Video DR1.avi

Additional discussion of numerical model illustrating the relationships among climate, erosion, topography, and delamination in the Andes

Additional equations

Orogens in nature cannot continue to grow in height indefinitely. Past a certain critical height, orogens tend to grow via an increase in width with no further increase in maximum height (Molnar and Lyon-Caen, 1988). Height-limited orogenic growth is included in the model by applying equation 2 only if the maximum elevation is below some prescribed threshold value, h_{pl}. Otherwise, width and area grow proportionately, i.e.

$$\frac{dx}{dt} = \frac{1}{x(\alpha+\beta)}\frac{dA}{dt} \quad \text{if} \quad h < h_{pl} \qquad \text{(DR1)}$$

$$\frac{dx}{dt} = \frac{\alpha}{h_{pl}(\alpha+\beta)}\frac{dA}{dt} \quad \text{if} \quad h = h_{pl} \qquad \text{(DR2)}$$

where h is the maximum elevation. By geometry:

$$x = \frac{h}{\alpha} \quad \text{if} \quad h < h_{pl} \qquad \text{(DR3)}$$

$$x = \frac{A\alpha}{h_{pl}(\alpha+\beta)} \quad \text{if} \quad h = h_{pl} \qquad \text{(DR4)}$$

and

$$\beta = \frac{w}{x} \qquad \text{(DR5)}$$

where w is the depth to the base of the crust. Isostatic compensation of the whole wedge (including eclogitic root) over large length scales requires

$$wx(\rho_{\mathrm{m}} - \rho_{\mathrm{c}}) = hx\rho_{\mathrm{c}} + A_{\mathrm{ec}}(\rho_{\mathrm{e}} - \rho_{\mathrm{m}}) \qquad \text{(DR6)}$$

where ρ_{m} is the density of the mantle (nominally 3300 kg/m^3). The first two terms in equation DR6 is the isostatic balance of a buoyant crustal root with a topographic load. The third term quantifies the negative buoyancy associated with the eclogitic root. Equations 1-4 and DR1-DR6 provide 7 equations for 7 unknowns (A_{ec}, A, x, h, w, β, and x_{e}) that must be solved for during each time step of the model. In the model, thickening of the lithospheric mantle is neglected based on the fact that lithospheric mantle is similar in density to the underlying asthenosphere (i.e. a 50 kg/m^3 density contrast between mantle and mantle lithosphere compared to a 300 kg/m^3 contrast between mantle and eclogite). As such, any lithospheric mantle that participates in delamination will produce relatively little isostatic uplift compared to the uplift produced by eclogite removal.

Choice of parameters for the reference model

Apatite fission track (AFT) ages north of the Bolivian orocline, where MAP rates are approximately 2 m/a, are generally Miocene (5-20 Ma) and hence imply Miocene to recent exhumation rates of 0.3-1.0 km/Ma (Barnes et al., 2006). An analysis that includes zircon fission track and zircon (U-Th)/He ages, however, yields Eocene-to-recent rates of approximately 0.2 km/Ma. The Eocene-to-recent rates are more appropriate for this paper since a constant rate is assumed in the model over that same period. South of the orocline, where MAP rates are 0.2-0.8 m/a, AFT ages are Oligocene to Miocene and imply exhumation rates of 0.1-0.3 km/Ma (Ege et al., 2008; Carrapa et al., 2009), i.e. three times lower than areas north of the bend using the equivalent method. These data specify a nominal value for E, the mean long-term (Eocene-to-recent) erosion rate per unit precipitation rate, of 0.0001 (i.e. 100 m/Ma of erosion for each meter of MAP). This value could be larger or smaller by at least a factor of two, however, given uncertainty in the available data for long-term erosion rates and their spatial variability. The limited constraints on E are not a major limitation for the model, however, because the model results, as shown in the Figure 2B, are not very sensitive to variations in the value of E.

The parameters for the model reference case are: $\alpha = 0.025$, $h_{pl} = 6$ km, $T = 35$ km (Beck et al., 1996), $E = 0.0001$, $h_{ec} = 3$ km (Quinteros et al., 2008), $h_e = 3$ km (Bookhagen and Strecker, 2008), $A_{de} = 2500$ km^2, and $P_e = 18$ km. The values of α and h_{pl} were calibrated by comparing forward model results for the relationship between the height and width of the modern Andes to observations. Figure DR1 plots the mean height versus the width of the Andes averaged in 1º latitudinal bins along with the results of the model using $\alpha = 0.025$ and $h_{pl} = 6$ km. The width of the Andes was calculated as the ratio of the cross-sectional area to the mean height in order to minimize the role of structural variations in the calculation of this variable. As Figure DR1 illustrates, mean height increases proportionately to width in the model until the mean elevation reaches 3 km. Above that value, there is no increase in maximum height in the model as width increases, but mean height continues to increase, albeit more slowly compared to topographic states with $h < h_{pl}$. The assumption of a uniform topographic slope on the flanks of the Andes is clearly a gross approximation. Figure DR1 illustrates, however, that it works within the context of the geometric assumptions of the model (i.e. a triangular range evolving to a trapezoidal range over time).

Typical long-term magmatic fluxes in Cordilleran systems are approximately 2-3 Armstrong units (AU) (1 AU equals 30 km^2/Ma per unit km arc length) (Ducea and Barton, 2007). The ratio of melt to residue (eclogite) ranges between 1:1 and 1:3 (Ducea, 2002). This implies eclogite production rates of 2 to 9 AU or 60-270 km^2/Ma in Cordilleran-type orogenic systems, with higher values and significant additional production of metamorphic eclogite (Sobolev and Babeyko, 2005) expected in systems with higher shortening rates. Here we assume eclogite production rates in the middle of this range, i.e. 100-150 km^2/Ma, and hence P_e is estimated to be approximately 18 km. The critical eclogite thickness for delamination can be estimated to be approximately 25 km based on crustal thickness variations between areas that have and have not experienced late Cenozoic delamination in the central Andes (Beck et al., 1996; Beck and Zandt, 2002; Yuan et al., 2002). The cross-sectional width at which gravitational foundering takes place depends on the width of the orogen but in the central Andes will be approximately 100 km. This yields 2500 km^2 as an approximate value for $A_{de.}$

The set of parameters for the reference model are not the only combination of parameter values consistent with middle Cenozoic and late Miocene delamination events in the central Andes. Similar results to those of the reference case can be obtained by changing A_{de}, P_e, and T by similar proportions. For example, $A_{de} = 4000$ km^2, $P_e = 25$ km, and $T = 35$ km yields very similar results as those of the reference case in terms of the timing of delamination events but the final topography is significantly lower than observed. As such, there are multiple sets of parameter values that are consistent with constraints on delamination history in the central Andes, but matching both the delamination history and the modern topography requires a set of parameters very close to those of the reference case.

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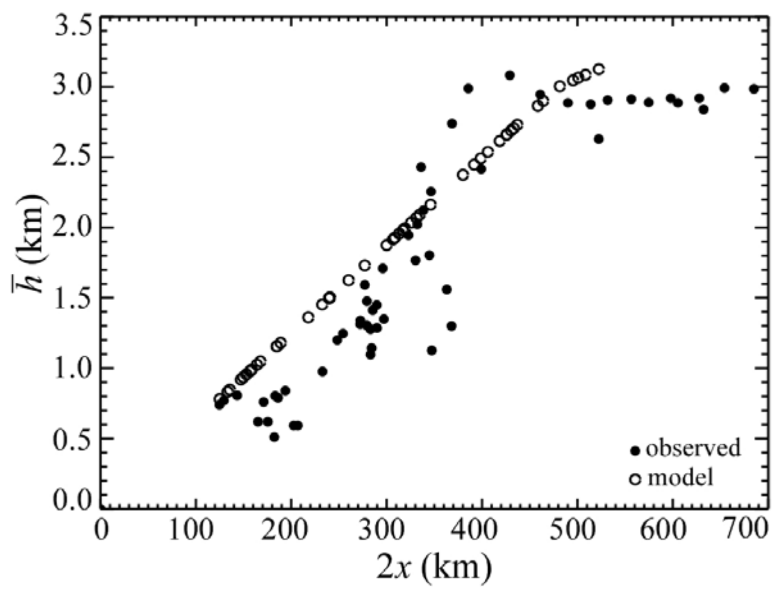

Figure DR1. Plot of the mean elevation of the Andes as a function of width (filled circles) for different latitudes, along with predictions of the numerical model using α = 0.025 (m/m).

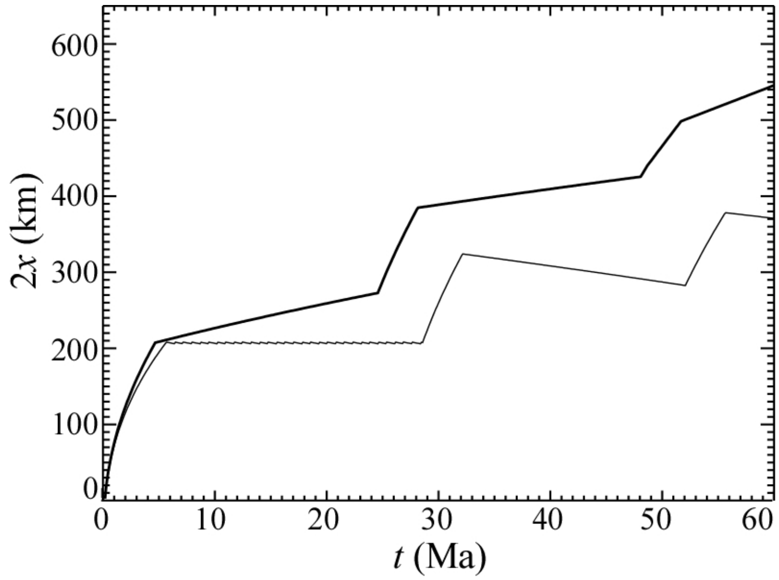

Figure DR2. Plot of orogen width, $2x$, of the model for a relatively humid (P = 3 m/a, thin line) and a relatively arid (P = 0.5 m/a, thick line) case. Model starts at t = 0 (i.e. t = 60 Ma is the present). In both cases, the shortening rate is assumed to be 7 km/Ma and the remaining values are equal to those of the reference case.

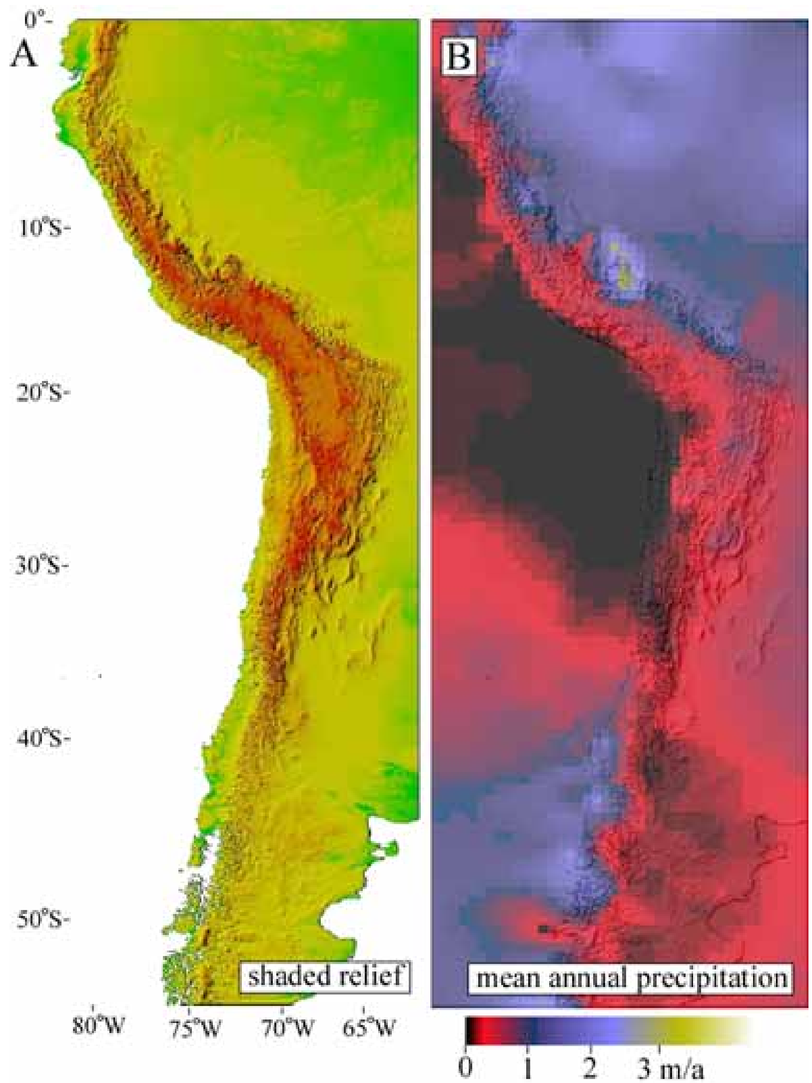

Figure DR3. (A) Shaded relief image of topography (GTOPO30) and (B) color map of mean annual precipitation (from Legates and Willmott (1990)) of the Andes from 0º to 50ºS latitude.