Relationships among climate, erosion, topography, and delamination in the Andes: A numerical modeling investigation

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ABSTRACT

Cordilleran orogenic systems such as the Andes are controlled by shortening rates, climatically-controlled erosion rates, and, in some cases, eclogite production and delamination. All of these processes are coupled, however, making it difficult to uniquely determine the relative importance of each process and the feedbacks among them. In this paper we develop a mass-balanced numerical model that couples an actively-shortening orogen and crustal root with eclogite production, delamination, and climatically controlled erosion. The model provides a first-order quantification of the sources (shortening) and sinks (erosion and eclogite production and delamination) of crustal volume during the Cenozoic in the Andes as a function of latitude and time. Given reasonable estimates for the rates of eclogite production and the threshold size of the eclogitic root required for delamination, the model suggests that, in the central Andes between 5° S and 32° S, the orogen has grown to a sufficient height to produce and maintain eclogite, which in turn has promoted delamination in the lower crust and mantle. In this region, climatically controlled erosion rates influence the size of the orogen through two separate mechanisms: by exporting mass via surface processes and by controlling the lithostatic pressure in the lower crust, which modulates the rates of eclogite production and/or delamination. To the north and south of the central Andes, relatively low shortening rates and high precipitation and erosion rates have slowed eclogite production such that delamination likely has not occurred during the Cenozoic.

INTRODUCTION

The roles of tectonics, climate, and erosion, as well as the feedbacks among them, have attracted a great deal of interest in the past decade. As a modern convergent orogen that spans a wide range of climatic zones, the Andes Mountains are an ideal natural laboratory for examining these processes and feedbacks. Shortening rate is clearly a first-order control on the morphology of the Andes (Isacks, 1988; Kley and Monaldi, 1998; Oncken et al., 2006). The Andes achieve their greatest height and width in the central region, where shortening rates (both long-term and measured by global position system [GPS]) are also highest (McQuarrie, 2002; Kendrick et al., 2006).

The importance of climatically-controlled erosion on the morphology of the Andes has also been emphasized in recent years (Horton, 1999; Montgomery et al., 2001; Strecker et al., 2007). Although climate and topography are closely correlated in many mountain belts worldwide, in some cases that correlation may be a result, not a cause, of mountain building (Molnar and England, 1990). Recent studies have also emphasized the role of lower crustal and upper mantle petrologic and geodynamic processes in controlling the evolution of the central Andes. Paleoelevation proxies indicate that the Altiplano-Puna region gained 1.5–3 km in elevation during late Miocene time (Garzione et al., 2008), an event contem-

poraneous with an eastward shift in the location of thrusting from the Eastern Cordillera to the Subandes in Bolivia. This interpretation is controversial because the paleoelevation proxy data may partly reflect a climatic signal (Ehlers and Poulsen, 2009). Nevertheless, rapid elevation gain in the central Andes is also consistent with the isostatic response to delamination of a dense eclogitic root, the occurrence of which has been deduced independently from petrologic, seismologic, and geodynamic studies (e.g., Kay and Abbruzzi, 1996; Beck and Zandt, 2002; Sobolev and Babeyko, 2005; Schurr et al., 2006). In Cordilleran systems, eclogite forms by pressure-dependent phase transitions (Sobolev and Babeyko, 2005) and by magmatic differentiation (Ducea, 2002). Eclogite formation by both mechanisms, and subsequent gravitational removal, may have significant consequences for topography.

Because eclogite can only form when sufficient lithostatic pressure exists, erosion may modulate the occurrence and timing of delamination, establishing the possibility of feedbacks among climate, erosion, and eclogite production and delamination. Geomorphologists tend to conclude that erosion is the predominant secondary mechanism controlling the morphology of the Andes (after differences in shortening rate) (e.g., Montgomery et al., 2001; Meade and Conrad, 2008) while geophysicists and petrologists tend to conclude that the presence or absence of eclogite production and delamination is the key secondary factor (Kay et al.,

1994; Beck and Zandt, 2002). The coupling between these processes makes any argument based solely on one or the other process incomplete, however. Periodic cycles in Cordilleran systems involving shortening, arc magmatism, and the formation and subsequent gravitational foundering of eclogite may exist and have a controlling influence on changes in retroarc and forearc tapers and elevation (DeCelles et al., 2009). Our goal here is to provide a first-order quantitative assessment of the potential magnitudes of these effects in a coupled model that can be used in testing the general concept of Cordilleran cyclicity.

MODEL DESCRIPTION

The numerical model of this paper is a two-dimensional representation of the Andes at a given latitude (Fig. 1A). The model is applied to different latitudes using tectonic data (i.e., shortening rates) and climatic data (i.e., mean annual
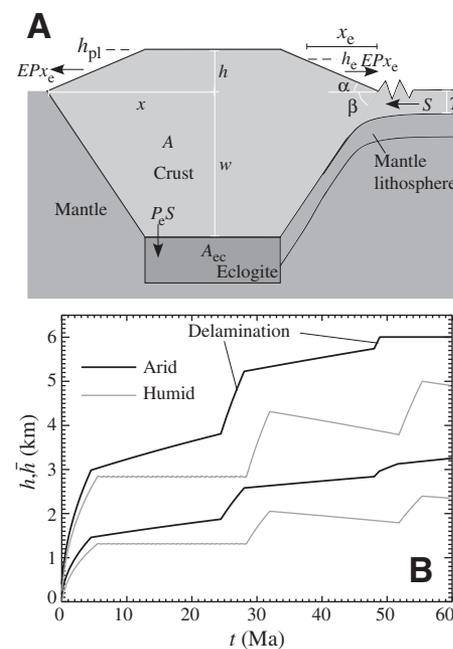
Figure 1. A: Schematic diagram of the model, illustrating key geometric and rate parameters and inflows and outflows of crustal volume (see text for definitions). B: Plots of maximum and mean elevation, h and $\bar{h}$, produced by the model for a relatively humid (mean annual precipitation, P = 3 m/a, gray line) and a relatively arid (P = 0.5 m/a, black line) case with shortening rate, S = 7 km/Ma.

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precipitation [MAP] rates) specific to that latitude. The model tracks the rate of change of crustal mass as the difference between inflows (shortening) and outflows (erosion, eclogite removal) and partitions the crust into changes in orogen height and width according to isostatic balance and a prescribed topographic slope at the flanks of the orogen until the orogen grows high enough for a plateau to form. Once a plateau forms, the topography becomes trapezoidal in cross section and an increase in the cross-sectional area of the crust manifests itself as an increase in the orogen width without an increase in maximum height because gravitational potential energy limits the maximum elevations of orogens (Molnar and Lyon-Caen, 1988).

The rate of increase (t, time) of the cross-sectional area (A) of the crust, dA/dt, is the sum of the product of shortening rate, S, and the thickness of the crust in the foreland, T, minus erosion and the conversion of crust to eclogite:

$$\frac{dA}{dt} = ST - 2EPx_e - \frac{\rho_e}{\rho_c}\frac{dA_{ec}}{dt} \quad \text{if} \quad \frac{dA_{ec}}{dt} > 0$$
$$= ST - 2EPx_e \quad\quad\quad \text{if} \quad \frac{dA_{ec}}{dt} < 0, \quad (1)$$

where $x_e = \min(x, h_e/\alpha)$, E (dimensionless) is the erosion rate per unit precipitation rate P (m/a), x_e is the distance over which erosion takes place on one side of the orogen, A_{ec} is the area of the eclogitic root, ρ_e and ρ_c are the densities of eclogite and crust, respectively (nominally 3600 and 2750 kg/m^3), x is the half-width of the orogen, h_e is the elevation above which precipitation decreases significantly due to orography, and α is the topographic slope of the flanks of the orogen. Erosion in the model is assumed to be proportional to P and x_e. Precipitation in the Andes decreases significantly above 3 km elevation (Bookhagen and Strecker, 2008) due to orography. The distance x_e in the model represents the lateral distance over which significant precipitation (and hence erosion) occurs on the flanks of the orogen below 3 km. Correlations between long-term erosion rates and MAP rates in the Andes have been documented by Kober et al. (2007) and can be expected on theoretical grounds (e.g., stream-power models of bedrock channel erosion, e.g., Whipple and Tucker [1999]). Erosion is assumed to occur on both sides of the range with comparable rates (leading to the factor of 2 in Equation 1). As such, the variable E should reflect a representative average of erosion rates on both sides of the orogen.

Although the modern Andes are an asymmetric two-sided orogen, here we assume a symmetric two-sided orogen with topographic slope $\alpha = 0.025$ (m/m) on the flanks because the asymmetric shape of the modern Andes is likely a relatively recent development (Oncken

et al., 2006). This value for α was chosen to match data for the ratio of the mean height to the width of the modern Andes. Figure DR1 in the GSA Data Repository[1] plots this data from the model (applied to the length of the Andes from 5° N to 50° S) using $\alpha = 0.025$ (m/m). While the ratio of mean height to width is guaranteed to match the average value for the modern Andes, the absolute height and width of the model at different latitudes are emergent properties that depends on sources and sinks of crustal volume and their variation with latitude and time. An increase in crustal mass translates into an increase in orogenic half-width via (DeCelles and DeCelles, 2001)

$$\frac{dx}{dt} = \frac{1}{x(\alpha+\beta)}\frac{dA}{dt}, \quad (2)$$

where β is the slope at the base of the crust. The value of β is allowed to vary as determined by isostatic balance of the topographic load and the crustal and eclogitic roots.

In cross section, an eclogitic root grows in the model when the maximum elevation (a proxy for lithostatic pressure) is greater than a certain threshold value, h_{ec}, required for eclogite production and maintenance. A plateau exists for most of the model duration, hence the maximum and mean elevations are similar. For simplicity, we do not distinguish between eclogite produced by metamorphic reactions and that produced magmatically. Although there are significant differences between these two mechanisms, our approach is focused more on developing the pressure conditions sufficient to maintain eclogite to a point at which it becomes gravitationally unstable. Numerical models suggest that sufficient pressure for eclogite production and maintenance (i.e., stability of garnet in the lower crust) exists when the surface elevation reaches 3 km (Quinteros et al., 2008). The root is assumed to delaminate when its cross-sectional area, A_{ec}, is greater than a prescribed threshold value for delamination, A_{de}. If sufficient pressure exists, eclogite forms in the model at a rate proportional to the shortening rate, at a rate P_eS (in units of km^2/Ma) where P_e has units of kilometers. Mathematically, the rate of increase in the area of the eclogitic root, dA_{ec}/dt, is given by

$$\frac{dA_{ec}}{dt} = P_eS \quad \text{if} \quad A_{ec} < A_{de} \quad \text{and} \quad h \geq h_{ec}$$
$$= 0 \quad \text{if} \quad A_{ec} < A_{de} \quad \text{and} \quad h < h_{ec}$$
$$= \frac{-A_{de}}{T_{de}} \quad \text{if} \quad A_{ec} \geq A_{de}. \quad (3)$$

In the model, delamination and the accompanying surface uplift and thrust-tip propagation take place over a time scale $t_{de} = 3$ Ma, consistent with geophysical models (Molnar and Garzione, 2007) and paleoelevation proxies (Garzione et al., 2008). Geometric relations and isostatic balance (see the Data Repository) provide the remaining equations.

When applying the model to the Andes, input data are needed for the latitudinal variation in shortening rates. Kendrick et al. (2006) used GPS measurements to infer a linear decrease in convergence and/or shortening rates from a maximum value at 16° S to a value one fifth as great at 34° S. Schellart (2008) also documented a linear relationship between convergence rate and lateral slab edge distance. These studies suggest that the most appropriate functional form for shortening rate is given by a piecewise linear function of latitude, i.e.,

$$S = S_{max}\left(1 - \left|\frac{y - y_{max}}{y_{range}}\right|\right) \quad \text{if} \quad y < 41°$$
$$S = S_{min} \quad\quad\quad\quad\quad \text{if} \quad y \geq 41°, \quad (4)$$

where $S_{max} = 7$ km/Ma (for a maximum shortening of 420 km in the central Andes, assuming 60 Ma of convergence, consistent with maximum geologic estimates [McQuarrie, 2002; Oncken et al., 2006]), $S_{min} = 1$ km/Ma, y is latitude, $y_{max} = 16°$ is the latitude of maximum shortening, and $yr_{ange} = 25°$ (Kendrick et al., 2006). The value of S_{min} is not well constrained, but we assume a shortening rate of 1 km/Ma for the Andes south of 41°.

The central Andes contain regionally extensive marginal marine sedimentary rocks of Maastrichtian to mid-Paleocene age (El Molino and Santa Lucía Formations) (Sempere et al., 1997; Horton et al., 2001), indicating that the region was near sea level ca. 60 Ma. As such, a reasonable (although simplified) starting point for the model is no topography and initiation of shortening at 60 Ma. 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, $T_{de} = 3$ Ma, and $P_e = 18$ km. These values were determined using empirical data where constraints are available (described in the Data Repository) together with a parameter tuning procedure that simultaneously honors the modern topography of the Andes along their length from 5° N to 50° S and

the timing of inferred delamination events in the central Andes, where a late Miocene event has been inferred from multiple studies and a magmatic flareup at ca. 45 Ma indicates that delamination also may have occurred during the mid Cenozoic (Haschke et al., 2002; DeCelles et al., 2009). Using the modern topography as a model constraint is appropriate given that our goal is to constrain the paleotopographic history and rates of crustal sources and sinks leading up to the modern state.

MODEL RESULTS

Example output of the model is illustrated in Figure 1B for a relatively humid (P = 3 m/a) and a relatively arid (P = 0.5 m/a) case. The shortening rate is assumed to be 7 km/Ma in order to isolate the effects of climatically-controlled erosion in this comparison. Figure 1B illustrates the maximum and mean elevations as a function of time from the beginning of the model (i.e., t = 0). Mean elevation increases through time until an eclogitic root begins to form at t = ca. 4–5 Ma. The negative buoyancy associated with the eclogitic root keeps the maximum elevation close to 3 km until delamination begins occurs t = ca. 25 Ma in the arid case and t = ca. 30 Ma in the humid case. In the humid case, eclogite grows more slowly because erosion periodically reduces the surface elevation below the threshold for eclogite production, thereby delaying the delamination event relative to the arid case. Delamination triggers maximum surface uplift of 1 km, followed by a second phase of eclogitic production (which causes surface elevations to increase more slowly or to decrease, depending on climate) until a second, late Cenozoic delamination event occurs. Delamination is accompanied by an abrupt 100 km increase in the width of the orogen (Fig. DR2). An increase in orogen width accompanies delamination because surface uplift creates gravitational body forces that favor the migration of thrusting to lower elevations (Royden, 1996, Hilley and Strecker, 2004). In the model, this aspect of the system is enforced in a simplified way via the prescribed topographic slope α at the flanks of the range.

Eclogite production and delamination are five times more effective at removing mass from the crust compared to erosion in the arid case. In this case, which broadly represents the tectonic and climatic conditions of the central Andes, erosion also influences the size of the orogen by modulating the pace and timing of eclogite production and delamination, as illustrated by comparing the height and width of the orogen predicted by the model for an arid climate with that of a humid climate. As Figure 1B illustrates, erosion influences topography significantly by removing part of the lithostatic load that drives eclogite production, hence delaying delamination in the humid case relative to the arid case.

Figures 2A–2C illustrate the application of the model to the length of the Andes from 5° N to 50° S. To obtain these results, shortening rates (Equation 4) and MAP rates (extracted from Legates and Willmott [1990]; Fig. DR3) for 1° latitude bins were input into the model. All of the remaining parameter values were set equal to those of the reference case. Figure 2A (also see animation in the Data Repository) illustrates the mean elevation as a function of time and latitude in the model, illustrating the pulses of surface uplift that result from delamination. The model suggests that delamination events are time transgressive, with removal first occurring in the central Andes near 20° S because that region has undergone the optimum combination of high tectonic shortening rates and aridity. Elsewhere

Figure 2. A: Plot of maximum elevation of the Andes predicted by the model as a function of time *t* and latitude *y*. B: Plot of mean elevation ($\bar{h}$) of the modern Andes (filled circles) as a function of latitude *y* together with the model topography for a range of values of *E* (erosion rate per unit precipitation). C: Plot of shortening rate (dashed curve) assumed in the model (Equation 4), mean annual precipitation, *P* (gray curve), and the difference between the mean Cenozoic rates of mass loss by eclogite production and delamination, E_p, and mass loss by erosion, E_g, as a function of latitude.

in the central Andes, more time is needed to reach the threshold for delamination, and in the northern and southern ends of the Andes the threshold is never reached. This is consistent with available data from the Andes, where more recent delamination has been inferred in the topographically higher Puna Plateau compared to the Altiplano, which may be lower because the next cycle of eclogite production is already under way (DeCelles et al., 2009). Model results for modern topography are shown in Figure 2B with three different values of E, illustrating the robustness of model with respect to uncertainty in the erosivity value. In the central Andes, the mean Cenozoic rate of mass removal by eclogite production, E_p, is much larger than the rate of removal by erosion, E_g (Fig. 2C). From 3°S to 36°S, $E_p > E_g$, while in the northern and southern Andes erosion is dominant, i.e., $E_p < E_g$.

CONCLUSIONS

Tectonic shortening, climatically-controlled erosion, eclogite production, and delamination all exert significant control on the evolution of the Andes. These processes are coupled, however, and hence a multi-disciplinary approach is needed to understand the feedbacks among them. Here we described a mass-conservative model that self-consistently honors the topography of the modern Andes and the timing of inferred Cenozoic delamination events. Our model illustrates that while erosion likely plays a relatively minor role in exporting mass from the central Andes, it exerts an additional control on topography by modulating the timing of delamination events. This suggests that feedbacks between geomorphic, petrologic, and geodynamic processes play a significant role in controlling along-strike variability in the morphology of the Andes.

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