Earth and Planetary Science Letters 292 (2010) 371–382

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Evidence for the development of the Andean rain shadow from a Neogene isotopic record in the Atacama Desert, Chile

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A R T I C L E I N F O

Article history:
Received 3 June 2009
Received in revised form 30 January 2010
Accepted 3 February 2010
Available online 4 March 2010

Editor: M.L. Delaney

Keywords:
Andes
Atacama Desert
oxygen isotopes
paleoaltimetry
rain shadow

A B S T R A C T

Varying ages from Triassic to Pliocene have been proposed for the onset of hyperaridity in the Atacama Desert. The exact timing for the initiation of hyperaridity is critical for determining potential causes, which range from regional effects of global cooling to Andean uplift above elevations conducive to extreme rain shadows. Analysis of the stable isotopic composition of lower Miocene–Quaternary (21–0.015 Ma) palustrine and lacustrine carbonates in the Calama Basin reveals extreme changes in their oxygen and carbon isotopic composition during the Miocene. Limestone $\delta^{18}O$ values increased by ~5‰ from middle to late Miocene, ranging from −5.5‰ at 12 Ma to −1‰ at ~6 Ma. Carbon isotopic values increase by 9‰ over the Neogene, from average values of −3‰ at 21 Ma to +3‰ at 12 Ma, and reaching a maximum of +6‰ at 5 Ma. The increase in oxygen isotopic values occurred over a time span in which the catchment area of the basin experienced significant uplift, causing the $\delta^{18}O$ value of precipitation to become more negative. We attribute the shift towards higher $\delta^{18}O$ values to enhanced evaporative enrichment both of soil water or snow prior to infiltration, and within shallow lakes or wetlands prior to carbonate precipitation. The large increase in $\delta^{13}C$ values was likely caused by a transition from a vegetated landscape influenced primarily by soil-respired CO_2 to a landscape largely devoid of vegetation and influenced by atmospheric and volcanic CO_2. Isotopic values of palustrine carbonates therefore indicate that hyperaridity commenced in the Calama Basin during the middle to late Miocene, in agreement with other paleoclimatic records from the basin. The cause for the onset of this climate change is thought to be due to the development of a strong Andean rain shadow associated with the uplift of the Andes to mean elevations >2 km.

1. Introduction

The high-elevation Andean Cordillera has a pronounced influence on modern atmospheric circulation. The Andes disrupt zonal circulation in the Southern Hemisphere (Lenters and Cook, 1995), drive the South American Summer Monsoon (Zhou and Lau, 1998), and produce a pronounced rain shadow over the southern mid- and low-latitudes of South America (Houston and Hartley, 2003). Moreover, the strong influence of the Andes on atmospheric circulation is thought to control erosion rates and the subsequent morphology of the Andes (Montgomery et al., 2001), which may in turn influence orogenic processes (Lamb and Davis, 2003). Identifying when the Andes attained their modern elevation, or when the Andes began to exert a strong influence on atmospheric circulation, is therefore of critical importance to various avenues of research in paleoclimatology and tectonics.

Various methods have been employed to reconstruct the uplift history of the Andean Cordillera. In a review of these studies, Gregory-Wodzicki (2000) concluded that the Central Andes had attained no more than a third of its modern elevation (3700 m) by 20 Ma and no more than half by 10 Ma. More recently, oxygen isotopes of surficial authigenic carbonates (e.g., soil, lacustrine, fossil) have been used increasingly to assess the uplift history of mountain belts due to the strong influence of topography on the isotopic value of precipitation (Chamberlain and Poage, 2000; Garzione et al., 2000; Blisniuk et al., 2005; Ghosh et al., 2006; Quade et al., 2007a; Rowley and Garzione, 2007). In the Andean Cordillera, Blisniuk et al. (2005) inferred >1 km of surface uplift by ~16.5 Ma in the Patagonian Andes (~48°S) based on a ~3‰ increase in $\delta^{13}C$ values and a >2‰ decrease in $\delta^{18}O$ values of pedogenic carbonate in lower Miocene strata. These authors also interpreted the increase in the scatter of oxygen isotope values as

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doi:10.1016/j.epsl.2010.02.004

indicative of the coeval development of a strong orographic rain shadow. Ghosh et al. (2006) and Garzione et al. (2006) inferred ~3 km of surface uplift for the Bolivian Altiplano (18°S) between 10.3 and 6.8 Ma based on a 3‰ decrease in the oxygen isotopic value of soil carbonate (Fig. 1). In a review of the isotopic, paleobotanical, and geomorphological evidence for Andean uplift, Garzione et al. (2008) and Hoke and Garzione (2008) suggested an average elevation of ~1.5 km for the central Andean plateau at 10 Ma with elevations of the western Cordillera averaging >3 km. Isotopic evidence for paleoaltimetry is critical to tectonic studies as these results, in conjunction with crustal shortening data, have been used to constrain different geodynamic scenarios for the formation of the Andes and Altiplano (e.g. Garzione et al., 2008).

Results from these studies provide compelling evidence for the application of stable isotope analysis of surficial authigenic carbonates to reconstruct the uplift history of the Andean Cordillera. However, several factors can influence the isotopic value of surficial carbonates aside from orogenesis, including long- and short-term changes in global climate, changes in local vegetation assemblages, and the influence of local topography on climate (Blisniuk and Stern, 2005; Ehlers and Poulson, 2009). Latorre et al. (1997) recorded a 3–4‰ increase in the $\delta^{18}O$ of soil carbonate between 9 and 3.5 Ma in northwest Argentina. These authors noted that the observed shift may have been produced by climate change related to Andean uplift, but also stress that upper Neogene records of soil carbonate from Asia, Africa, and North America also show similar trends toward higher $\delta^{18}O$ values. As higher ^{18}O values from these records are concomitant with trends towards higher $\delta^{13}C$ values, Latorre et al. (1997) suggested that the observed positive isotopic shifts may be the result of greater evaporation in soils developed during the late Neogene global expansion of grasslands. Kleinert and Strecker (2001) suggested that late Miocene and Pliocene climate change in the Santa María basin in Argentina, recorded by changes in the $\delta^{13}C$ and $\delta^{18}O$ of soil carbonate, resulted from the development of localized high topography adjacent to the basin.

In order to use isotopic data to test hypotheses regarding the uplift history of the Andes and to constrain geodynamic scenarios for the rise of the Andes and Altiplano, we first need to reconstruct the isotopic record of surficial authigenic deposits from many locations in and around the modern Andes. A more complete isotopic data set, integrated with both regional geologic and tectonic data and global climate history, is needed to isolate the influence of large-scale orogenesis on atmospheric circulation. Here we add to the Neogene isotopic record of the Andes by presenting a well-dated record of isotope values from lacustrine and palustrine carbonates in the Calama Basin of the Atacama Desert. This isotopic data is important for constraining changes in atmospheric circulation and climate that may or may not be associated with mountain uplift.

1.1. The Atacama Desert

The Atacama Desert is located in northern Chile (18–26°S), bounded to the east by the Andean Cordillera and to the west by the Pacific Ocean (Fig. 1). The Atacama Desert is widely regarded as the driest place on Earth, with the extreme hyperarid core receiving <10 mm/yr precipitation and rainfall events exceeding a few mm occurring only once every decade (Houston and Hartley, 2003; McKay et al., 2003). The extreme hyperaridity and atmospheric stability of the Atacama is the result of several factors. General aridity at this latitude globally results from divergent wind-flow, high-pressure, and atmospheric stability associated with the subtropics (Hare, 1961).

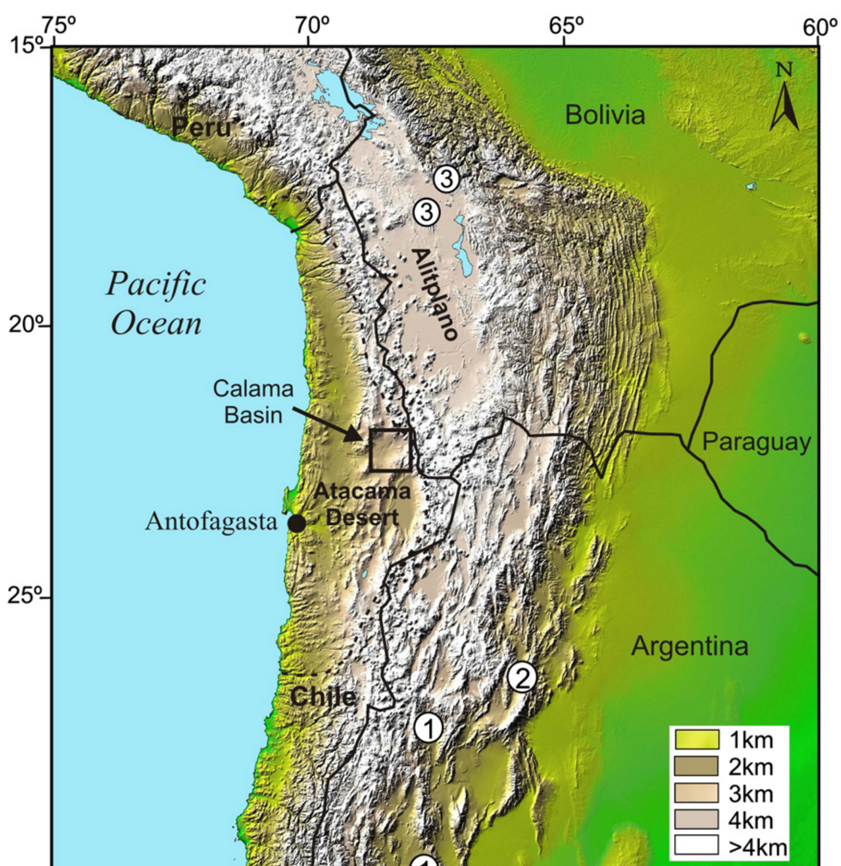

Fig. 1. Shaded relief digital elevation model, created by NASA/JPL/NIMA from Shuttle Radar Topography Mission data, with location of study area in Calama Basin and locations of stable isotopic studies of late Cenozoic deposits in the Central Andes: 1) Latorre et al., 1997; 2) Kleinert and Strecker, 2001; 3) Garzione et al., 2006.