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The stable isotope altimeter: Do Quaternary pedogenic carbonates predict modern elevations?

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ABSTRACT

Stable isotope altimetry is a useful tool for estimating paleoelevation in sedimentary records. Yet questions remain regarding how source moisture, climate, and local topography can influence these estimates. Here we present stable isotope altimetry results on late Quaternary pedogenic carbonates of known elevation on both flanks of the Andean orogen at 33°S. We measured $\delta^{18}O$ values of pedogenic carbonates and river water samples from small drainages at regular elevation increments within the Río Aconcagua (Chile) and Río Mendoza (Argentina) catchments. The $\delta^{18}O$ values of river waters correlate well with elevation and show similar isotopic gradients between the Chilean (–3.7‰/km) and Argentine (–4.8‰/km) sides of the range. Uncertainties associated with scatter in the river water data and assumptions about the temperature of carbonate formation indicate that elevation estimates have 1σ errors of 350–450 m. We estimate the isotopic composition of soil water from pedogenic carbonates on both sides of the range by assuming mean annual temperatures based the modern temperature lapse rate from meteorological station data. Combined, our data show that stable isotope altimetry produces reasonable estimates of modern elevation, with the majority of our samples (60%) within the 1σ uncertainties and 77% within 2σ.

INTRODUCTION

Stable isotope paleoaltimetry has emerged as a powerful tool for determining the spatiotemporal evolution of topography in mountain belts (e.g., Chamberlain et al., 1999; Garzione et al., 2000; Rowley et al., 2001; Mulch et al., 2006; Poage and Chamberlain, 2002;). Paleoelevation is a key parameter necessary for testing different geodynamic models of orogenesis (Molnar and England 1990) and potentially for testing the geomorphic response time to surface uplift.

Topographic reconstruction by stable isotope paleoaltimetry relies on pedogenic or biogenic minerals as proxies for the composition of meteoric water. Stable O or H isotopes in pedogenic carbonate, pedogenic clays, biogenic apatite, biogenic carbonates, and plant organic matter are all potential paleoaltimeters. Stable isotope–based paleoaltimetry studies also use the modern gradient in $\delta^{18}O$ values of meteoric water ($\delta^{18}O_{mw}$) and elevation, as well as past differences in the modeled $\delta^{18}O_{mw}$-altitude gradient (Rowley and Garzione, 2007). The isotopic composition of river water ($\delta^{18}O_{rw)}$-elevation gradient is constrained by elevation transects of river water sampled from small subbasins of large catchments (e.g., Garzione et al., 2000). The resulting $\delta^{18}O_{rw}$ is used as a proxy for constraining an empirical relationship for $\delta^{18}O_{mw}$ versus altitude. This relationship is used to calculate elevation from surface water compositions derived from carbonates, clays, and/or organic matter. Major sources of error in the $\delta^{18}O_{rw}$-elevation gradient could result from (1) evaporative effects in the surface water, (2) changes in moisture transport pathways related to secular climatic variations, and/or (3) changes in the initial isotopic composition of the air mass incident on the mountain front. These factors must be considered when applying the modern gradient for paleoelevation estimates (Rowley and Garzione, 2007), and have served as the focal point for criticisms of paleoaltimetry studies (e.g., Ehlers and Poulsen, 2009). Given the potential sources of uncertainty in applying stable isotopes as an altimeter, we test the method in a modern system with data from river water and Quaternary pedogenic carbonates, from the same catchments, along an east-west transect across the southern central Andes (33°S).

BACKGROUND

Our study area is located in two catchments that drain the high Andes at ~33°S, the Río Aconcagua and Río Mendoza basins that drain into the Pacific and Atlantic, respectively (Fig. 1). The area encompasses the Chilean Precordillera, Central Valley, Principal Cordillera, Frontal

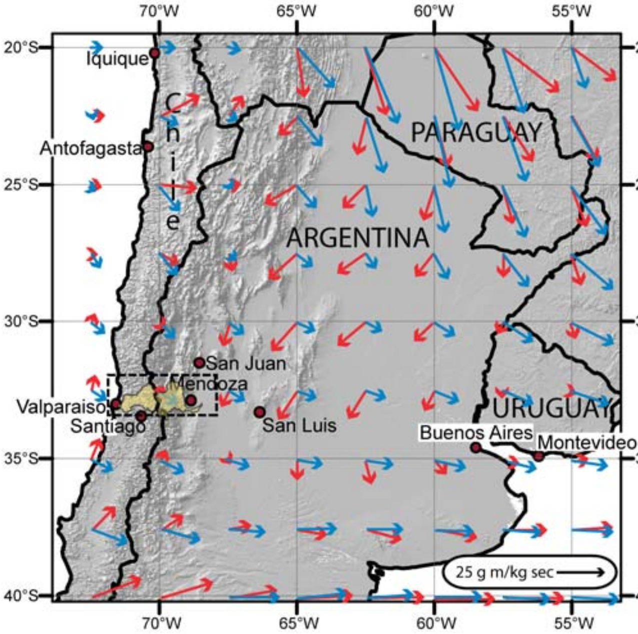

Figure 1. Shaded relief map of South American continent between 20° and 40°S. Vapor transport directions calculated at 850 hPa from National Centers for Environmental Prediction (NCEP 1) reanalysis data for period 1968–1996 for austral winter (blue) and summer (red). Río Aconcagua and Río Mendoza watersheds are indicated with thin black line and yellow shading, respectively. Cross section in Figure 2 is taken from area within dashed box.

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Cordillera, and Argentine Precordillera morphotectonic provinces. The Argentine Precordillera has an average crest elevation of 2.5 km, and the Principal and Frontal Cordilleras have maximum average elevations of 4.2 km (Fig. 2). The western slope is a much steeper, narrower front compared to the eastern slope. There is no evidence for significant Quaternary elevation change in the high Andes.

The Andes constitute an orographic barrier to atmospheric circulation, which directly influences the isotopic composition of precipitation. Atmospheric circulation and precipitation are dominated by the westerlies in austral winter and by the subtropical high-pressure belt in austral summer (Bluestein, 1993). The central part of Chile is semiarid (~400 mm/a; Falvey and Garreaud, 2007), whereas in central-western Argentina, climate conditions progress from arid (<200 mm/a) in the northwest to semiarid in the southeast (200–300 mm/a) (Hoffmann, 1992).

During austral winter, the subtropical Pacific anticyclone weakens and is displaced northward, enhancing westerly flow across the Andes, producing a precipitation maximum over the western slopes (Saavedra and Foppiano, 1992). Little of this Pacific moisture reaches the eastern Andean flanks. In austral summer, interaction of semipermanent low pressure in Argentina, and the subtropical South Atlantic anticyclone, generates a northeasterly flow over central regions of Argentina and a net moisture transport from the Atlantic and southern Brazil (Barros et al., 1996; Fig. 1). River discharge on both flanks of the central Andes is strongly correlated with the amount of snowpack and exhibits remarkably similar interannual variability, highlighting the existence of a clear regional hydrologic signal between 31° and 37°S (Masiokas et al., 2006).

The Andes are poorly represented in the Global Network of Isotopes in Precipitation (GNIP) data (IAEA/WMO, 2006), with only three stations in or near the study area: Santiago, Chile (520 m), Valparaiso, Chile (47 m), and Mendoza, Argentina (800 m). Spatially disparate sampling of river water by Vogel et al. (1975) in Argentina provided the first evidence of an isotopic elevation gradient of –0.3‰/100 m for the eastern side of the range. Rozanski and Araguás-Araguás (1995) combined Vogel et al.'s (1975) measurements with other low sampling density data and showed that elevation-induced isotopic depletion occurs on both sides of the orogen. Using a regional-climate model, Sturm et al. (2007) modeled isotopes in precipitation over modern South America between 15°N and 35°S and found the amount effect and continentality effect to be minimal, whereas the elevation effect was dominant in controlling the isotopic composition of precipitation.

DATA AND RESULTS

We collected stage I pedogenic carbonates from the undersides of conglomerate clasts in incipient soil exposures along with water samples from the adjacent Río Mendoza (Argentina) and Río Aconcagua (Chile) watersheds (Fig. 1). The isotopic composition of all samples was determined at the University of Rochester's SIREAL (Stable Isotope Ratios in the Environment Analytical Laboratory; also see the Data and Analytical Methods section of the GSA Data Repository[1])

Tributary water samples with drainage areas ≤ 100 km^2 were collected in ~100 m vertical increments along the trunk river. The 12 Río Aconcagua samples were collected in early April of 2007 and the principal suite ($n = 17$) from the Río Mendoza's tributaries was sampled in January 2007. In September 2007 two sites from the initial Río Mendoza sampling were resampled and one new site added (Fig. 2).

We assume that $\delta^{18}O_{rw}$ reflects an annual integration of $\delta^{18}O_{mw}$ across the entire relief of the sampled catchments, which is best represented by the average elevation of each catchment. Using river networks extracted from Shuttle Radar Topography Mission data, we calculated the average elevations of each subbasin upstream of the sampling points (see the Data Repository). There is a clear elevation dependence of the isotopic composition of river water for the small tributaries of both river systems, not only in longitudinal profiles across the range (Fig. 2), but also in $\delta^{18}O_{rw}$ versus mean catchment elevation (Fig. 3). The weighted means of $\delta^{18}O$ values from the GNIP (IAEA/WMO, 2006) stations at Valparaiso, Santiago, and Mendoza, also shown in Figure 3A, are included in linear regressions for their respective sides of the range. These station data provide a low-elevation reference for the isotopic composition of precipitation before air masses begin their ascent on either side of the Andes. The 1σ uncertainty on the regression is ±460 m for the Río Aconcagua data and ±350 m for the Río Mendoza data. The overlap of the lines at the 1σ level (shaded areas in Fig. 3A) demonstrates the similarity of the isotopic gradient on both sides of the range.

We analyzed stage I pedogenic carbonates (Gile et al., 1966) from late Pleistocene–Holocene fluvial and glacial deposits. Carbonate material was collected at ~200 m vertical increments along an east-west swath. The majority of the pedogenic carbonate samples are from a depth range of 40–50 cm below the vegetated surface. We estimated the soil water $\delta^{18}O$ values from the pedogenic carbonate $\delta^{18}O$ values by assuming an average temperature for each site based on an air temperature lapse rate of 6.25 °C/km determined from mean annual temperature data at four different meteorological stations (Servicio Meteorológico Nacional, 2008; see the Data

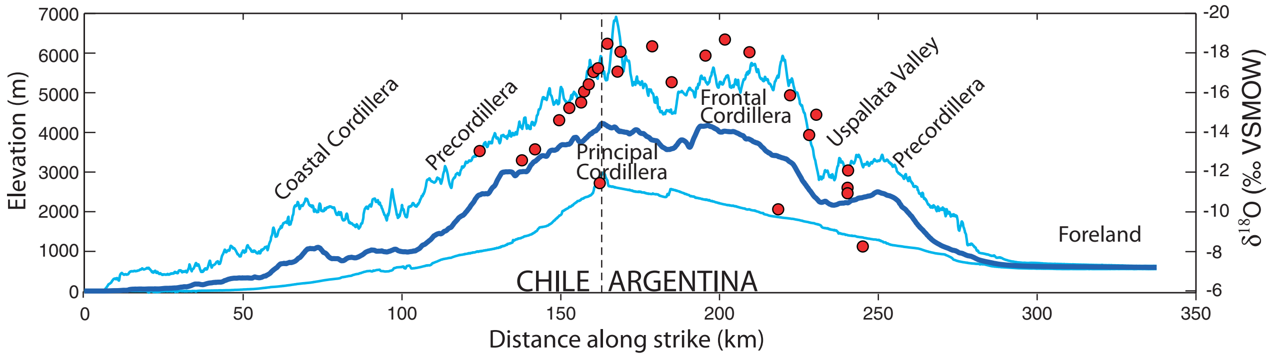

Figure 2. Maximum (upper blue line), mean (black line), and minimum (lower blue line) topography of Andes based on Shuttle Radar Topography Mission data (http://www2.jpl.nasa.gov/srtm/) along 100-km-wide swath centered at 33°S (red box in Fig. 1). Red dots denote isotopic composition (relative to Vienna standard mean ocean water, VSMOW) of sampled tributaries at their sampling localities. Majority of data correspond well with changes in topography across the range.

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[1] GSA Data Repository item 2009256, sample locations and collection, data and analytical methods, temperature corrections, topographic analysis and drainage network analysis, and error analysis, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

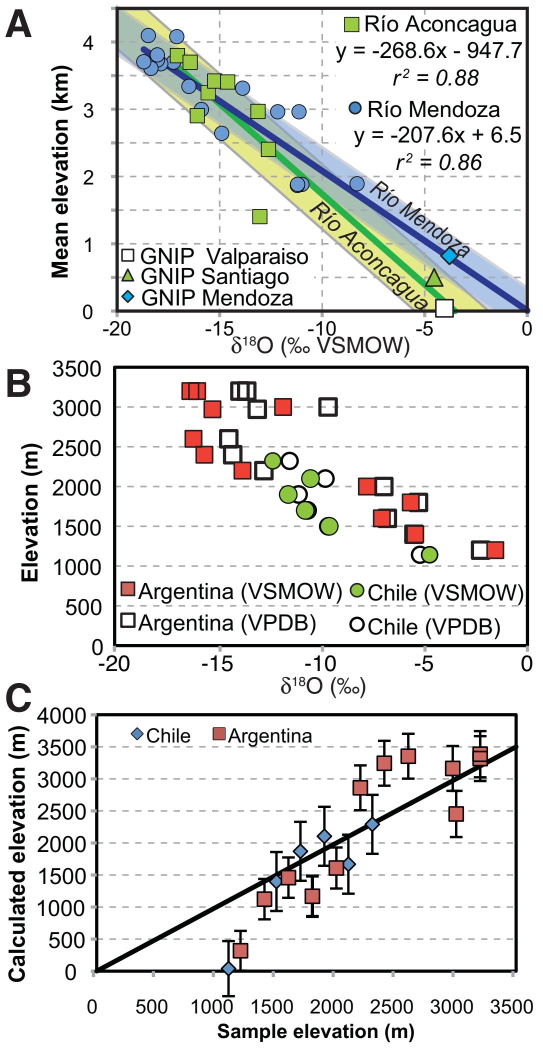

Figure 3. A: $\delta^{18}O$ data from Ríos Aconcagua (green squares) and Mendoza (blue circles) plotted versus mean catchment area and Global Network of Isotopes of Precipitation (GNIP) station data. Best-fit lines through each set of data are plotted as solid lines and 1σ uncertainties are represented by overlapping blue and green areas. B: $\delta^{18}O$ values for stage I pedogenic carbonates relative to Vienna Peedee belemnite (VPDB; open symbols) and $\delta^{18}O$ of soil water (filled symbols) determined using temperature-based fractionation equation of Kim and O'Neil (1997). VSMOW—Vienna standard mean ocean water. Linear regressions though soil water values have r^2 values of 0.66 and 0.79 for Chile and Argentina, respectively. C: Plot of calculated versus known sample elevations for both data sets. Error bars on each point shown at 1σ level were determined using Monte Carlo simulation of uncertainties related to each parameter (see text for discussion).

Repository) and applying Kim and O'Neil's (1997) temperature-dependent fractionation relationship (Fig. 3B). Breecker et al. (2009) demonstrated that calcite formation in desert soils does not occur in the wet season, but rather during the dry season, which has implications for temperature corrections of calcite formation. Wet seasons in our study area occur in either the winter (Chile) or summer (Argentina); therefore calcite formation likely occurs in the spring or fall, justifying our use of mean annual temperature here. The calculated isotopic values of soil water ($\delta^{18}O_{sw}$) (Fig. 3B) show significant correlations with elevation, yielding r^2 values of 0.79 for the Argentine side (n = 12) and 0.66 on the Chilean side (n = 6).

We estimate site elevations by applying our calculated $\delta^{18}O_{sw}$ values (Fig. 3B) to the best-fit $\delta^{18}O_{mw}$ versus altitude relations on each side of the range (Fig. 3A). These estimated elevations are then compared to their actual elevations (Fig. 3C). We assess uncertainties in our calculated elevations using a Monte Carlo simulation that assigns uncertainties to each parameter associated with the elevation calculation, including uncertainties on the best-fit regressions and uncertainty of ±5 °C in the temperature of carbonate formation (see the Data Repository).

DISCUSSION

Systematic sampling of small catchments across the southern central Andes demonstrates that, despite having different initial moisture sources, the gradient of $\delta^{18}O_{rw}$ versus elevation is nearly the same for the western and eastern sides of the range (Fig. 3A). Our highest elevation samples in Argentina also have the most negative $\delta^{18}O_{rw}$ values (Fig. 2) and are likely related to westerly winter precipitation in the form of snow (Fig. 1). The dominance of winter precipitation near the range crest is reflected in the seasonality of the Río Mendoza's discharge (Araneo and Compagnucci, 2008) and the highly negative $\delta^{18}O$ values of local groundwaters at low elevations (Panarello and Dapeña, 1996). Such negative values could lead to them being interpreted as reflecting a rain shadow effect on precipitation, yet our $\delta^{18}O_{rw}$ data from small tributaries at low elevations show no such effect.

Small (<100 km² drainage area) perennial rivers do not exist below 1400 m on either side of the Andes. The data from the GNIP stations provide low-elevation anchor points (Fig. 3A) for constraining the relationship between $\delta^{18}O_{mw}$ and elevation. The Argentine side of the Andes has an isotopic gradient of –4.8‰/km, whereas a depletion of –3.7‰/km is observed on the Chilean side of the range. These values are substantially different from previously reported gradients from much lower density sampling of –0.3‰/100 m for Argentina (Vogel et al. 1975) and –0.2‰/100 m above 1500 m (n = 3) in Chile (Rozanski and Araguás-Araguás, 1995). The isotopic fractionation model presented in Figure 3 of Rowley and Garzione (2007) is heavily dependent on the initial temperature of an air mass and less so on relative humidity. Our data plot near the 14 °C curve of their model, which is comparable to average temperatures of 16 °C at Mendoza and 13 °C at Valparaiso. The lower initial air mass temperature in this region may account for the steeper $\delta^{18}O$-altitude gradient as compared to shallower isotopic gradients observed in well-studies tropical regions (Rowley and Garzione, 2007, and references therein). At present, stable isotope paleoaltimetry (Garzione et al., 2000; Rowley et al., 2001; Chamberlain and Poage, 2000; Poage and Chamberlain, 2002; Mulch et al., 2006) relies on using the modern relationship between $\delta^{18}O_{rw}$ values and elevation to constrain paleoelevation estimates. A major criticism of stable isotope paleoaltimetry (e.g., Ehlers and Poulsen, 2009; Blisniuk and Stern, 2005) is that changing moisture source regions due to the development of high topography and temporal variation of the $\delta^{18}O$ of precipitation or other extrinsic factors leading to variability in $\delta^{18}O$ values are difficult to constrain, and could generate erroneous paleoelevation estimates. However, we observe similar isotope-elevation gradients at high elevations (>2000 m) despite distinct moisture sources, suggesting that changing moisture source may have a smaller effect than previously thought.

Data from stage I carbonates collected along the same transect show a systematic trend toward more negative pedogenic carbonate $\delta^{18}O$ values with elevation (Fig. 3B). These data thus represent the changing isotopic composition of local precipitation and soil water from which carbonate precipitates at each sampling site. The $\delta^{18}O_{sw}$-based estimates of elevation are reasonably good, with 60% of estimates plotting on the 1:1 line within their 1σ uncertainties, and 77% within a 2σ error margin. It is worth noting that the lowest elevation samples from both sides of the range dramatically underestimate their respective elevations (Fig. 3C). We speculate that evaporative enrichment of the soil water occurs at lower elevations in this region as precipitation decreases. Caution should therefore be used in drier regions (<350–300 mm/a) where evaporative enrichment of $\delta^{18}O_{sw}$ may lead to an underestimation of elevations (e.g., Quade et al., 2007).

Some previous paleoaltimetry studies used $\delta^{18}O$ and δD values of authigenic clays and sedimentary carbonates from lowland basins in the rain shadow of orographic barriers, where the westerlies are the principal moisture source (e.g., Blisniuk et al., 2005; Chamberlain et al., 1999). Despite strong zonal flow across north-south–trending mountain belts, our data suggest that even a minor amount of moisture from a different source could obscure a rain shadow signal in a leeward-side basin. Based on virtually identical isotopic gradients on both sides of the range (Fig. 3A) and the poor accuracy of elevation estimates obtained from the lowest elevation samples, we suggest that data from sediments in intermontane basins (e.g., the Uspallata Valley in Fig. 2) may represent the best potential recorders of paleoelevation as opposed to those obtained from low-elevation sedimentary basins. Improved characterization of surface water isotopic compositions over a broader latitudinal and climatic range is needed to better understand the rain shadow effect on estimates of paleoelevation.

CONCLUSIONS

Our river water data reveal a nearly symmetric gradient in $\delta^{18}O$ values across the range. Despite slightly offset intercepts these gradients are well correlated with elevation even with the dominance of westerly derived precipitation at high elevations and isotopic mixing from Atlantic and Pacific Ocean moisture sources on the eastern slopes. The $\delta^{18}O_{sw}$ values calculated from pedogenic carbonates are well correlated to elevation, and the majority (~77%) of elevations determined from $\delta^{18}O_{sw}$ values are within 2σ uncertainties of their actual elevations. In deep time applications, where temperature and climatic variables are more difficult to constrain, changes in topography of ~900 m (2σ) could be detectable. The unreliable elevation estimates obtained from the lowest elevation samples on both sides of the range suggest that uncertainties increase as elevation decreases and, when coupled with drier climate conditions, could result in severe underestimates of elevations.

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