Extreme localized exhumation at syntaxes initiated by subduction geometry

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Extreme localized exhumation at syntaxes initiated by subduction geometry

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Abstract Some of the highest and most localized rates of lithospheric deformation in the world are observed at the transition between adjacent plate boundary subduction segments. The initiating perturbation of this deformation has long been attributed to vigorous erosional processes as observed at Nanga Parbat and Namche Barwa in the Himalaya and at Mount St. Elias in Alaska. However, an erosion-dominated mechanism ignores the 3-D geometry of curved subducting plates. Here we present an alternative explanation for rapid exhumation at these locations based on the 3-D thermomechanical evolution of collisions between plates with nonplanar geometries. Comparison of model predictions with existing data reproduces the defining characteristics of these mountains and offers an explanation for their spatial correlation with arc termini. These results demonstrate a “bottom-up” tectonic rather than “top-down” erosional initiation of feedbacks between erosion and tectonic deformation; hence, the importance of 3-D subduction geometry.

1. Introduction

Plate subduction is a primary mechanism of exciting convergent plate motion, recycling mass between the lithosphere and mantle, and producing deformation in overriding lithosphere [Conrad and Lithgow-Bertelloni, 2002]. Studies of deformation in convergent orogens are almost always investigated through the use of 2-D cross sections [Billen, 2008; Wu et al., 2008] or cylindrical bending of plates [Ribe, 2010; Schellart et al., 2007]. Both approaches omit the 3-D geometric constraints imposed by additional bending and stretching of nonplanar plates parallel to the subduction zone [Mahadevan et al., 2010; Howell, 1996]. While a reduction of geometric complexity may be reasonable for many parts of subduction zones, the 3-D geometric and stress effects become especially large at the transition between adjacent plate boundary segments. Here we address the question of how the 3-D geometry of a subducting plate (oceanic or continental) influences deformation in the overriding plate. In order to do so, we offer a narrow definition of a syntaxis, which includes only the narrow, cuspsate region linking two adjacent subduction segments (Figure 1), including both downgoing and overriding material, rather than all orogenic bends generically.

This conceptual model of subducting plate geometry influencing upper plate deformation is motivated by recent observational (Figures 1a and 1b) and modeling studies (Figure 1c) that indicate 3-D bending of plates at syntaxes results in geometric stiffening that resists further bending in the subduction direction [e.g., Crosson and Owens, 1987; Mahadevan et al., 2010; Hayes et al., 2012]. This stiffening effect is analogous to holding a sheet of paper on two adjacent corners. The paper curves downward under its own weight unless it is bent in the third dimension by pushing the hands together, in which case it becomes geometrically stiffened and can support its own weight (see http://www.youtube.com/watch?v=IyrSHWdrjU). When applied to subducting plates, geometric stiffening arises from a symmetry-breaking instability in the trench region (where lithospheric bending is localized) producing alternating concave subduction arcs separated by narrow, cuspsate, convex syntaxial indenters. Essentially, the downgoing plate must fold in the along-strike direction so that it can fit into the interior of the Earth; the wavelength of this folding pattern is set by a tradeoff between the different stiffnesses of the lithosphere and mantle. Syntaxial arches are especially rigid, shallowlly dipping indenters that can influence deformation in the overriding plate (Figures 1b and 1c) [Mahadevan et al., 2010]. Alternative explanations for the low dip angle of subducting plates at syntaxes have been proposed. These include anomalously thick lithosphere [e.g., Elliott et al., 2013], anomalously buoyant lithosphere [e.g., Cloos, 1993], or even the presence of seamounts or other a priori topography on the downgoing plate [e.g., Vogt, 1973]. Differences in the thickness or composition of the downgoing plate interact nonlinearly with the buckling instability, so both may contribute to the final shape of the downgoing plate.
Seismic images of subducting plate geometries (Figure 1) [e.g., Crosson and Owens, 1987; Hayes et al., 2012] show that localized shallow dips in downgoing plates are observed at syntaxes regardless of the causal mechanism and therefore warrant investigation of consequent effects on upper plate deformation. In this study we model the effect of a convex upward indenter geometry (Figure 2a) on the overriding plate deformation. Our modeling approach is intentionally simplified and can be applied to any collisional setting (continental or oceanic). Our results demonstrate a previously unrecognized tectonic mechanism for initiating extreme exhumation.

2. Syntaxes Characteristics

Three “extreme” syntaxial orogens have so far been identified: Nanga Parbat and Namche Barwa on the Himalayan termini, and Mount St. Elias on the easternmost end of the Aleutian-Alaskan subduction arc (e.g., Figures 1a and 1b). These syntaxes have a set of unusual characteristics including (i) rapid exhumation (>3 mm/yr), (ii) high-grade metamorphic rocks, (iii) steepened temperature gradients, (iv) strong “bull’s-eye” spatial localization of deformation (~100 km in any direction), and (v) a combination of kinematic shortening and shear [Koons et al., 2012; Enkelmann et al., 2010, 2011; Zeitler et al., 2001, 2014]. These characteristics are manifested in very young mineral cooling ages and high topographic relief over a small area. One proposed explanation for the coincidence of all five characteristic features is called the “tectonic aneurysm” model [e.g., Zeitler et al., 2001, 2014]. In this model, vigorous erosion removes the cold uppermost crust, leading to crustal warming, temperature-dependent weakening, and focused deformation. However, in other locations globally with very high erosion rates (e.g., central Nepal and Taiwan) the characteristic features within localized syntaxial settings are not observed. Instead, all known settings with all five defining characteristics listed above are associated with the specific tectonic setting at the ends of subduction arcs (Figure 1), suggesting a critical role of the tectonic context, provided by the subduction geometry.

Limited direct observations are available for this geometry of subducting flexurally stiffened indenters at orogen syntaxes. Existing observations come from seismology (Figure 1a) [e.g., Crosson and Owens, 1987;
Hayes et al., 2012] where the 3-D geometry of subducting plates is inferred from earthquake hypocenters and seismic velocity anomalies. Unfortunately, the studies of slab geometry typically emphasize the central arc portion of subducting plates and often terminate near plate syntaxes (e.g., Figure 1a). What is known from available observations is that the geometry of indenters at syntaxes approaches the shape of a plunging ellipsoid. The theoretical scaling relation for the ellipsoid's semiminor axis in the elastic limit is

$$\lambda = \frac{E_l h_l}{H_m} \frac{E_m}{E_m}$$

where $E_l$ and $h_l$ are Young's modulus and the thickness of the lithosphere, respectively, and $E_m$ and $H_m$ are Young's modulus and the thickness of the mantle [Mahadevan et al., 2010]. For Earth, this corresponds to subduction arcs with lengths from 500 to 1000 km and syntactical bends with widths from 100 to 500 km. Variations in the scaling result from differences in the elastic thickness and material properties of the subducting plate. A diverse range of subducting plate material exists from oceanic plates (e.g., Cascadia) to more buoyant material (oceanic or continental) in the St. Elias (Figures 1a and 1b) or Himalayan syntaxes. Where available, seismic observations of syntaxes are consistent with the theoretical scaling. [e.g., Crosson and Owens, 1987; Hayes et al., 2012].

3. Model Setup

We present a set of numerical solutions for the interaction between a rigid indenter at a syntaxis with an overriding viscous material (Figure 2a). The model setup is intentionally simplified to identify how the 3-D geometry of a subducting plate influences upper plate deformation and therefore necessarily omits many of the complexities of collision interfaces, such as transfer of mass between the downgoing and overriding plates. Our approach is broadly applicable to oceanic or continental settings. Because syntaxes define the intersection between two adjacent plate boundary segments (Figure 1c), usually with very different mean
Table 1. Description of Differences Between the Simulations Presented

<table>
<thead>
<tr>
<th>Simulation Name</th>
<th>Viscosity Exponent (n)</th>
<th>Indenter Width</th>
<th>Maximum indenter height from base of lithosphere</th>
<th>Associated Figures in Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>3</td>
<td>150 km</td>
<td>60 km</td>
<td>Figures 2b–2d; Figure 3a color</td>
</tr>
<tr>
<td>Constant viscosity</td>
<td>no eta (T)</td>
<td>150 km</td>
<td>60 km</td>
<td>Figure 2c solid black line</td>
</tr>
<tr>
<td>n2</td>
<td>2</td>
<td>150 km</td>
<td>60 km</td>
<td>not shown</td>
</tr>
<tr>
<td>n5</td>
<td>5</td>
<td>150 km</td>
<td>60 km</td>
<td>Figure 2c dashed line</td>
</tr>
<tr>
<td>n10</td>
<td>10</td>
<td>150 km</td>
<td>60 km</td>
<td>not shown</td>
</tr>
</tbody>
</table>

Variable Indenter Geometry Simulations

| Wide indenter           | 3                      | 300 km         | 60 km                                         | Figure 2d, Figure 3a dashed black line      |
| Narrow indenter         | 3                      | 70 km          | 60 km                                         | Figure 2d, Figure 3a solid gray line        |
| High indenter           | 3                      | 150 km         | 85 km                                         | Figure 2d, Figure 3a solid black line       |
| Low indenter            | 3                      | 150 km         | 35 km                                         | Figure 2d, Figure 3a dashed gray line       |

strikes, the angle between the overall flow direction and the strikes of each boundary defines the broader kinematic setting (Figure 2a). Specifically, for net convergence at a syntactical structure, if the adjacent boundary is approximately normal to the flow direction, then that boundary is convergent, such as the main Himalaya or the Aleutian trench (Figure 1b). If the boundary is approximately parallel to the flow direction, then it is a transform, such as the Fairweather Fault in the St. Elias Range, Alaska. Other studies such as Whipp et al., 2014 investigate in more detail the strain partitioning arising from kinematic conditions.

Calculations are done using the finite element method (COMSOL) for a rigid body, whose elliptical shape approximates available observations [Crosson and Owens, 1987; Hayes et al., 2012] and the numerical solution for the edge instability (indenter) in a subducting spherical cap (Figure 1c) [Mahadevan et al., 2010]. Our base model includes an indenter size with axes of 400 km, 150 km, and 60 km, in the x, y, and z directions, respectively. This rigid indenter collides with a lithospheric scale (100 km thick) upper plate (Figure 2a). Deformation in the upper plate is calculated in 3-D assuming Stokes flow of a temperature-dependent nonlinear viscous material with dimensions of 800 km in the x and y directions. We explore a range of geometries consistent with the solution for a subducting spherical cap (Figure 2d) and viscosity distributions whose integrated average viscosity agrees with constraints from thin viscous sheet models for the whole lithosphere [e.g., Flesch and Bendick, 2012; Sonder and England, 1986] (Figure 2c). Temperature-dependent viscosities in the deforming volume are calculated using an Arrhenius relation, \( \mu = A^{-\frac{1}{n}} \exp \left( \frac{Q}{RT} \right) \). In this expression, \( \mu \) is the viscosity, \( A \) is a conditioning coefficient, \( n \) is the viscosity exponent, \( \dot{\varepsilon} \) is the strain rate, \( Q \) is the activation energy, \( R \) is the ideal gas constant, and \( T \) is the temperature. We fix the strain rate to the average for the whole volume and use \( n \) and \( A \) to force the average integrated viscosities to agree with bounds from thin viscous sheet models (Figure S2 in the supporting information).

Differences between the simulations for the viscosity and geometry of the indenter are summarized in Table 1. Kinematic boundary conditions are applied with a material inflow on the boundary opposite the indenter and free outflow of material on the opposite face above the indenter. The other sides have free slip conditions with no outflow. These boundary conditions are equivalent to previous advancing crustal-scale singularity (S point) simulations applied to the Himalaya [Beaumont et al., 2004] and other settings where the interface (S point) between subducting and nonsubducting material advance into the hinterland with time.

Temperatures are calculated using the 3-D advection diffusion equation with radiogenic heat production. The thermal and Stokes flow solutions are fully coupled and evolve throughout the simulation. Frictional heating between the upper and lower plates is assigned as a boundary condition on the top of the rigid indenter [Molnar and England, 1990]. Finally, the surface of the upper plate is “eroded” flat, as topographic mass is removed that is advected above the initial flat surface. This approach assumes totally efficient erosion across the entire upper surface, thereby allowing enhanced thermal gradients and mechanical weakening from erosion. Simulations were also conducted with no erosion (not shown), and the general bull’s-eye pattern of vertical uplift described below is identical. Thus, the geometry of vertical surface velocities presented below is not dependent on our assumed erosional efficiency. We present below simulations that include erosion because they result in rock exhumation and allow prediction of, and comparison to, thermochronometer cooling ages. Model-predicted cooling ages are compared to observed cooling ages.
from published bedrock and detrital thermochronology studies [Enkelmann et al., 2010, 2011; Burg et al., 1998] by calculating cooling rate-dependent (effective closure temperature) mineral cooling ages [Ehlers et al., 2005]. Addition details of the model setup and governing equations used are provided in the supporting information.

4. Results

Results indicate subduction of a stiff indenter, and overriding lithosphere reproduces the primary characteristics at syntaxes. The stiff, low dip angle, localized indenter in a subducting plate interacts strongly with the overriding material, both because of its geometry and stiffness. As a result, the deformation associated with the indenter is also localized within the overriding plate (Figure 2b). High vertical velocities enhance thermal gradients above the indenter, leading to reduced viscosity and a positive feedback between erosion, thermal structure, and deformation. Shortening is focused around the front of the indenter, and shear on the sides, as overriding material flows both up and over the obstruction and around it. Thus, deformation in a viscous material colliding with such an indenter matches four of the five critical characteristics of syntaxial orogens: rapid (~3 mm/yr) vertical advection of mass, localized deformation over length scales of ~100 km, high-temperature gradients (and hence very young cooling ages, see below), and the presence of both shortening and shear in the velocity field.

This localized deformation is relatively insensitive to either the exact parameterization of the viscosity relation (Figure 2c) or the geometry of the indenter (Figure 2d). Regardless of the upper plate viscosity and lower plate geometry used (Table 1), all of the models reproduce the concentric bull’s-eye pattern of vertical advection observed in the known examples in the Himalaya and St. Elias. Variations in the viscosity sensitivity to temperature influence the magnitude of the surface velocity (Figure 2c); when the sensitivity is high, when high viscosity

Figure 3. Predicted and observed variations in syntaxial orogen rock exhumation as indicated by mineral cooling ages. (a) Predicted zircon fission track (ZFT) cooling ages of rocks exhumed to the surface. The color field is the baseline simulation (Figure 2b) with the 4 Ma ZFT age contour in red, gray, and black contours are the 8 Ma ZFT age contours from the alternative geometries using the identical line patterns as the results shown in Figure 2d. The gray 8 Ma ages contours are shown instead of the 4 Ma ages because the exhumation rates are slower for these alternative geometries in Figure 2d. (b) Known distribution of ZFT ages <4 Ma in the Namche Barwa area, Himalaya [Enkelmann et al., 2011; Burg et al., 1998]. (c) Known distribution of ZFT ages <4 Ma in the Mount St. Elias region, SE Alaska [Koons et al., 2012; Enkelmann et al., 2010]. Dashed lines in Figures 3b and 3c represent the inferred extent with uncertainty stemming from limited sample locations.
occurs at low temperatures, and when the advection of mass near the surface is damped. The indenter geometry influences the aspect ratio of the zone of rapid vertical velocity (Figure 2d); shallower and narrower indenters excite exhumation in a zone stretched in the direction parallel to collision, and deeper and wider indenters excite exhumation in a zone stretched in the direction normal to collision. The diagnostic observation of localized bull’s-eye surface deformation is always honored. In the absence of an indenter, a linear band of high exhumation occurs perpendicular to the subduction direction to produce an orogen parallel zone of high exhumation [e.g., Thiede and Ehlers, 2013].

Finally, numerical predictions agree with observed spatial variations in mineral cooling ages and metamorphic grade exposed at the surface. Our comparison is restricted here to the zircon fission track (ZFT) system because of its abundance in the literature and because its higher closure temperature (~250°C) integrates sample cooling histories over longer length scales than lower temperature systems. The steepened geotherm in the overriding lithosphere combined with rapid vertical velocities (Figure 2b) leads to a bull’s-eye region of predicted young (<4 Ma) ZFT ages (Figure 3a). The spatial extent of predicted 4 Ma ZFT ages ranges from ~100 to 250 km and from ~100 to 700 km in the directions parallel and perpendicular to subduction, respectively. In both the St. Elias and Namche Barwa syntaxes the extent of young (<4 Ma) ZFT cooling ages occurs on similar spatial scales to those predicted (compare Figure 3a with Figures 3b and 3c). A similar bull’s-eye pattern of young cooling ages has also been observed for the Olympic Mountains, USA [Brandon et al., 1998] which shares the same 3-D subducting plate geometry considered here [Crosson and Owens, 1987]. Differences in the predicted and observed geometry of ages results from the distribution of erosion, subduction geometry and rate, and sampling extent. Thus, despite the simplicity of the 3-D model geometry considered, predicted ages are in good agreement with observed cooling ages.

The deep exhumation required (typically >10 km) to produce young ZFT cooling ages would also result in a localized pattern of higher-grade metamorphic rocks present in highlighted regions of Figure 3 compared to the outer regions that have lower exhumation magnitudes. The presence of higher-grade metamorphic rocks in syntaxes relative to adjacent areas is well documented in the Himalaya and St. Elias regions [e.g., Zeitler et al., 2014, and references therein; Grabowski et al., 2013] and provides additional support for the model predictions. It is worth noting that our model setup cannot reproduce one key characteristic of the Himalayan syntaxes, that the highest-grade rocks are actually derived from the footwall, or downgoing plate, rather than the hanging wall, or overriding plate. This is a consequence of our approximation of the downgoing indenter as a rigid body, which does not capture the full complexity of subduction interfaces, where material from the downgoing plate is often underplated on to the overriding plate.

5. Conclusions

Our calculations of syntaxs deformation over a geometrically stiffened subducting plate reproduce the characteristic exhumation features of extreme orogens. These models complement a set of models showing that initiation by an erosional perturbation is possible [Koons et al., 2012]. There are several broader implications of our findings for understanding mountain-building processes. First, numerous studies attempt to quantify the role of climate in establishing a coupling between erosion and tectonics [Burbank et al., 2003; Reiners et al., 2003; Beaumont et al., 2001]. While the role of enhanced precipitation as an instigator of enhanced deformation has been suggested [e.g., Grujic et al., 2006; Wobus et al., 2005; Reiners et al., 2003], we demonstrate here that tectonic processes, specifically the geometry of subducting plates, are important for producing many of the observations previously used to demonstrate a strong influence of climate on tectonic processes. From our analysis, it is evident that tectonic and surface processes must act together to produce the observed patterns of deformation and exhumation at syntaxes. The nonlinearity of the interaction between these processes has long been documented [Koons et al., 2012; Wobus et al., 2005; Beaumont et al., 2001], but efforts to quantify their relative contributions to observed characteristics of active orogens has proven difficult (e.g., Burbank et al. [2003] compared to Reiners et al. [2003]). This work suggests that neither high erosion rates nor nonplanar subduction alone suffices to excite extreme orogens where exhumation is both rapid and localized. For example, a recent synthesis of exhumation rates across the Himalaya [Thiede and Ehlers, 2013] shows that erosion rates comparable to those in syntaxes (~3 mm/yr) are observed over large lateral distances across the Himalaya over the past 10 Ma without leading to the localized bull’s-eye pattern characteristic of syntaxial orogens. On the other hand, a contorted slab alone is also
insufficient to excite positive feedback in Kamchatka [Steblov et al., 2010] and the mid-Andean syntaxis. If, however, structural context is critical to these extreme orogens, then less well-developed examples may exist at other subduction segment transitions, with potential candidates including Cascadia, Northern Japan, and the Nicoya Peninsula. Studying these may help identify which additional threshold conditions are requisite and how such a system evolves over time.

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References
Brandon, M. T., M. K. Roden-Tice, and J. I. Garver (1998), Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic
Closs, M. (1993), Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs,
Crust, R. S., and T. J. Owens (1987), Slab geometry of the Cascadia Subduction Zone beneath Washington from earthquake hypocenters
Grabowski, D. M., E. Enkelmann, and T. A. Ehlers (2013), Spatial extent of rapid denudation in the glaciated St. Elias syntaxis region, SE Alaska,
Grujic, D., I. Coutand, B. Bookhagen, S. Bonnet, A. Blythe, and C. Duncan (2006), Climatic forcing of erosion, landscape, and tectonics in the
Bhutan Himalayas, Geology, 34, 801–804.
Hayes, G. P., D. J. Wald, and R. L. Johnson (2012), Slab1.0: A three-dimensional model of global subduction zone geometries, J. Geophys. Res.,
Malnar, P., and P. England (1990), Temperatures, heat flux, and frictional stress near major thrust faults, J. Geophys. Res., 95, 4833–4856,
Schellart, W., J. Freeman, D. Stegman, L. Moresi, and D. May (2007), Evolution and diversity of subduction zones controlled by slab width,
Steblov, G., N. Vasilenko, A. Pyrytkov, D. Frolov, and T. Gerekova (2010), Dynamics of the Kuril-Kamchatka subduction zone from GPS data,
Whipp, D., C. Beaumont, and J. Braun (2014), Feeding the “aneurysm”: Orogeny-parallel mass transport into Nanga Parbat and the western
434, 1008–1011.
and the easternmost Lhassa Block, Tibet, in Towards an Improved Understanding of Uplift Mechanisms and the Elevation History of the Tibetan