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Clumped isotope evidence for diachronous surface cooling of the Altiplano and pulsed surface uplift of the Central Andes

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ABSTRACT

Spatially extensive paleoelevation records of the Altiplano plateau are critical to determining the geodynamic mechanisms that formed and support high elevations over a broad area. Prior stable isotope data reveal a climate history for the northern Bolivian Altiplano that has been interpreted to show rapid surface uplift of 2.5 ± 1.0 km between ∼10 and 6 Ma. This study applies clumped isotope paleothermometry to paleosol carbonates formed at both a low-elevation site and temporally overlapping high-elevation sites in the southern Altiplano/Eastern Cordillera during the middle to late Miocene. Surface paleotemperature decreased by 14 °C in the southern Altiplano/Eastern Cordillera relative to stable low-elevation paleotemperatures, implying surface elevation increase of 1.9 ± 0.7 km between 16 and 13 Ma and an additional 0.7 ± 0.6 km between 13 and 9 Ma. Both the large magnitude of surface temperature decrease and earlier onset (7 ± 4 Myr) in the south as compared to the north suggest rapid elevation increase by piecemeal removal of lower lithosphere beneath the plateau and possible northward lower crustal flow.

1. Introduction

The Altiplano plateau of western South America lies within the Central Andes above the subducting Nazca plate. The region stretches from ∼14 °S to 22 °S, reaches 300 km wide (measured approximately east to west), and has an average elevation of ∼4 km. It is enclosed by the Western Cordillera magmatic arc and Eastern Cordillera fold-thrust belt (Fig. 1), whose development has left the Altiplano internally drained since at least late Oligocene time (Horton et al., 2001). This resulted in the accumulation of an extensive sedimentary archive that reflects the Altiplano's Neogene paleoclimate and surface uplift history.

This record has the potential to inform us about the geodynamic processes that raise orogenic plateaus. The possible surface elevation histories can be described by two end-member models: rapid, substantial pulses of uplift vs. gradual, continuous uplift (e.g., Barnes and Ehlers, 2009). Rapid surface uplift of portions of the Andes on the order of ⩾1 km over no more than several million years would require specific geodynamic processes, such as the loss of the lower lithosphere (e.g., Houseman et al., 1981) or lower crustal flow (e.g., Husson and Sempere, 2003), whereas gradual surface uplift that reflects the rate of crustal shortening and thickening must be accompanied by continuous removal of the dense lower lithosphere via a process such as ablative subduction (Pope and Willett, 1998).

1.1. Existing paleoelevation constraints

Previous to this study, few measurements of paleo-surface elevations constrain the processes responsible for the surface uplift of the Altiplano and the Eastern Cordillera, and those that do exist are solely from the north-central Altiplano and Eastern Cordillera (16 °S to 19 °S). The oldest information comes from 73–60 Ma coastal marine deposits, indicating that the region was at or near sea level at that time (Sempere et al., 1997). Structural and sedimentological data indicate that the Eastern Cordillera crust began to thicken by crustal shortening by at least Eocene time (DeCelles and Horton, 2003; Isacks, 1988; McQuarrie,

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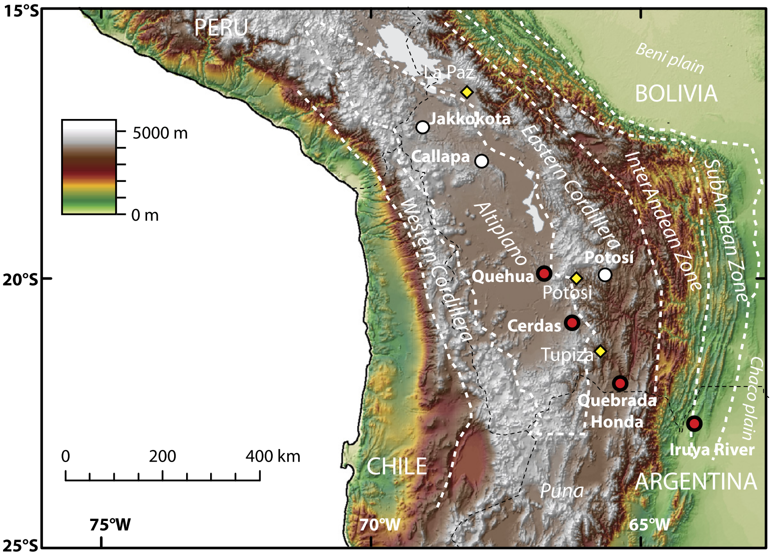

Fig. 1. Topography of the central Andes between 15° and 25 °S (SRTM30 dataset) showing physiographic divisions in italics, modified from McQuarrie (2002). Localities (red circles) are sections sampled in this study; white circles designate localities from northern Altiplano paleotemperature studies (Ghosh et al., 2006b; Gregory-Wodzicki, 2002; Gregory-Wodzicki et al., 1998). Diamonds identify major cities in Bolivia.

2002), likely resulting in some surface uplift. Thermochronometric data indicate that this shortening resulted in significant exhumation (~4 to 7 km) of the Eastern Cordillera (Gillis et al., 2006; Barnes et al., 2008). Despite significant shortening and exhumation of the Eastern Cordillera, climate proxy data—paleotemperatures and the oxygen isotope composition of paleo-precipitation—suggest the Eastern Cordillera remained at relatively low elevations of 0–1.5 km in the late Oligocene to earliest Miocene time (Bershaw et al., 2010; Leier et al., 2013) and rose to ~2.5 to 3 km in between 24 and 17 Ma (Leier et al., 2013). The mid-Miocene to earliest late Miocene record (~11 to 10 Ma) of paleoelevation of the Altiplano, including leaf physiognomy, paleotemperatures, and oxygen isotope composition of paleo-precipitation, places the north-central Altiplano at low-elevations of $\leqslant 2$ km. By ~6 Ma, climate proxy estimates indicate the north-central Altiplano had reached near-modern elevations (Bershaw et al., 2010; Garzione et al., 2006; Ghosh et al., 2006b). In combination, these studies suggest that the Eastern Cordillera experienced an earlier (early-middle Miocene) pulse of surface uplift while the adjacent Altiplano rose in late Miocene time.

The record that emerges from data in the north-central Altiplano and Eastern Cordillera is one of significant regional climate change—cooling temperatures, changing oxygen isotope composition of precipitation, and shifting ecology in middle-late Miocene time—that is consistent with different pulses of surface uplift of the Eastern Cordillera and Altiplano. However, recent general circulation modeling (GCM) experiments have suggested that the response of regional climate to surface uplift is non-linear, due to significant thresholds in the response of climate to rising surface topography (Ehlers and Poulsen, 2009; Insel et al., 2012; Poulsen et al., 2010). The numerical results of these GCM experiments suggest that the surface elevation history of the Altiplano may be more gradual when threshold climate response is considered.

Clarifying the nature and pace of the surface uplift history of the Altiplano requires better spatial resolution in the climate record; the existing record is limited almost entirely to the northern Altiplano. Here we expand the spatial extent of the paleoelevation record for the central Andes by determining middle to late Miocene surface paleotemperatures in the southern Altiplano and Eastern Cordillera (19 °S to 22 °S). The magnitude and temporal evolution of surface cooling across this region provides insights into whether cooling was related to surface uplift or climate change.

2. Methods

Conventional stable isotope approaches (e.g., O and H) provide a robust proxy of paleoelevation in regions that receive significant rainfall (>30 cm/yr) and show limited complexity in the source of vapor masses (e.g., Rowley and Garzione, 2007). In the arid southern Altiplano, however, climate simulations show high variability in O isotopic composition of rainfall and a less pronounced $\delta^{18}O$ versus elevation gradient, with rainfall composition primarily influenced by precipitation amount (Insel et al., 2013). Under extremely arid conditions (<30 cm rainfall/yr), pedogenic carbonates, a proxy for paleo-rainfall composition, have been shown to strongly deviate from the isotopic composition of local meteoric water as a result of extreme evaporative enrichment of ^{18}O in soil water (Quade et al., 2007). In order to avoid the complexity of the lack of correspondence between $\delta^{18}O$ values of rainfall and elevation, as well as soil–water evaporation associated with the aridity of the southern Altiplano (Garreaud et al., 2003; Minvielle and Garreaud, 2011) that would both tend to lead to a bias toward under-estimation of paleoelevation, this study is focused on the use of “clumped C–O isotope thermometry” that constrains the temperature of soil carbonate formation.

The degree of “clumping” between ^{13}C and ^{18}O in carbonates (expressed as the parameter (Δ_{47})) is related to the temperature of carbonate formation (Eiler, 2007, 2011; Ghosh et al., 2006a). The carbonate clumped isotope thermometer can be applied to paleosol and lacustrine carbonates to retrieve information about surface paleotemperatures (Ghosh et al., 2006b; Huntington et al., 2010; Passey et al., 2010) that can be used to quantify climate change and elevation.

We investigated paleosols in three high-elevation middle-late Miocene exposures of terrestrial sedimentary rocks (Cerdas, Quebrada Honda, and Quehua). Nodular paleosol carbonates were sampled at depths of ~0.2 to 2 m below the tops of paleosols, where paleosol tops could be identified, in an effort to limit the magnitude of seasonal and diurnal variation in ground temperature (Fig. 2). Based on the Mack et al. (1993) classification scheme, the paleosols include calcisols and argillic calcisols. The Cerdas section includes argillic calcisols. The tops of paleosols are defined by