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Nonuniform surface uplift of the Andean plateau revealed by deuterium isotopes in Miocene volcanic glass from southern Peru

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A B S T R A C T

Proposals for rapid late Miocene surface uplift driven by large-scale lithospheric removal beneath the central Andean plateau have been based largely on temperature-sensitive paleoaltimeters. Both the magnitude and mechanism of this proposed pulse of uplift have been challenged. First, climatic general circulation models support protracted uplift with predicted temperature and isotopic shifts enhanced by attainment of threshold elevations. Second, tectonic models in which surface elevations are compensated by regional contraction and crustal thickening question the need for lithospheric removal and predict broadly coeval uplift of the entire plateau. We present hydrogen isotope data using a novel temperature-insensitive volcanic glass proxy from continuous, well-dated lower to middle Miocene basin fill in the Western Cordillera of the northern plateau that show a rapid decrease in δD values (−62.8‰) at 19–16 Ma, with extremely negative values continuing into the Pliocene. We propose that the basin reached its current elevation by 16 Ma, >6 Myr earlier than proposed for the central plateau. The rapid decrease in δD values is consistent with punctuated surface uplift of 2.2–3.7 km between 19 and 16 Ma. Whereas the 3.7 km upper estimate assumes a static climate similar to modern, the 2.2 km lower estimate conservatively incorporates modeled changes in the isotopic composition of precipitation associated with elevation change. Comparison of these results to existing paleoelevation estimates from the Andean plateau facilitates a tentative reconstruction of earliest middle Miocene paleotopography showing a central depression with flanking hinterland and thrust-belt highlands. This apparent pattern of nonuniform plateau uplift contradicts shortening-proportional topographic growth over tens of Myr. We propose that temporally and spatially irregular surface uplift may be linked to pronounced local variability in crustal shortening and/or piecemeal removal of dense mantle lithosphere. Insofar as these irregularities reflect the scale of heterogeneity for surface uplift processes, available paleoelevation estimates point to a principal uplift mechanism that varies over relatively short (<250 km) horizontal distances.

1. Introduction

Shortening since ∼50 Ma has produced crustal thicknesses of 60–75 km below the central Andean plateau (CAP), which includes the 4 km-high Altiplano–Puna plateau and flanking 5–6 km-high peaks of the Eastern and Western Cordilleras (Lamb and Hoke, 1997; Coutand et al., 2001; Horton et al., 2001; Beck and Zandt, 2002; DeCelles and Horton, 2003; McQuarrie et al., 2005; Gillis et al., 2006). Though deformation is broadly synchronous in the central Andes, the magnitude of east–west shortening decreases from a maximum of 250–300 km at ∼20°S (Bolivia) to 50–120 km at 13°S (Peru) and 27°S (Argentina) (Baby et al., 1997; Kley and Monaldi, 1998; McQuarrie, 2002; Oncken et al., 2006; Gotberg et al., 2010). The long history of upper crustal shortening has been linked to an equally long-lived and steady rise in topography (Isacks, 1988; Gubbels et al., 1993; Barnes and Ehlers, 2009). Contrasting with this prediction, several lines of evidence point to a pulse of large-magnitude surface uplift in the Altiplano and flanking Eastern and Western Cordilleras of Bolivia at 17–22°S (Fig. 1). Punctuated late Miocene surface uplift has been inferred from wholesale tilting and linked reverse faulting in the Western Cordillera, which is likely a continuation or rejuvenation of deformation that began in the late Oligocene–early Miocene (Wörner et al., 2002; Farias et al., 2005; Hoke et al., 2007; Jordan et al., 2010). Farther east, elevated river profiles indicating 1705 ± 695 m of rock uplift since 12–9 Ma in the Eastern Cordillera (Barke and Lamb, 2006), and paleotemperature estimates from fossil leaf physiognomy suggesting low paleoelevations in early through middle Miocene time (<1.3 km Altiplano at 20.8–13.8 Ma, <1.6 km Eastern Cordillera at ∼10.6 Ma) (Gregory-Wodzicki et al.,

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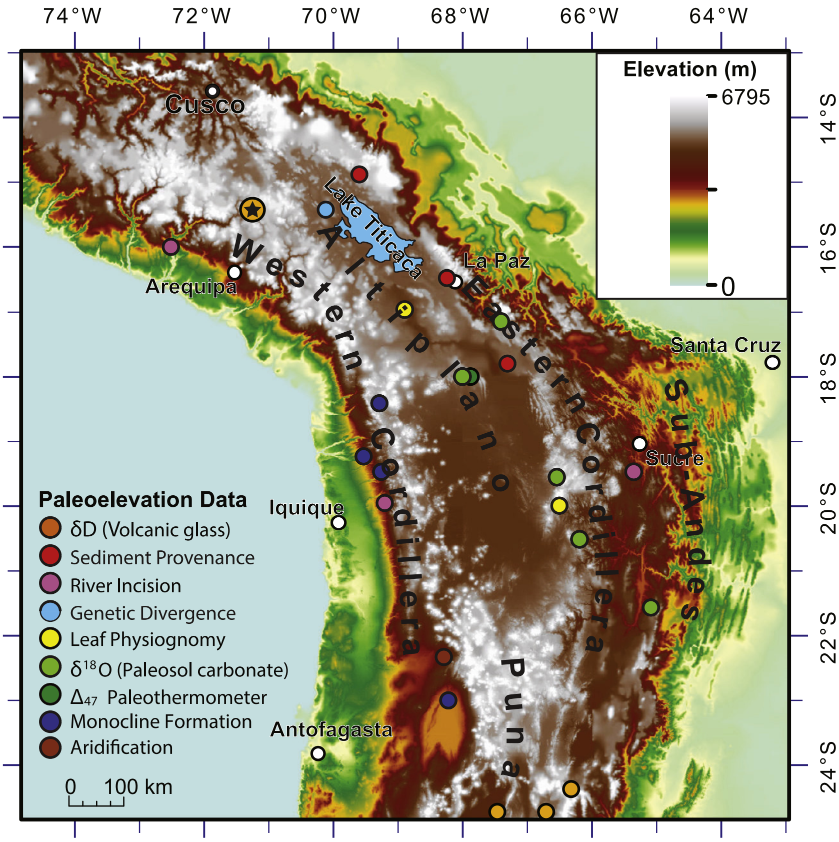

Fig. 1. Topographic map of the central Andean plateau (CAP) showing the locations (circles) and techniques (color codes) employed in paleoelevation studies, including this study (black star: Condoroma Basin). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1998; Gregory-Wodzicki, 2000), are consistent with a pulse of late Miocene surface uplift.

Most significantly, Ghosh et al. (2006) and Garzione et al. (2008) documented a decrease in Δ_{47}-based paleotemperature coupled with a 3–4‰ decrease in the $\delta^{18}O$ values of paleosol carbonate nodules. These results have been used to argue for 2.5–3.5 km of surface uplift in the central Altiplano between 10.3 and 6.8 Ma. This rapid late Miocene surface uplift has been interpreted as an isostatic response to wholesale removal of accumulated dense, eclogitic lower crust and mantle lithosphere (Garzione et al., 2006; Molnar and Garzione, 2007).

Many paleoaltimeters require knowledge of paleoclimate conditions in order to accurately establish past elevation. For example, Rayleigh distillation of water vapor as air masses are adiabatically cooled during orographic lifting results in progressive depletion of the heavy isotopes in remaining air masses and precipitation derived from them (Rowley, 2007). This generates a systematic decrease in δD (and $\delta^{18}O$) values with increasing surface elevation (Poage and Chamberlain, 2001; Rowley and Garzione, 2007). Measurement or modeling of the syndepositional δD (or $\delta^{18}O$) *versus* elevation lapse rate allows estimates of paleoelevation. However, additional factors, notably low-elevation temperature and precipitation amount, can alter the down-wind stable isotope lapse rate.

Both the magnitude and mechanism of the proposed late Miocene surface uplift event have been questioned (Barnes and Ehlers, 2009; Ehlers and Poulsen, 2009; Poulsen et al., 2010; Lamb, 2011; Insel et al., 2012). General circulation models incorporating the effects of changing topography (here referred to as "linked climate-topography models") suggest that attainment of elevations 50–75% of modern can result in a threshold climate response involving non-adiabatic cooling and precipitation amount-induced decreases in $\delta^{18}O$ and δD values. These models demonstrate that raising topography results in climatic changes, including coupled decreases in precipitation stable isotopic composition and temperature, both of which affect the paleosol carbonate record. This has led to the alternative conclusion that significant isotopic shifts in the CAP are the result of abrupt climate change rather than surface uplift (Ehlers and Poulsen, 2009; Insel et al., 2010; Poulsen et al., 2010; Insel et al., 2012). We incorporate these advances in our understanding of potential threshold responses by comparing new results from a CAP basin to the predictions of linked climate-topography models, thus guiding the interpretation of stable isotopic data.

Tectonic models in which Andean surface uplift is explained by crustal shortening and thickening (here referred to as "shortening-related models") have questioned the need for lithospheric delamination as a mechanism for rapid uplift. For example, Lamb (2011) concluded that surface uplift within the uncertainties of that inferred from paleoelevation proxies could be a product of pure shear shortening localized in the Altiplano and lower crustal simple shear shortening driven by underthrusting of the Brazilian Shield and propagation of the Subandean fold-thrust belt. To evaluate the potential impact of shortening on the surface uplift history of the northern Altiplano, we compare deformation records in southern Peru to the timing of the major isotopic shift identified here and predictions from numerical models of delamination.

In linked climate-topography models and in regional shortening-related models surface uplift proceeds uniformly across the entire CAP. Climate-topography models have assumed steady topographic growth, usually as some percentage of modern altitude. As modeled uplift proceeds to ~50% of modern elevations, a low-magnitude decrease in weighted mean-annual precipitation $\delta^{18}O$ values (~−2 to −5‰) develops between 8 and 17°S, centered in the Eastern Cordillera at ~12°S, but is not observed south of 17°S (Poulsen et al., 2010; their Fig. S3B). When models proceed to 100% of modern elevation, or account