, increase
- 10 with the indenter width. While the narrow indenter reaches only 6 mm a^{-1} , rock uplift rates increase to 8 mm a^{-1} and even 9 mm a^{-1} for the standard and wider indenter, respectively. Furthermore, in the narrow indenter model, the high uplift region is not as clearly separated from the uplift caused by the pro shear zone.

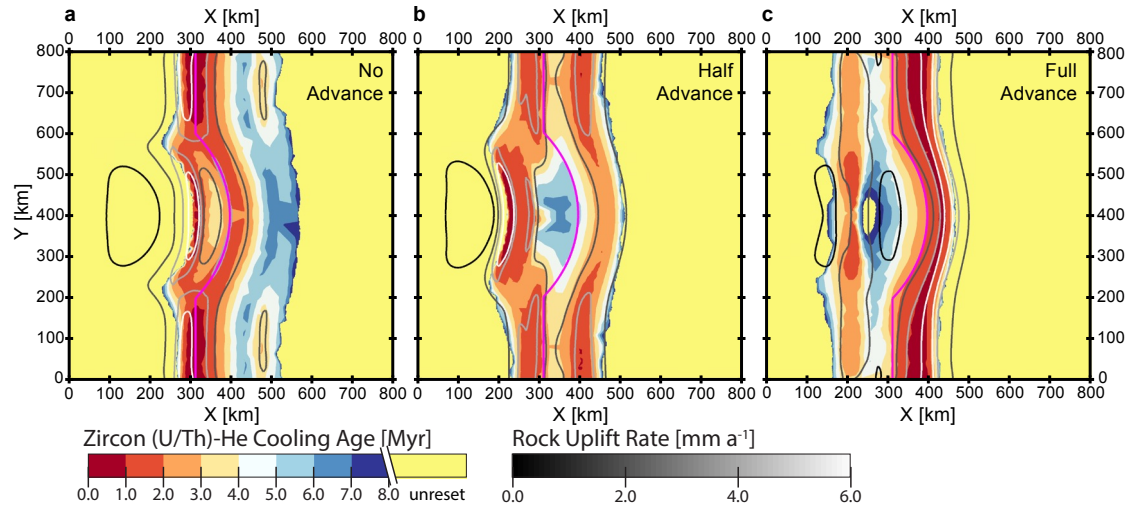


Figure 7. Comparison of zircon-(U-Th)/He cooling age for the three slab advance standard indenter flat erosion scenarios (models 4–6). In all cases, cooling ages match well with the distribution of rock uplift (see figures 4 and 5). The shift in deformation focus in toward the direction of the main material influx is clearly visible by the concentration of young ages shifting from the left to the right of the S-line with increasing upper plate advance.

3.3 Effect of variable erosion

For the standard indenter geometry, three additional experiments coupled to a landscape evolution model (*FastScape*, Braun and Willett (2013)) were performed under no, half and full upper plate advance boundary conditions. The distribution of strain rates and large-scale particle trajectories, as described in section 3.1.1, are only weakly affected by this switch to fluvial erosion. However, the creation of topography and the resulting variations in lithostatic pressure cause changes in upper crustal deformation as illustrated by Figure 9, which shows the half advance fluvial erosion model (model 11).

Panel Figure 9a shows the topography created after 6.0 Myr modeling simulation time, with highest peaks towards the model edge and lower topography and a curved flank above the indenter. The distribution of rock uplift shown in panel b (Fig. 9b) forms two broad bands situated on the flanks of the forming orogen. The left band follows the shape of the slab contour at 50 km depth, with a slight increase in uplift rate above the indenter apex, the right one is only slightly curved and located at $x = 500$ km. In comparison with flat erosion (shown in panel Fig. 9d), rock uplift zones are much wider, especially towards the model sides front and back, and uplift rates are reduced by roughly half. Additionally, there are strong local variations, with peaks in rock uplift situated in river valleys. These local maxima (up to 2.93 mm a^{-1} compared to an average 1.0 mm a^{-1}) correspondingly show deeper exhumation, as can be seen from panel Figure 9c. The two uplift peaks in the marked catchments show the deepest exhumation ($\sim 8 \text{ km}$). They are situated above the indenter and within the region of deepest exhumation in the flat erosion scenario, shown in panel Figure 9e for comparison. They also comprise locations where the youngest thermochronometric ages are predicted (not shown). The fluvial erosion models for no and full upper plate advance (shown

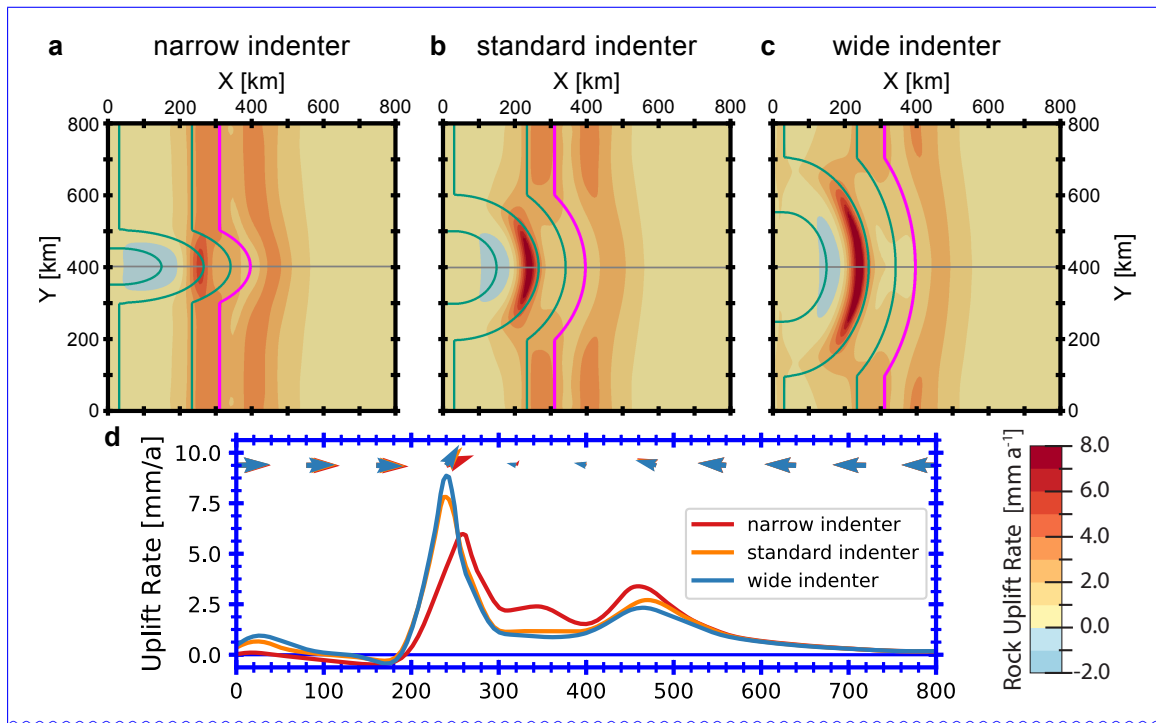


Figure 8. Comparison of different indenter geometries under half advance boundary conditions. Panels 1–3 show map of surface rock uplift rates for narrow, standard, and wide indenter geometry. Panel 4 compares rock uplift rates along a central cross section (grey line in panels 1–3). Basic distribution of uplift is similar in all models with a region of increased uplift above the indenter apex at $x \approx 225$ km, $y \approx 400$ km. Maximum rock uplift rates increase with indenter width.

in figure ??) a close correspondence to the flat erosion models, as well. However, only much smaller catchments cut across regions of increased tectonic uplift. Consequently, there is no local increase in rock uplift as substantial as observed in the half advance scenario. In summary, fluvial erosion leads to variation of rock uplift and exhumation on the catchment scale and maxima in rock uplift roughly 60 km in diameter, while regions of high uplift in the flat erosion scenarios extend ~ 250 km along strike. These zones of deepest and fastest exhumation are situated above the indenter apex.

4 Discussion

4.1 Summary of model results and indenter geometry effect

In all flat erosion scenarios, The simulations presented here with a rigid subducting plate indicate that shortening is accommodated by a lithospheric-scale pop-up structure comprising two shear bands that root formed by two broad shear zones rooting to the S-line along the background slab. They (pro and retro shear zone). Each shear zone comprises shallow detachments and steeply dipping faults. The shear zone oriented towards the direction of material influx is expressed more strongly. In

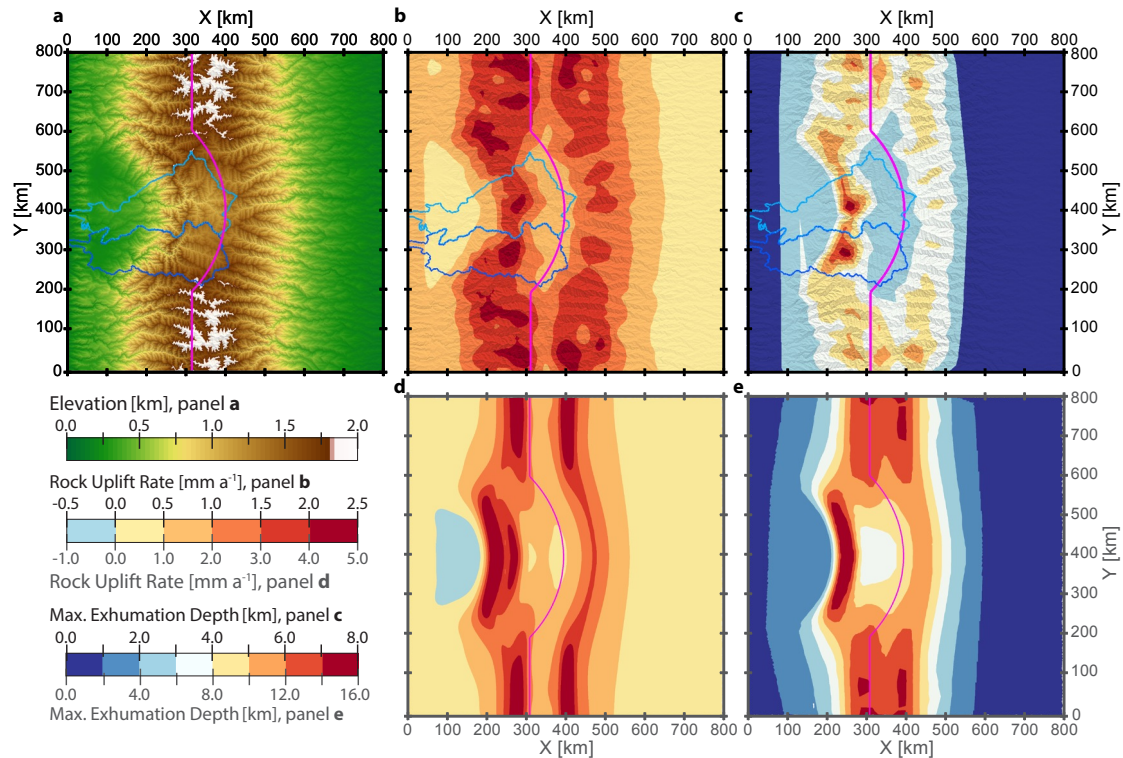


Figure 9. Comparison of rock uplift and exhumation depths with fluvial versus total erosion. **a)** **a** Surface elevations, **b)** **b** rock uplift rates, and **c)** **c** exhumation depth for the half advance scenario coupled to a landscape evolution model 11 (*FastScape* (Braun and Willett, 2013) half advance fluvial erosion) after 6.0 Myr modeling simulation time. Uplift is focused along the flanks of the orogen, with exhumation the two maxima in exhumation situated in river valleys of high erosion potential. Deepest exhumation occurs in the two uplift foci situated above the indenter ($x = 265$ km, $y = 410$ km and $x = 250$ km, $y = 300$ km), situated within the catchments outlined in blue. Predicted thermochronometric ages are: apatite (U–Th)/He: 1.3 and 1.1 Ma; apatite fission track: 1.9 and 1.65 Ma; and zircon (U–Th)/He 4.2 and 4.1 Ma for the upper (light blue catchment) and lower (dark blue) hotspot respectively. **d)** **d** and **e)** **e** show the flat erosion results for rock uplift rates and exhumation depth for comparison. Note the range is increased by a factor of 2 for those two plots (gray labels).

experiments with an indenter bulging forward from the subducting plate (models 4–12), a more intensively localized basal detachment forms above its apex (indenter detachment) and accommodates shortening there. Concurrently, shear across the pro shear zone is strongly reduced. This effect is limited to the indenter’s vicinity, as can be seen from models with a narrower and wider indenter (Fig. 8). These shear zones give rise to two bands of uplift that follow the S-line trace, while the pro-band diminishes towards the model center. There, above the indenter apex, a basal detachment forms and creates a spatially focused three regions of rock uplift in the flat erosion scenarios: the shallow crustal detachments of the pro and retro shear zones create two bands that follow along the trace of the S-line, offset to the left and right, respectively. The third zone of high uplift, created

by the indenter detachment, is shifted further trenchward (left) and forms an isolated, elliptical region of uplift ~~that is stronger in the no and half upper plate scenarios (e.g. Figs. 4 and 5).~~

~~The two main factors for~~

4.2 Model caveats and limitations

5 Our model setup is ~~generic and includes~~ generalized to include the first-order features of plate corner settings, but is not designed to reproduce a specific region. ~~Numerical, given limitations due to numerical~~ resolution and large uncertainties on rheologic and thermal parameters ~~do not permit this of any particular region.~~ Moreover, rock uplift rates in our model are overestimated for flat erosion simulations (~~section ?? models 1–9, shown in Figs. 3–??; figs. ??–58~~), which inhibits the creation of topography that would exert an isostatic counter-force to material uplift. With these caveats in mind, rock uplift rates in the flat erosion
10 models should be seen as upper bound in cases of extremely high erosion. Corresponding to the high rock uplift rates, our predicted cooling ages are very young, but nevertheless consistent with the range of exhumation rates reported at syntaxes: $\sim 1 \text{ mm a}^{-1}$ in the Olympic mountains (~~Brandon et al., 1998~~), (~~Brandon et al., 1998; Michel et al., 2018~~) $3\text{--}5 \text{ mm a}^{-1}$ in SE Alaska St. Elias range (Enkelmann et al., 2016), and $5\text{--}9 \text{ mm a}^{-1}$ in the eastern Himalayan syntaxis (Enkelmann et al., 2011; Lang et al., 2016).

15 It is also worth noting that in the fluvial erosion simulations, uniform precipitation was used throughout the model run. While this is justifiable for our study of contrasting erosional efficiency, it has been shown that changes in precipitation by orographic effects strongly influence the distribution of rock uplift and consequently orogen dynamics (Willett, 1999). ~~If wind comes from the pro-side, the increased erosion might increase the focusing effect observed above the indenter apex, whereas we expect weaker erosion maxima with wind from the retro-side.~~ Despite these limitations, several general lessons emerge from
20 our simulations that have bearing on understanding exhumation processes in plate corner settings. In the following, we will discuss key aspects and mechanisms of exhumation at plate corners.

4.3 Effect of indenter presence and geometry

The variation in subducting plate geometry from background slab to the ~~differences between the indenter and background sections of the subducting slab can be attributed to the slab geometry.~~ The indenter causes different structures to evolve to
25 accommodate shortening (e.g. Figs. 3 and 4). Through this change in structures along strike, localized exhumation is created. Once deformation is localized, both strain and thermal weakening contribute to intensify shear across those structures (see temperatures in figure ??) and focus deformation even further in that region, thereby increasing uplift rates. In our models, the indenter detachment is created by the shallower slab and lower dip angle of the indenter, which exerts a stronger traction on the overriding plate, both forward and downward ~~, that furthers the development of the observed basal detachments. (see Fig. 4 and~~
30 velocities in Fig. ??). Additionally, the ~~steeper dip of the indenter at depth provides better conditions for strain transfer along~~ indenter detachment partially takes up strain that would otherwise be accommodated by the pro shear zone. Strain transfer between these systems occurs along the weak subducting plate interface. Along the ~~interface than the~~ background slab, ~~so that no additional shear zone is needed to accommodate shortening in this region. It~~ the interface's lower dip angle seemingly makes

strain transfer less favorable (c.f. Fig. 4). The extent of the indenter detachment is limited to the indenter width, but a minimum size is required to observe its effect. For the narrow indenter, material is displaced laterally rather than exhumed. This is also evident by the higher uplift rates for the wider indenter, where lateral displacement is most strongly impeded. Detachment-like shallow faults dipping towards the subducting plate have been reported for the Andean orogen (e.g. Horton, 2018b). It is important to note that the ~~different depths~~ lateral variation in depth to the subducting slab ~~in our models~~ may contribute to those effects. Nevertheless, the variation of slab dip angles conforms to natural conditions. A prime example are the Olympic mountains, where the accretionary wedge is exposed on land only above the observed slab bulge (Brandon et al., 1998), which illustrates the substantial effects changes in the subducting slab geometry can cause the changing style of deformation. Still, the Cascadia subduction zone, template to our model geometry, is an example of such a change along strike. Above the indenter bulge, the Hurricane ridge fault warps from offshore to on-land and exposes the accretionary wedge in the Olympic mountains, directly above the indenter apex (Figure 1 and 10, Brandon et al. (1998)). This is supported by work of Calvert et al. (2011), who deduce strongly increased underplating of sedimentary material above the indenter bulge from seismic tomography.

4.4 Effect of ~~slab upper plate advance~~ on strain rates

The slab advance velocity has a first-order influence on the orogen dynamics, as the steeply dipping shear zone oriented toward the primary influx direction is expressed more strongly. Contrary to two other scenarios, the basal detachment in the full advance case. Many numerical models of subduction processes use a fixed overriding plate with respect to the trench position (see e.g. Koons et al., 2010; Braun and Yamato, 2010; Willett, 1999) In contrast, Bendick and Ehlers (2014) used a stationary indenter and advancing upper plate. Our models explore how focused uplift created by an indenter geometry varies with respect to different velocity boundary conditions. The indenter detachment is more active in the no and half upper plate advance scenarios, corresponding to the behavior of the pro shear zone. In the full advance scenario, however, the indenter detachment is only of transient nature (cf. Fig. 5), and rock uplift rates above this feature reach barely half those seen in the other scenarios: models (Fig. 5). Since localization of rock uplift by the indenter detachment corresponds to a different accommodation of shortening along strike caused by the indenter geometry, it seems evident that sufficient deformation in the indenters' vicinity is required to make those different structures observable. As much of the overall shortening in this the full advance case is taken up by the retro-shear band, even increasing by time through thermal and strain weakening, strain transfer along the weak subduction interface and thus uplift ~~on this side~~ above the indenter is strongly reduced.

The half and no advance scenarios, however, The increased deformation in the retro shear zone – associated rock uplift rates increase by $\sim 40\%$ from 4 to 8 Myr simulation time – leads to subsidence above the indenter (see panel a3 in Figure 5), because the correspondingly reduced material flow along the subducting plate interface can no longer support the thinned crust, which then relaxes isostatically. This conforms to observations of the Chilean forearc, where compression has induced flexural subsidence by thrust or reverse faulting in the late Cenozoic (see Horton, 2018a, and references therein).

Additional effects of the different velocity boundary conditions can be observed between the no and half upper plate advance scenarios. Both flat erosion models reach a dynamic steady state at ~ 4 Myr. ~~Due to no opposing influx, the peak position in the no slab advance scenario continues to move 50 forward in~~ with rock uplift rates of ~ 8 of modeling time, but the general

structure of shear zones and strain distribution stays the same. The mm a^{-1} above the indenter. Although maximum uplift rates are about the same, the region of focused uplift above the indenter appears more prominent in the half advance case. This is due to the even distribution of shear between the pro and retro shear zones in the half advance scenario is the intermediate case and shows features of both other scenarios, with a stronger retro-shear zone and a persistent, but spatially stable, basal detachment above the indenter.

4.5 Effect of slab advance on exhumation and cooling ages

Exhumation and rock uplift, which are the same in case of flat erosion, are defined by the orogen-scale dynamics discussed in the previous section. Deformation and uplift are strongest in a broad region along the S-line, with a localized region of uplift created by the basal detachment, if active. The amount of slab advance influences rock uplift through the relative activity (or rate of deformation) of shear bands as discussed in the previous section. Higher slab advance velocities cause faster rock uplift along the right uplift band, whereas more frontal accretion strengthens the left band and centers the uplift above the indenter. In the no and half advance scenarios, rock uplift rates above the indenter reach 7.5 at $3.5-4$, but only which creates uplift over a wider area at consequently lower rates. Their respective rock uplift rates at the front and back reach only 4 and 5 mm a^{-1} in the fully advancing slab scenario, decreasing again after 4 the half advance scenario, whereas uplift rates in the no upper plate advance model reach up to 9 mm a^{-1} . Finally, the indenter detachment in the no advance scenario is slowly shifting to the right (away from the trench). In the half advance model, this motion is prevented by opposing material inflow, focusing deformation and thus stabilizing deformation through increased thermal weakening. The exhumation of lower crustal material at 8 Myr simulation time (panel b4 in Figure 5) illustrates this focusing effect well.

Note that the overall rate of convergence has only limited effect on the distribution of deformation. Naturally rock uplift is twice as fast for the doubled convergence rate (see Fig. ??, but the relative distribution is mostly the same. Small deviations in strain rate fields stem from different isostatic adjustment and the strain-dependent material viscosity.

As expected, predicted cooling ages and exhumation parameters calculated conform with the model velocity fields and offer an additional option to illustrate the distribution of deformation in the overriding plate. They provide the best option to relate model results to natural observations. However, rock uplift in our models is exceptionally fast due to flat erosion, which prevents the creation of topography that would counteract rock uplift. Given this, it is important to take the resulting values as only a general representation of what could be observed in natural systems, and to focus on the age pattern rather than the absolute values.

4.5 Sensitivity of exhumation to different erosion parameters

On large scales, the relative distribution of rock uplift is similar for both perfect quite similar for the flat and fluvial erosion model runs. Nevertheless, the growing topography produces means an increased lithostatic overburden, causing both a general reduction in rate and redistribution of rock uplift. In general, rock uplift is spread out over a wider area than in the flat erosion model. Additional spatial variations in rock uplift occur on the catchment scale. Higher uplift rates are situated in valleys, and the deepest and fastest exhumation is observed. Strong erosion removes lithostatic overburden and engenders higher uplift

rates, mostly so in steep and sufficiently large catchments along the orogen flanks. Under half advance, two rivers with large upstream catchment area cut across the region of localized uplift above the indenter apex (Fig. 9). It is there, where strong tectonic forcing coincides with a high erosion potential, ~~in this case through the large upstream catchment area.~~

5 ~~From the previous~~ such that the deepest and fastest exhumation is observed. Both other fluvial erosion models (no and full advance) show variation in uplift on the catchment scale as well (Fig. ??), but lack comparably large rivers transecting regions of high tectonic uplift. Thus, ~~no equivalent localization effects can be observed.~~ From these results, we hypothesize that both focused deformation and focused erosion are necessary in order to form a region of localized and rapid uplift. The curved 3D-geometry of the subducting plate at plate corners sets the stage, as proposed by Bendick and Ehlers (2014), but only when this concurs with a sufficiently high erosion potential, a spatially limited area of intense uplift can ~~form (cf. Zeitler et al., 2001)~~

10 ~~form~~
~~A prime example~~ be formed (see Zeitler et al., 2001). Prime examples for this are the Himalayan syntaxes, where the Yarlung and Ganges river, respectively, cut across the Himalayan range and steepen rapidly (Finlayson et al., 2002). In combination with active crustal-scale structures (Burg et al., 1998; Schneider et al., 1999), this has given rise to spatially limited, rapid exhumation as indicated by very young thermochronometric cooling ages (Zeitler et al., 1993; Winslow et al., 1996; Burg et al., 1998; Malloy, 2004; Zeitler et al., 2014).

Figure 10 shows model results atop topography of the Cascadia region, which served as template for the subducting plate geometry used in this study (see Fig. 1). In general, the modeled distribution of rock uplift rates reflects topographic highs and lows. Moreover, the catchment-scale variations in rock uplift introduced by fluvial erosion are also comparable to natural variations. For the interior of the Olympic mountains, an area of about 60 km diameter with increased uplift of $\sim 1.0 \text{ mm a}^{-1}$ and Apatite (U-Th)/He cooling ages of less than 2 Myr in contrast to background uplift rates of $< 0.25 \text{ mm a}^{-1}$ has been observed (Brandon et al., 1998; Michel et al., 2018) A comprehensive representation of this setting certainly calls for more rigorous tuning of model parameters, but even with our generalized approach the results presented here capture important first-order properties.

4.6 ~~Comparison to previous work~~

25 4.6 Comparison to previous studies

This work combines and builds upon previous ~~work~~ studies. Koons et al. (2002) showed that locally enhanced erosion rates and pre-weakened crust can lead to focused exhumation. However, they used a uniform visco-plastic material for both overriding and down-going plate and a straight S-line and material influx ~~and with~~ basal drag only on one side, ~~corresponding to our no advance scenario.~~ This approach corresponds to our straight-slab no advance simulation. Flat erosion was applied in only a limited region, while surrounding areas were not eroded, resulting in highest rock uplift rates in this very region. In contrast, Bendick and Ehlers (2014) used an indenter-type geometry, but temperature-dependent viscous rheology for the overriding plate and uniform, flat erosion. Due to the viscous rheology, no strain localization was observed and rock uplift rates increased

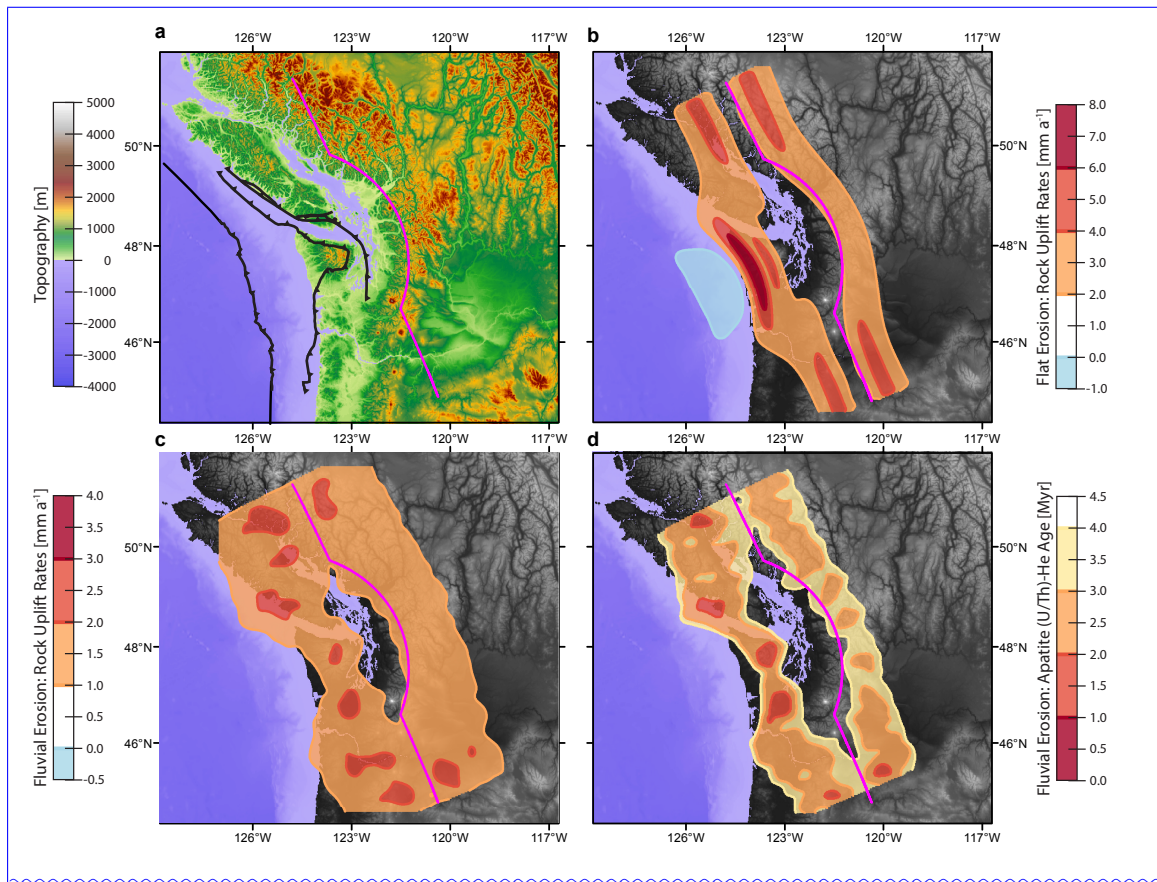


Figure 10. Comparison of **a** Cascadia topography (major structures in black) with model results (models 5 and 11): **b** flat erosion rock uplift, **c** fluvial erosion rock uplift, and **d** fluvial erosion predicted Apatite (U-Th)-He cooling ages. Model S-line in magenta for orientation. The region of increased uplift above the indenter for the flat erosion model coincides with the location of the Olympic mountains. The fluvial erosion model shows smaller variations in rock uplift rates and cooling ages that are roughly the same size as the Olympics.

gradually from the edges toward the center, forming an uplift region of several 100 km extent. While they explored effects of viscosity and indenter geometry, only full **slab-upper plate** advance velocity boundary conditions were used.

The In contrast, the addition of frictional plasticity in this study naturally allows for strain localization. In combination with fluvial erosion, this illustrates possible mechanisms that create localized regions of uplift without relying on a priori defined structures.

4.7 **Model caveats and limitations**

5 **Conclusions**

~~In a generalized 3D curved slab subduction setting, the effect of~~ This study investigates the thermomechanical response of upper plate deformation and erosion to subduction of a rigid indenter. We do this by exploring the effect of the presence and shape of a subducting indenter, velocity boundary conditions (i.e. amount of upper plate advance), and erosion on the ~~deformation resulting deformation pattern~~ in the overriding plate ~~is investigated, with focus on the emergence and properties of localized~~ rock uplift. Particle tracking and thermochronometric age prediction has been added to an existing model (DOUAR) to allow for direct and more tangible evaluation of crustal deformation. Key results from this study include:

~~The common point of all models is the localization of deformation in two major systems. One is an~~

1. For a straight subducting slab (without an indenter), shortening is accommodated by a lithospheric-scale pop-up structure composed of two steeply dipping shear bands broad shear zones rooting to the S-line and cutting across the entire lithospheric mantle and crust. The shear ~~bands are expressed more strongly towards the model sides and toward the primary direction of inflow. For the no slab advance scenario, the retro-side shear band almost disappears, and in the case of a fully advancing slab, the pro-side shear band is much weaker. The second zone oriented toward the side of influx accommodates more shortening; at half advance, shear is distributed evenly.~~
2. Adding an indenter to the subducting plate creates another major shear system is a, and a strongly localized basal detachment situated above the indenter apex. ~~This detachment is strongly expressed only for a not or half advancing slab and~~ Concurrently, shear across the pro shear zone is strongly reduced. The indenter detachment gives rise to a zone of localized rock uplift ~~that~~. Its extent along strike is governed by the indenter width. While Bendick and Ehlers (2014) showed this indenter effect solely for upper plate advance, we find that this localization effect is stronger if shortening is accommodated at least partially by lower plate subduction.
3. Under no or half upper plate advance boundary conditions, uplift above the indenter reaches a quasi-steady state with uplift rates of 7.5 mm a^{-1} at $\sim 4 \text{ Myr}$. In case of a fully advancing slab, ~~uplift rates reach only upper plate, however, maximum uplift rates above the indenter are~~ 4 mm a^{-1} and decreases after a peak at 3.5 Myr , when larger amounts of shortening are accommodated by the retro-shear zone.
4. Applying a landscape evolution model ~~and the~~ for the erosional response to rock uplift modifies rock uplift through the consequent creation of topography. The increased lithostatic overburden reduces uplift rates by roughly half and distributes uplift over a wider area. Furthermore, fluvial erosion causes rock uplift to vary on a smaller (catchment-) scale than previously set by tectonics alone. Deepest
5. The deepest and fastest exhumation occurs where tectonic forcing coincides with large erosion potential. From this we conclude that both the subducting plate geometry as well as possible erosion effects need to be taken into account in order to understand the exceptional exhumation rates observed in orogen syntaxes.

Code and data availability. Model output is available upon request from T. Ehlers. The software DOUAR is currently not open source. Requests for use should be made to the main author, Jean Braun (GFZ Potsdam) and Todd Ehlers (University of Tübingen).

Appendix A: Numerical model details

Lithospheric deformation and temperatures in this study are calculated with the program DOUAR (Braun et al., 2008; Thieulot et al., 2008), a fully coupled three-dimensional thermomechanical model. Further details can also be found in Braun and Yamato (2010) and Whipp et al. (2014).

DOUAR solves the three-dimensional Stokes (creeping) flow equations for incompressible fluids, constituted by conservation of momentum (Eq. A1) and conservation of mass (Eq. A2):

$$\nabla \cdot \mu (\nabla \mathbf{V} + \nabla \mathbf{V}^T) - \nabla P = \rho \mathbf{g}; \quad (\text{A1})$$

$$\nabla \mathbf{V} = 0, \quad (\text{A2})$$

where μ is the material shear viscosity, \mathbf{V} is the velocity field, P the pressure, ρ is the density and \mathbf{g} gravity acceleration. The solution is computed with the finite element method using Q1P0 elements, i.e. the pressure is calculated from the velocity field by the penalty formulation (e.g. Bathe, 1982):

$$P = -\lambda \nabla \cdot \mathbf{V}. \quad (\text{A3})$$

For this, conservation of mass is amended to near incompressibility with a penalty factor λ , which is typically eight orders of magnitude larger than the viscosity μ . The model domain is subdivided into elements by a regular grid, on which the finite element solution is calculated.

The material properties of each element are defined by marker particles of two types, that a) track material interfaces (*surfaces*) or b) record strain and pressure (*cloud*). Particles will be created or deleted automatically to ensure both a roughly homogeneous particle density and adequate base for material property calculations (*self-adapting density*). Additionally, a third type of particles stores position, temperature and pressure for each time step. If those particles are exhumed at the surface, the p-T-t path is compiled from storage and registered at the current time step. From these paths, thermochronometric cooling ages can be calculated.

Materials can be either purely viscous or frictional visco-plastic. The viscosity μ follows a thermally activated creep law:

$$\mu = \mu_0 \dot{\epsilon}^{1/n-1} e^{Q/nRT} \quad (\text{A4})$$

where μ_0 is the intrinsic viscosity, $\dot{\epsilon}$ the second invariant of the deviatoric strain rate tensor, n the stress exponent, Q the activation energy, R the gas constant and T the temperature. If the stress exponent $n = 1$, the material is linear viscous and $n > 1$ denotes non-Newtonian viscosity, where viscosity increases under higher strain rates.

When plasticity is enabled, material deformation is dictated by the Mohr-Coulomb failure criterion:

$$\tau = C_0 - \sigma_n \tan \phi \quad (\text{A5})$$

where τ is the deviatoric shear stress, C_0 the material cohesion, σ_n the normal stress and ϕ the material angle of friction. For each model element, the effective stress τ_{eff} is calculated from strain rate:

$$\tau_{eff} = 2\mu\dot{\epsilon}. \quad (\text{A6})$$

If this effective stress exceeds the Mohr-Coulomb yield stress τ , elemental viscosity is reduced to an effective viscosity

$$5 \quad \mu_{eff} = \frac{\tau}{2\dot{\epsilon}}, \quad (\text{A7})$$

otherwise viscosity is kept at the initial value.

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10 *Competing interests.* The authors declare that they have no competing interests.

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Response to anonymous reviewer 1

We would like to thank the reviewers for their critical assessment of our work and their constructive comments. In the following, we will address the reviewers' concerns point by point. For better readability and because of the extensive modification of this manuscript, we provide references to the differenced document rather than showing differences directly in this response letter.

Reviewer 1

Reviewer Point P 1.1 — The work by Nettesheim et al. uses numerical models to investigate the effect of subducting and overriding plate velocities on overriding plate deformation, shear zone structures and erosion patterns. The topic is of general interest, but I believe this work needs a big improvement before being suitable for publication. In terms of modelling, I think more models are needed to really understand the results and the effects of the initial setup choices. In terms of style, I think the conclusions are not clear and the message of this paper is not conveyed. Moreover, the discussions need to be expanded and re-worked, since as they are now they are mostly a repetition of the results.

Reply: We thank the reviewer for their assessment and constructive comments to improve our work.

Reviewer Point P 1.2 — I think the use of the terminology "plate corners" is used in an erroneous way. The authors show in Figure 1 what they consider plate corners. However, I do not understand the logic behind these choices. I can see how the regions highlighted by the red circles in the Aleutian and Himalayas can maybe be considered as corners, but I'm struggling to see corners in all the other circles. In South America or Indonesia, for instance, those are simply regions of curved trench, I see no corners there. And they have an opposite curvature too, which does not match the definition used at the beginning of the Introduction. Moreover, if those in South Sandwich, Mariana, Caribbean are plate corners, then why not consider corners the edges or changes in trench curvature in other subduction zones like Tonga-Kermadec, Calabria, Aegean, New Hebrides, and many more? I think the authors should be very careful in using a terminology that I found vague and wrong. Moreover, except for the places labelled in the figure, the other regions are hardly, if not never, mentioned in the manuscript, so I do not see the point of saying that those red circled regions are plate corners and then never mention them.

Reply: We agree that the expression "plate corner" might be misleading. It is arguably not directly applicable to all regions depicted in the original Figure 1, which was a compilation of all strongly bent subducting plates that might act as rigid indenters, in order to convey the wide applicability of our presented approach. We have clarified our terminology in the introduction and replaced Figure 1 with a more detailed map of the Cascadia subduction zone (page 3) as well as shifted the focus of our manuscript more towards this region.

Reviewer Point P 1.3 — Another definition that I find confusing and, in my opinion, wrong is what the authors define "slab advance". First of all, it is confusing and counter intuitive that the model called "full slab advance" is the one where the slab

has null velocity and the overriding plate is moving towards the trench. Secondly, Heuret and Lallemand (2005) do not define slab advance as the "migration of the overriding plate towards the down-going plate" as suggested by the authors (page 2 lines 5-6). Instead, they talk about "upper plate advance", which I believe is much more appropriate here to describe the model in which the overriding plate (and not the subducting plate) is moving towards the trench. This is not just semantic, but an important point because I am not sure that slab advancing is the cause of what the authors observe in the models. If the slab was advancing in the models forces might be distributed differently and stresses might be accommodated in different regions compared to these models in which is the upper plate that is forced towards the trench.

Reply: We acknowledge the reviewer's concern about the term "slab advance", which is a question to the frame of reference. In our chosen, moving frame of reference centered on the indenter's toe, trenchward motion of the overriding plate is equal to a slab or trench advance in a frame of reference fixed to the overriding plate. Physically, forces, strain rates and uplift velocities are not affected by this uniform addition of horizontal velocity (i.e. a Galileian transformation). Nevertheless, in order to avoid confusing the reader, we have replaced the term "slab advance" with "upper plate advance" throughout the manuscript. See the reworded definition in the introduction on page 3, line 1.

Reviewer Point P 1.4 — Results and conclusions of this work are based on solely 3+1 models. How do the authors know the effect of the indenter geometry (paragraph 4.1) if there are no models with different indenter geometries? I think this work needs more models. The authors should at least show results from models with the 3 different types of velocities in a setup with a straight trench and no changes in slab dip. How do the shear zones forming in the overriding plate look like with a straight trench? And how do they compare to the models with a curved one? This would really help understanding the effect of the chosen geometry.

Reply: We understand this to be one of the central points in the reviewer's concerns and agree that additional models will help the reader understand the effect of an indenter-type geometry more clearly. We have added three models with a straight trench for our three velocity boundary conditions. Results are shown in Figures 3 (page 14) and 4 (page 15) in section 3.1.1 (pages 9 ff.), as well as in supplemental figure ???. Moreover, we have added two more models with a narrower and a wider indenter, shown in figure 8 in section 3.2 (pages 19 and 17, respectively). These results are discussed in section 4.3 (pages 21 f.).

Reviewer Point P 1.5 — Considering the regions that this work aims to study (mostly Himalayas and Alaska), I am puzzled by the choice of the subducting plate geometry in the models. Those areas are slab edges and they have a shape that is more similar to a cusp than a smooth convex arc as modelled here. My point is that, although I do understand that models are inherently simplified and cannot be exactly like nature, I am not sure this is the best geometry to use to model those areas. The authors should discuss more in details their choice and, perhaps, even consider a different initial geometry.

Reply: As mentioned above, we have replaced figure 1 with a detailed map showing the subducting slab geometry of the Cascadia subduction zone in order to document our choice of subduction plate geometry (page 3). Moreover, we have

run and discussed additional models with wider and narrower indenter geometry (section 3.2 on page 17 and section 4.3 pages 21 f.). Nevertheless, we do not aim to reproduce any particular region, but rather study the effect of a rigid indenter on upper plate deformation. In this, our focus admittedly lies more on regions that are well studied and show exceptional properties, and thus interest a broader audience. Our findings are transferable to cusp-like, asymmetric subduction zones. Figure R1 shows that the main difference between a cusp-type geometry, modeled after the Alaskan plate corner, and symmetric indenter geometry lies in the transition to a transfer fault on one side. These results agree with observed fault patterns (see Koons et al. (2010) and references therein). However, we think that adding this specific plate geometry will go beyond our generic approach and intended scope of this manuscript.

Reviewer Point P 1.6 — The Discussion part needs to be more exhaustive. Most of the text in the Discussion is just a repetition of the results with no or little interpretation. The differences between the models are described, but why are those difference present? What is causing them? What is the effect of the chosen 3D shape? Again, a comparison with models with straight trench would help with this. For instance, would a straight trench produce slower exhumation rate? What is the effect of the chosen plate velocities? Why are these results important? How do they compare to natural cases (not only in terms of uplift rates, but also in terms of structures)? [. . .]

Reply: We thank the reviewer for his helpful suggestions to improve the discussion section. We have added straight-slab models (Figs. 3 and 4 on pages 14 and 15, respectively) as well as models with different indenter geometries (Fig. 8 on page 19) to this manuscript in order to discuss the questions raised here in more depth. Furthermore, we have added a model with twice as fast convergence (??), which shows that in our setup and to our line of investigation, the total rate of convergence is less important than its partitioning in subduction and upper plate advance. Alongside the addition of these models, we have substantially revised the discussion section (see sections 4.3 and 4.4 on pages 21ff.) . In doing that, we have put more emphasis on the underlying mechanisms that cause the observed results. Moreover, we relate our results more closely to natural observations, including the newly added figure 10 on page 25. For example, detachment-like shallow faults dipping toward the subducting plate, similar to our models, have been observed in South America. Likewise, the shallow detachment dipping towards the continent, joined by a steeper fault at depth, in our full advance models, well matches the geometry of the Hurricane Ridge Fault of the Olympic mountains as described by Willett (1999). Due to our simplified approach, such comparisons can only be done qualitatively, but we're confident these additions will help the reader transfer our results to nature more easily.

Reviewer Point P 1.7 — [. . .] Are these "plate corners" the only places with rapid exhumation? Can there be other causes for it other than the geometry? What is the main message of this paper? [. . .]

Reply: The discussed regions are certainly not the only ones with rapid exhumation. For example, exhumation in Taiwan has been found to range from 3 to 5 mm a⁻¹ over the last 2-3 Ma (e.g. Fuller et al., 2006; Willett et al., 2003). However, the aim of this study is not to investigate rapid erosion in general, but to further investigate the effects of an indenter geometry and its contribution to localized uplift as observed in orogen syntaxes. In previous studies, two main hypotheses were

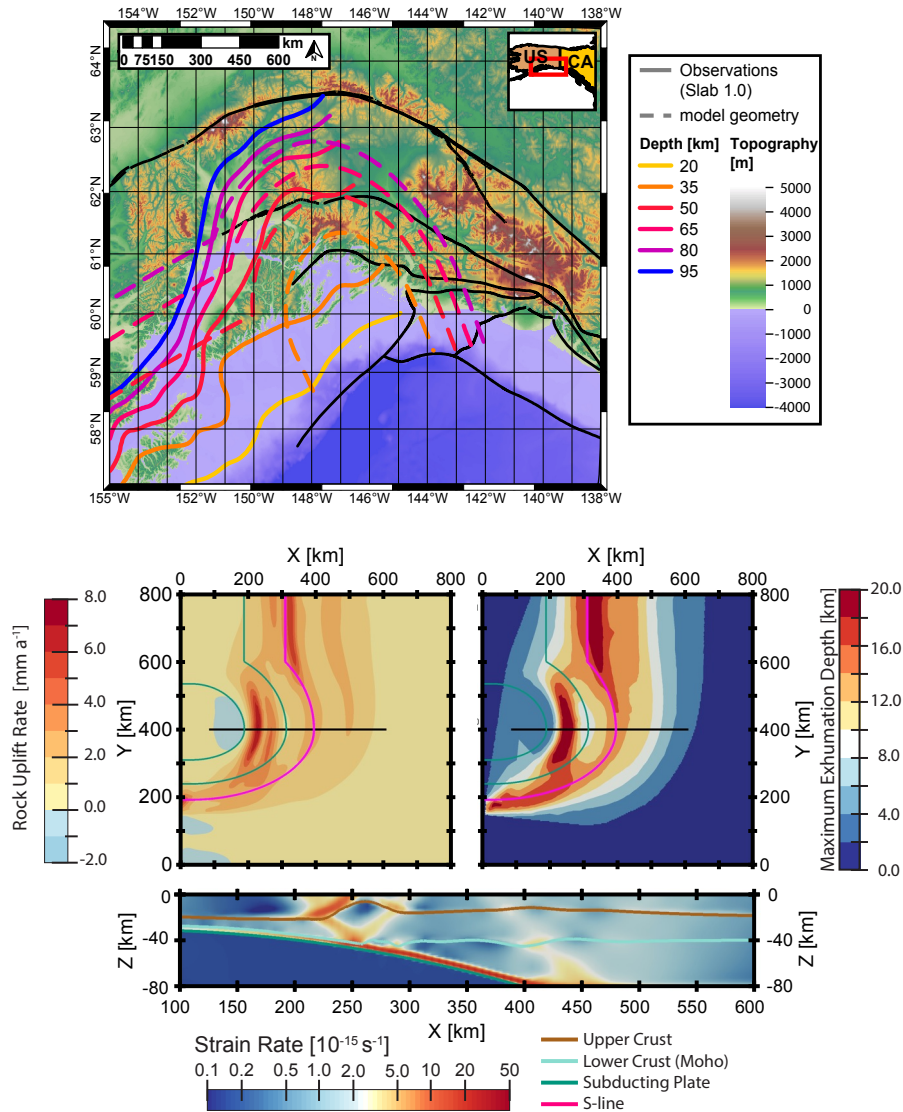


Figure R1. Plate Geometry of the St. Elias Syntaxis and model results of asymmetric indenter geometry for half upper plate advance (rock uplift rates, exhumation depth and strain rates after 6 Myr modeling time). Color scales are identical to those used in figures of manuscript.

proposed: the "tectonic aneurysm" hypothesis (e.g. Zeitler et al., 2001, 2014; Koons et al., 2002) stresses the importance of localized erosion in order to initiate a positive feedback loop, whereas Bendick and Ehlers (2014) find a forward bent (indenter) subducting plate geometry sufficient to induce localized uplift. In this manuscript, we follow the latter approach, but use a more realistic rheology and expand the range of velocity boundary conditions. Moreover, we try to assess the effect of erosion feedback through our coupled fluvial erosion models. Our main point is that for all our more sophisticated

models, the effect of an indenter geometry signifies an important contribution to localized uplift, as proposed by Bendick and Ehlers (2014), and cannot be neglected when investigating regions with a curved subducting plate. We have edited the discussion and conclusion accordingly, to make this point clearer to the reader.

Reviewer Point P 1.8 — [...] All these points are examples of what can help expanding the Discussion, improving the conclusions and the impact of the paper. These are lithospheric scale models and, thus, do not include mantle flow. What do the authors think would be the effect of the mantle flow especially on the evolution of stresses and topography?

Reply: We agree that mantle flow may have a strong effect. Mantle flow and slab penetration determine relative plate motion (e.g. Heuret and Lallemand, 2005; Faccenna et al., 2013). This causes partitioning of shortening into subduction and upper plate motion, which is one of main parameters in this study. We added a related note to the methods section on page 3, line 1. We also understand that mantle vertical movements that are not included might be important for geodynamics. However, we assume their role limited in the subduction convergent settings comparing to extensional ones.

Reviewer Point P 1.9 — Info on velocity and temperature boundary conditions should be given for every boundary. For instance, what are the temperature conditions at sides (at x and y 0 and 800km)? What are the velocity boundary conditions at the bottom and the top? Also, from the plots it seems to me that the top boundary is free slip and not free surface. If this is the case, how is the topography computed?

Reply: We have added the desired information and furthermore revised methods sections 2.2.4 and 2.2.5 to convey information more clearly (see pages 7 f. and also Fig. 2 on page 5).

Reviewer Point P 1.10 — I'd suggest a more comprehensive explanation on thermochronometric ages. If a reader is new to this technique will not be able to follow the paper and understand the results.

Reply: We have added an explanatory paragraph, see section 2.2.6 on page 8

Reviewer Point P 1.11 — Paragraph 3.1 would be easier to follow if the "pro-shear band", "retro-shear band", and "basal detachment" would be labeled explicitly in Fig. 3 and 4. Paragraph 3.2 and Figure 6.

Reply: In order to clarify this for the reader, we have adopted a consistent terminology of "pro shear zone", "retro shear zone" and "indenter detachment" throughout the manuscript and added labels of \textcircled{P} , \textcircled{R} , and \textcircled{I} , respectively, to all figures. See e.g. Figure 4 on page 15.

Reviewer Point P 1.12 — The model "full slab advance" is the only one that shows subsidence between the structures the left and right of the S-line. This is worth mentioning and discussing.

Reply: The subsidence developing in the full advance case is caused by isostatic relaxation. In the early stages of the model, upward material flow along the subduction interface causes crustal uplift and thinning by flat erosion. When the retro-shear zone becomes more localized and accommodates more deformation, the upward push ceases and isostatic relaxation causes subsidence. This feature is reminiscent of the flexural subsidence of the Chilean forearc by thrust or reverse faulting in the late Cenozoic (Horton, 2018a, b, and references therein). See page 22, line 27 f.

Technical Comments

Reviewer Point P 1.13 — Table 2 has two vsub in the header.

Reply: Fixed, see table 1 on page 9.

Reviewer Point P 1.14 — Spell out the acronyms in the caption

Reply: Figure 1 has been replaced

Reviewer Point P 1.15 — Change "around plate plate corners" to "around plate corners"

Reply: Done, see page 1, line 18.

Reviewer Point P 1.16 — Remove 's' from impacts: "Slab advance and erosion impacts"

Reply: Done, see page 3, line 11.

Reviewer Point P 1.17 — Specify what is the thickness range of the weak layer that decouples the plates

Reply: Values added, see page 6, line 10.

Reviewer Point P 1.18 — Unit of strain rate is wrong, shouldn't it be s-1?

Reply: Fixed, see page 9, line 12.

Reviewer 2

Reviewer Point P 2.1 — In this paper the authors show a fully coupled thermo-mechanical numerical model to investigate the effect of a curved slab advancing on overriding plate deformation and they test different erosion scenarios on the resulting topography. This coupling between 3D thermo-mechanical models and erosion is ambitious, the subject could be very interesting as it is dealing with an emblematic problem, the curved subduction zones and the syntaxes. But as it is presented now

it is a bit disappointing, as the setup is presented as global, corresponding to all the observations of figure 1, with no specific case study proposed, and I find the conclusions of the paper hard to compare with a natural case. The authors said that their setup is similar to the Cascadia subduction zone or the Alaskan plate corner (p2, line2), in that case they have to show a map of the plates boundary and of the slab geometry in these regions, so that the reader is able to compare with the model. Having worked upon the India/Asia collision zone, for me the models presented in this paper could not be compared with the Indian slab corners in the Himalayas or with the Indonesian trench smooth curvature.

Reply: We thank A. Replumaz for her assessment of and constructive suggestions to improve our work. We understand her main concern lies in the limited transfer to natural settings. We have edited our discussion section to include more references to natural systems and added Figure 10 on page 25 to illustrate the relation of our results to nature. Figure 1 (page 3) now shows the geometry of Cascadia subduction zone. As discussed above (see figure R1), we are convinced that our results are also transferable to asymmetric cusp-like geometries. We agree that detailed adjustment of initial and boundary conditions is required before conclusions about a specific subduction setting can be drawn.

Reviewer Point P 2.2 — I suggest 1/ to better analyze the case studies, to properly differentiate different cases as trench curvature (Andes), slab corner (Himalayas), but also sense of curvature (convex for himalayas versus concave for andes or alps), see below analogue modeling Bajolet et al., 2013. I suggest [...] 2/ to choose 2 very different cases to model, for example trench curvature / slab corner or concave / convex curvature.

Reply: This point is closely linked to concerns expressed by the first reviewer. We intentionally limit ourselves to convex plate corners, where flexural stiffening of the downgoing plate (see Mahadevan et al., 2010) is thought to occur, in order to specifically investigate a possible focusing effect on upper plate deformation as proposed by Bendick and Ehlers (2014). We agree with both reviewers that additional models will be very helpful to illustrate this effect. We have added three models with a straight trench well as two more models with a narrower and a wider indenter. Results are shown in figures 3 (page 14), 4 (page 15), and 8 (page 19) in sections 3.1 and 3.2 on pages 9 ff. and 17. See also discussion in sections 4.3 on page 21 f.

Reviewer Point P 2.3 — Remove the low convergence case (half slab advance name is not clear at all) which is of low interest according to me.

Reply: Perhaps we were unclear in the manuscript as it seems the half advance case may have been misunderstood. For example, the half-advance scenario is quite similar to the convergence between India and Eurasia in the Himalaya, where India moves into Eurasia at around 45-50 mm/a, but only ~40-50% of that convergence is shortening in the Himalaya (e.g. Ader et al., 2012). In addition, we note that the convergence rate is the same in all models presented in this study. To ensure readers are not misled, we have edited the description of our boundary conditions (see section 2.2.4 on page 2.2.4) and expanded table 1 (page 9) in the revised version in order to provide a clearer explanation of the different boundary conditions and their geodynamic implication.

Reviewer Point P 2.4 — I suggest [...] 3/ show the erosion pattern for each case (as figure 9a), as it is an important issue of your work.

Reply: We have added the requested models to our study, results are shown in figure ??.

Reviewer Point P 2.5 — figures should be bigger, and better focus. Show the plates boundaries and find a way to represent slab geometry on figure 1. It will be better for the reader as it will be possible to see what you are talking about, and it will help to differentiate the kind of curvature/slab corner.

Reply: Figures 1 (page 3), 3 (page 14) and 4 (page 15) have been replaced in the revised version. Additionally, we have added four figures to the supplement for a more detailed understanding of the reader. We will request large figure sizes in the final publication for best perception.