Mid-latitude glacial erosion hotspot related to equatorial shifts in southern Westerlies

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ABSTRACT

Glaciation has affected the shape of mountain ranges and has induced a global increase in erosion rates during the past 2 m.y. The observed increase in erosion rates appears to vary with latitude, reaching a maximum at mid-latitudes that is particularly well defined in the Southern Hemisphere. Although it is likely that climate played an important role, the processes responsible for such latitudinal distribution of erosion are unclear. Here we exploit the meridional extent of the Patagonian Andes and identify an erosion hotspot at ~44°S. Using a glacial erosion model and formally inverting the available thermochronometric and geobarometric data, we show that this hotspot coincides with the location of maximum precipitation that follows the Southern Hemisphere Westerlies during glacial periods. We propose that the increased precipitation rates at ~44°S led to greater ice sliding velocities and faster glacial erosion. Our results imply that the migration of the westerly wind belt toward the equator since 2–3 Ma may have played an important role in determining the distribution of mountain erosion in the Southern Hemisphere.

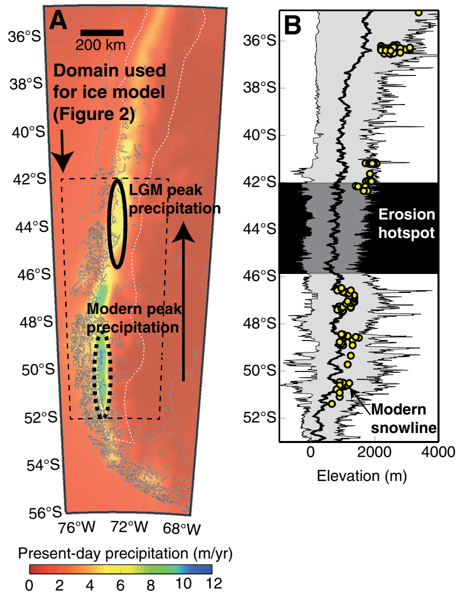

Figure 1. Climate, topography, and modern snowlines, Patagonian Andes. A: Modeled modern precipitation (Garreaud et al., 2013). Thin black dashed line represents model domain used for glacial erosion model (Fig. 2). LGM—Last Glacial Maximum. B: Swath of topography within zone shown by white dashed line in A. This corresponds to pro- and retro-shear demarking limits of deformation (Thomson et al., 2010). Yellow dots depict modern snowlines extracted from World Glacier Inventory database (nsidc.org/data/g01130).

INTRODUCTION

During the late Cenozoic, climate cooled and led to the development of glaciers and ice caps in most mid- to high-latitude mountains on Earth (Shackleton and Opdyke, 1977). Although this is still subject to discussion (Willenbring and von Blanckenburg, 2010), global climate changes related to the onset of Northern Hemisphere glaciation at ca. 2.7 Ma are thought to have led to the modification of mountainous landforms through a global acceleration of glacial erosion (Zhang et al., 2001; Molnar, 2004; Herman et al., 2013). Furthermore, the global wind and precipitation patterns also changed through a progressive equatorward migration of the westerly wind belts during the Quaternary (e.g., Brierley et al., 2009; Lawrence et al., 2013) that led to latitudinal changes in storm-track location in the Southern Hemisphere (Heusser, 1989; Hulton et al., 1994; Lamy et al., 1999; Moreno and León, 2003; Kaplan et al., 2008). The modern glacial coverage in the Patagonian Andes coincides with the modern storm track and precipitation, centered on 50°S (Garreaud et al., 2013). If the storm track and precipitation were to be offset, then we might anticipate that the pattern of glacial extent and ice flux would be offset as well.

It has been proposed that glacial and periglacial erosion may have also set a limit on the height of mountains globally, an idea that is corroborated by an observed correlation between the location of the equilibrium line altitude (ELA, i.e., where ice accumulation rate equals ice ablation rate) and the mean elevation of mountain ranges (e.g., Egholm et al., 2009). This idea relies implicitly on the postulate that glaciers and ice caps are sufficiently efficient to reduce summits within a few million years. However, the correspondence between the ELA and mountain height breaks down toward high-latitude regions, where mountains have attained elevations above the snowline of the Last Glacial Maximum (LGM, ca. 19 ka) or the present day (Broecker and Denton, 1989; Egholm et al., 2009). This observation is supported by patterns of Quaternary erosion that is fast at mid-latitudes (~45°S) but significantly slower toward high latitudes (Herman et al., 2013; Champagnac et al., 2014), at least in the Southern Hemisphere. Yet the specific processes responsible for such patterns remain elusive. Here we quantify how glacial erosion rates have varied with latitude during the Pliocene and Pleistocene Epochs, using the glaciated landscape of the Patagonian Andes as a natural laboratory (Fig. 1). We propose that equatorward shifts of the southern Westerlies have played a significant role in setting erosion patterns in the southern Andes.

MODERN AND PALEO-CLIMATE SETTING

The Patagonian Andes are particularly appropriate to study glacial erosion because their nearly 2000 km meridional extent exhibits large gradients in temperature and precipitation rates, and they have experienced mountain glaciation for ~6 m.y. (Mercer and Sutter, 1982). The southern Westerlies currently show a distinct maximum in precipitation and storms at ~50°S, while paleoclimate studies have also revealed a well-defined maximum in precipitation at ~44°S during the LGM (Heusser, 1989; Hulton et al., 1994; Lamy et al., 1999; Moreno and León, 2003). These observations indicate that the polar jet and its associated precipitation maximum were shifted by ~600 km toward the equator during the LGM relative to the present day. Furthermore, we observe a strong correlation between snowline and mountain height between 40° and 46°S that becomes less clear with increasing latitude (Fig. 1B) (Montgomery et al., 2001). This pattern coincides with the distribution of erosion, with higher erosion rates in the northern parts compared to the south (Thomson et al., 2010; Herman et al., 2013).

GLACIAL EROSION MODEL

Most physical models for glacial erosion assume that erosion is dominated by abrasion and plucking, which are both a function of the ice sliding velocity (e.g., Hallet, 1979, 1996; Iverson, 2012). The sliding velocity is itself nonlinearly proportional to ice thickness and ice surface slope, which are set by the balance between the divergence of the ice flux and the surface mass balance (i.e., the balance between ice accumulation and ablation rate). It is also well established that the surface mass balance of ice sheets and glaciers depends on precipitation and tempera-

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ture (Cuffey and Paterson, 2010). Therefore, small changes in precipitation may cause large changes in ice extent and ice flux, a point that has been highlighted for the LGM Patagonian ice sheet (Hulton et al., 1994; Kaplan et al., 2008).

To investigate the effect of such a northward shift on erosion, we conducted a series of numerical experiments in which we imposed a surface mass balance and computed the resulting erosion rates (see the GSA Data Repository[1] for model details). We reduced the complexity of our model to concentrate on the effects of changing precipitation and temperature with latitude (Equations 8 and 9 in the Data Repository) during glacial periods and report the results of three end-member experiments (Fig. 2). In all three experiments, temperatures are everywhere cooler by ~6 °C compared to the present. Experiment 1 highlights the influence of an ~600 km northward shift of the modern patterns of precipitation and ice accumulation (Casassa et al., 2002). Experiment 2 focuses on the influence of the latitudinal variation in temperature, with the latitudinal variation in precipitation held constant. Experiment 3 provides a reference, where temperatures are reduced by ~6 °C, but the pattern of precipitation and ice accumulation is maintained equivalent to the modern precipitation patterns. (The mass balance for each experiment is shown in Fig. DR1 in the Data Repository.)

The only numerical experiments capable of reproducing a large ice sheet, i.e., comparable to the ice extent for the Greatest Patagonian Glaciation (GPG, ca. 1 Ma) and the LGM, in the northern Patagonian Andes are those that have high precipitation at ~44°S. Previous modeling studies (Hulton et al., 1994) required a northward migration of peak precipitation to explain the uniform ice extent between 52°S and 42°S, despite the large gradient in temperature with latitude. More importantly, these end-member examples clearly show that high precipitation rates in the northern regions lead to an increase of the mass-balance gradient, ice volume, ice sliding velocities, and therefore erosion rates centered at ~44°S during glacial periods. Although we only model one glacial cycle, the influence of northward shifts in precipitation on erosion has probably been acting cyclically for at least 1 m.y., and possibly since the onset of Pliocene-Pleistocene glaciation, given the observed similarity between GPG and LGM ice extents (Fig. 2).

BASAL TEMPERATURE CONDITIONS

Thomson et al. (2010) proposed that the latitudinal variation in erosion rates in the Patagonian Andes is due to an increase in frozen-based conditions with increasing latitude. To test this hypothesis, our ice-sheet model includes a one-dimensional thermal solution (see the Data Repository). In this model, the difference between the surface and basal temperature depends on the basal heat flux, ice thickness, mass balance, and ice surface temperature (see the Data Repository). This calculation shows that the temperature difference between the surface and base of the ice sheet increases as the accumulation rates decreases (Fig. 3). We estimate that in glacial valleys, surface temperatures were mostly >–6 °C and accumulation rates <2 m/yr, even during glacial maxima. In addition, ice thickness in valleys has been generally >~400 m. This combination of conditions strongly favors basal temperatures >0 °C. Furthermore, fine-grain sediment can induce a depression of the freezing temperature, down to temperatures as low as –17 °C (Cuffey and Paterson, 2010). As a result, we conclude that wet-based conditions have prevailed during glacial times. The exception would be the most elevated parts of the landscape, where the atmosphere is very cold and the ice is thin.

INVERSION OF THERMOCHRONOMETRIC AND GEOBAROMETRIC DATA

We formally inverted the extensive set of thermochronometric, geobarometric, and geochronologic data (see the Data Repository) to quantitatively estimate the erosion history. We used a modified version of the method proposed by Fox et al. (2014). This procedure involves a weakly nonlinear least-squares inversion (see Data Repository) and allows efficient treatment of a large number of spatially distributed data. We have modified the procedure to better account for the log-normal distribution of erosion rates and thermochronometric ages and to constrain positive values for estimated erosion rates. The compiled data and derived erosion rates for the past 6 m.y., resolved into 2 m.y. time steps, are presented in Figure 4. The color map is grayed

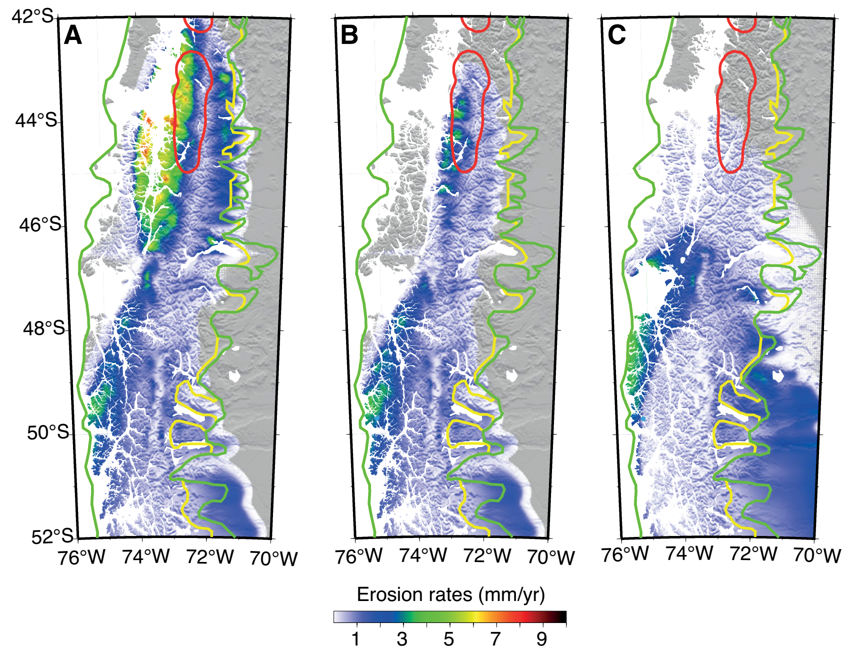

Figure 2. Glacial erosion model, Patagonian Andes: computed erosion rates for experiment 1 (A), experiment 2 (B), and experiment 3 (C) (see text for experiment parameters). Red contours highlight region where erosion rates are >0.6 mm/yr (i.e., erosion hotspot) in inversion results shown in Figure 4. Green and yellow depict ice extent at Greatest Patagonian Glaciation and Last Glacial Maximum respectively (Kaplan et al., 2008). See the Data Repository (see footnote 1) for further details on the model.

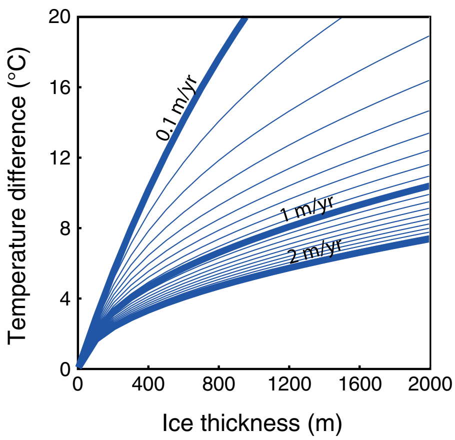

Figure 3. One-dimensional thermal model: estimated temperature difference between surface and base of modeled ice sheet versus ice thickness. Each line is for an accumulation increment of 0.1 m/yr, from 0.1 to 2 m/yr. Thick lines are for 0.1, 1, and 2 m/yr.

[1]GSA Data Repository item 2015333, glacial erosion model, thermochronometric and geobarometric data, and methods for inversion of the data, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

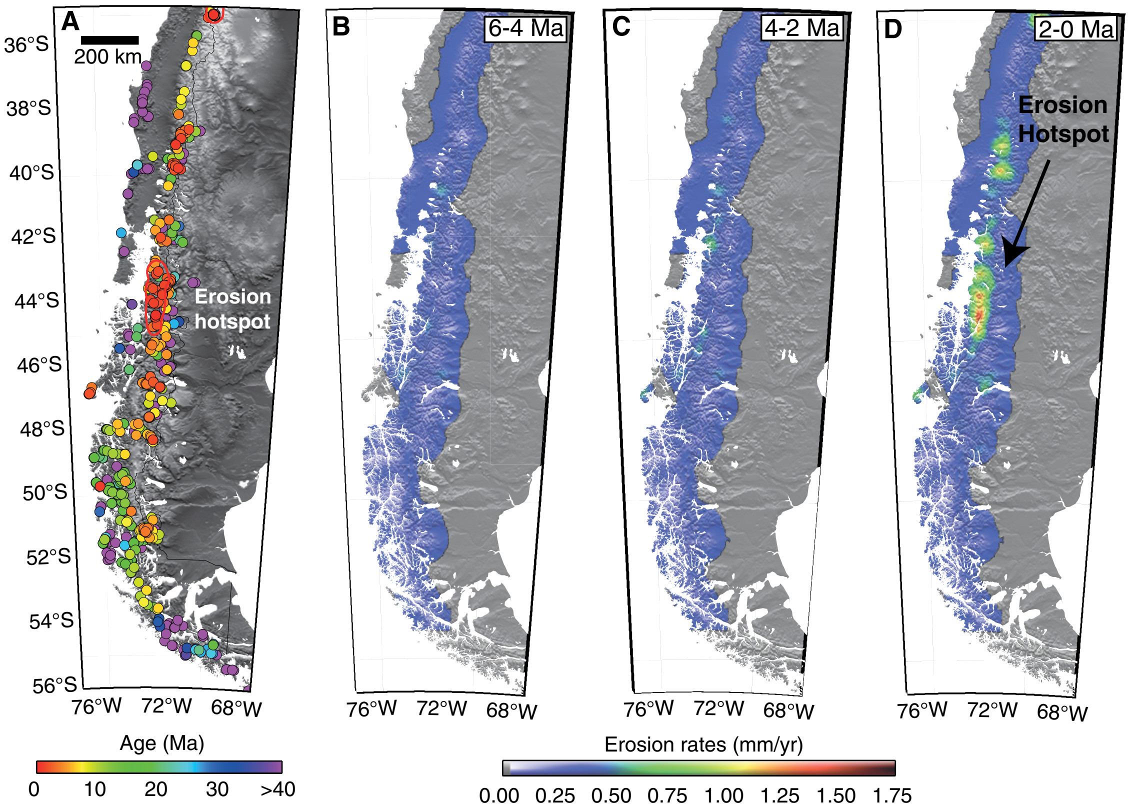

Figure 4. Inversion of thermochronometric and geobarometric data, Patagonian Andes. A: Existing thermochronometric data including apatite (U-Th)/He, apatite fission track, zircon (U-Th)/He, zircon fission track, and Al-in-hornblende data. Red contours highlight region where erosion rates are >0.6 mm/yr (i.e., erosion hotspot) in inversion results. B–D: Erosion history in 2 m.y. time-step intervals. Inverse model was obtained for 40 m.y., using 2 m.y. time-step intervals. We only show the last 6 m.y. See the Data Repository (see footnote 1) for all other inversion parameters.

out in areas where there are insufficient thermochronometric data to resolve erosion rates. The results show that the high-latitude southern part of the Patagonian Andes has eroded at a slow and steady rate (~0.25 mm/yr), whereas the northern part of the landscape has seen a six-fold increase, from ~0.25 to ~1.5 mm/yr toward the present. The spatial correlation in cooling ages indicates that these patterns are resolvable down to a horizontal length scale of ~50 km.

DISCUSSION

Our results provide further support to previous interpretations that highlighted slow erosion rates at high latitudes (Thomson et al., 2010; Herman et al., 2013). More importantly, they reveal an erosion hotspot at ~44°S, with erosion rates increasing most rapidly during the past 2 m.y., perhaps in association with the strengthening of the Northern Hemisphere glaciation. The erosional hotspot is bordered to the west by the Gulfs of Ancud and Corcovado in the Sea of Chiloé, which consist of a continuous series of deep marine basins mainly formed by glacial erosion (e.g., Denton et al., 1999). We anticipate that, if we had thermochronologic data from this submarine region, the estimated region of the hotspot would expand to cover this area.

Our interpretation is that fast erosion in the hotspot is directly caused by a localized high discharge of glacial ice. However, we speculate that the combination of increased ice discharge and tectonic thickening has sustained the high erosion rates we observe. The southern Andes have formed by long-lived thrusting along the east side of the range, starting at ca. 100 Ma (Folguera and Ramos, 2011). Studies adjacent to the hotspot indicate a recent phase of thrusting, starting at ca. 25 Ma and perhaps ending at ca. 5 Ma (Folguera and Iannizzotto, 2004; Giacosa et al., 2005). The reduced activity on thrust faults in the foreland may be due to the enhanced erosion, and predicts a focus of deformation within the core of the range, which needs to be tested.

The estimated erosion rates are integrated over 2 m.y. and thus are averaged over many glacial cycles. Over this time span, the landscape has thus experienced both glacial and fluvial erosion. However, it has been shown that erosion rates are higher during glacial maxima in the southern Andes (Hebbeln et al., 2007). As an example, the modern Patagonian Andes are dominated by glacial landforms even after some 15 k.y. of interglacial climate. Therefore, it would seem likely that glacial, rather than fluvial, erosion is the main erosive agent.

Most previous studies on glacial erosion have focused on the morphological evolution of glacial valleys rather than on understanding the full influence of climate, including variations in precipitation and temperature with latitude, on long-term erosion by glaciers. In particular, emphasis has been put on the role of frozen- versus warm-based conditions as a control on glacial erosion patterns (e.g., Garwood, 1910; Thomson et al., 2010). As a result, it is often argued that glacial erosion rates at high latitudes are lower because lower temperatures imply that the base of the glacier is more frequently frozen to its underlying bedrock. If this cold-based glacier interpretation were correct, then we would expect to find a gradual change in glacial erosion rates with latitude. Instead, our results clearly show that erosion rates were more localized around the location of peak precipitation during glacial maxima, indicating that shifts in westerly winds have played an important role.

The Chile triple junction has long been viewed as an important driver in the tectonic and topographic evolution of the southernmost Andes. Between 15 and 6 Ma, the triple junction migrated rapidly northward along the Chile subduction zone, but it has remained relatively stationary at its present location, ~46.5°S, since then (Cande and Leslie, 1986). One proposal is that the triple junction has produced tectonic shortening and topographic uplift due to "ridge collision" (e.g., Lagabrielle et al., 2004). Another more recent proposal is that the area around the triple junction has been uplifted due to convectively induced dynamic topography (Braun et al., 2013; Guillaume et al., 2013). Both proposals predict that the topographic uplift of the triple junction should be marked by an erosional hotspot. This prediction is refuted by our thermochronologic inversion, which shows relatively steady erosion rates near the triple junction during the past 6 m.y. The erosional hotspot resolved by our analysis lies far to the north, so cannot be attributed to the triple junction.

CONCLUSIONS

Our results provide support for large-scale linkages between glacial erosion and global climate. More importantly, our new observations are consistent with mid-latitude changes in erosion rates in response to Pliocene-Pleistocene cooling at a global scale (Herman et al., 2013; Champagnac et al., 2014), although the magnitude of erosion rates, and changes in erosion rates, may vary locally depending on tectonic activity and local climatic conditions. Several recent studies have shown that the strengthening of the meridional temperature gradient led to an intensification and latitudinal contraction of the atmospheric convective cells at the Pliocene-Pleistocene transition at ca. 2.7 Ma (Brierley et al., 2009; Lawrence et al., 2013). Therefore, our findings imply that the combined effects of cooling and the establishment of latitudinal shifts in Southern Hemisphere Westerlies during glaciations may have promoted erosion toward mid-latitudes in the Patagonian Andes and maintained relatively low erosion rates at higher latitudes since the onset of Pliocene-Pleistocene glaciation.

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