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Reply to Comment on “Rapid late Miocene rise of the Bolivian Altiplano: Evidence for removal of mantle lithosphere” by Garzione et al. (2006), Earth Planet. Sci. Lett. 241 (2006) 543–556

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1. Introduction

In their discussion of our paper, Hartley et al. suggest that existing structural, stratigraphic, sedimentological, and geochemical observations do not support the inference that the rapid late Miocene surface uplift of the Bolivian Altiplano reflects the removal of mantle lithosphere at this time. We review their contentions, and we attempt to demonstrate that these observations are consistent with the removal of the dense lower lithosphere. We also correct minor errors in our paper.

2. Oxygen isotope data and paleoelevation estimates

Hartley et al. assert that our data show a “lack of a change in δ^{18}O values between 10.3 and 6.8 Ma”, and support this assertion via their Figure 1. As we and others have discussed, evaporative enrichment of surface waters makes the lowest δ^{18}O values the most representative of elevations at the time that the carbonate sediment formed (Garzione et al., 2006; Rowley and Currie, 2006). For example, studies cited in our paper show that closed-lake waters in the Altiplano and Eastern Cordillera have higher values of δ^{18}O than local rainfall (Wolfe et al., 2001). Paleosol carbonates, likely to represent actual rainfall values, on the Altiplano do indeed show a marked and distinct difference in isotopic signature between 10.3 and 6.8 Ma from that before and after this period. Like others we acknowledged evaporation as a potential challenge in stable isotope paleoaltimetry and have advocated applying multiple proxies to determining paleoelevations (Currie et al., 2005; Garzione et al., 2006).

Hartley et al. note that correlations of leaf morphology to climatic parameters like mean annual temperature from leaves in modern forests in the northern hemisphere differ from those from the southern hemisphere, citing the extreme value of 15 °C given by Kowalski (2002). Kowalski (2002), however, reported 95% confidence bounds on the difference of 1.6 °C to 7.9 °C. Applying a typical free-air lapse rate (6 °C/km) to surface air temperature as a function of altitude, for instance, would add a systematic error of 250–1300 m to the paleoelevation reported by Gregory-Wodzicki et al. (1998) for that flora in this region. Thus, their data would still suggest Q1 elevations at ~10 Ma well below the present 3800 m, hardly enough to negate our conclusions based on other

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data. Moreover, taken as a whole, the fossil assemblage suggests a similarly low paleoelevation at that time (Graham et al., 2001).

3. Evidence for surface uplift

We disagree with Hartley et al. that we did not consider the structural and sedimentological evolution of the Andes in our discussion. On the contrary, in our discussion of this evidence we specifically we addressed how and why shortening would have ceased across much of the Andean plateau in the late Miocene time and the mechanisms for transferring this shortening into the Subandes. We did not suggest that there was no relief between the Altiplano and Eastern and Western Cordilleras prior to late Miocene surface uplift, but merely that the Altiplano was lower and perhaps both Cordilleras were lower as well.

The statement by Hartley et al. that “Reconstruction of the development of the western Altiplano (Victor et al., 2004) showed that 2600 m of structural uplift took place between 30 and 7 Ma with maximum shortening between 17 and 10 Ma” suggests to us a poor understanding of isostasy and surface uplift. The study that they cite (Victor et al., 2004) documents the development of structural relief, not surface uplift (i.e. changes in mean elevations). Structural relief need not lead to significant surface uplift; isostasy shows that thickening the crust by ΔT produces surface uplift of only $\sim(\Delta T)/6$ (e.g., Holmes, 1965). Although geologists sometimes equate rock uplift and surface uplift, we note that none of the five studies referenced by Hartley et al. provide direct constraints on surface uplift (England and Molnar, 1990).

4. Delamination model and implications for lithospheric processes

We answer the following questions that Hartley et al. posed: (1) “why should the lower lithosphere start to delaminate while the lithosphere is still unthickened?” and, (2) “when (and how) was the Altiplano crust thickened?” First, we did not assume that the lower lithosphere was removed without crustal thickening. Instead, we discussed a thickening history in which crustal thicknesses may have been great enough for eclogite to form. Being denser than mantle lithosphere, eclogite can facilitate the removal of lower lithosphere (Kay and Mahlburg-Kay, 1991). We inferred a history of crustal thickening from the shortening history of the upper crust, as have many previous workers (Kley and Monaldi, 1998; McQuarrie, 2002; Elger et al., 2005). Beck and Zandt (2002) used the observation of a thick crustal layer with relatively low P- and S-wave speeds to argue that most of the crust is of felsic composition. They suggested that the thin high-speed layer of presumably more basic composition at the base of the crust reflects removal of most of the basic lower crust. We cannot rule out the possibility that some of the crustal thickening in the Altiplano has occurred by lower crustal flow (Husson and Sempere, 2003), but we imagine that this process would have been aided by the removal of mantle lithosphere beneath the Eastern Cordillera and/or southern Altiplano and Puna through the development of greater gravitational potential energy per unit area between the region of removal (which would have risen most) and the Altiplano.

Hartley et al. assert that “when delamination-related magmatism occurs, it can be identified.” Kay et al. (1994) inferred from the chemistry of mafic lavas in the Puna plateau that they contain a significant component of mantle partial melt, but they have been contaminated by >20 to 25% crustal melts. The Puna shows a shallower Moho than the Altiplano (Yuan et al., 2002). We suggest that extreme crustal thicknesses (55 km to >70 km) and the presence of middle crustal melts in the central Altiplano hinder the diagnosis of contributions from the mantle asthenosphere because of contamination by middle crustal melts. The magmatic product of the detachment of the lower lithosphere was perhaps the eruption of middle crustal melts throughout the central and southern Altiplano and Puna, as we discussed in our paper (Garzione et al., 2006).

Hartley et al. are correct in pointing out the error in our calculation of surface uplift rate. We note that the rate of 0.25 mm/yr calculated by Hartley et al. (as opposed to 0.3 mm/yr in our original paper) makes it evident that crustal shortening alone could not have produced late Miocene surface uplift in excess of 2.5 km.

We would also like to take this opportunity to correct a typographical error in the $\delta^{18}O_{mw}$ vs. altitude equation reported in [3]:

$$h = -3326 - 491.9\delta^{18}O_{mw} - 16.45(\delta^{18}O_{mw} + 12.60)^2 \qquad (1)$$

The elevation estimates reported in our paper were calculated using Eq. (1). Realizing that Gonfiantini et al. (2001) mislabeled data in their Table 5 as weighted means,[1] when they are in fact unweighted means, we carry out the same exercise using rainfall amount reported in Table 6 of Gonfiantini et al. (2001). Using the weighted mean values for 3 years of data, only seven

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[1] Table 5 (Gonfiantini et al., 2001), which is the source of data for this regression, mislabels the columns such that reported weighted means are actually unweighted means.

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sites for which rainfall amount was also reported can be used for the regression. The linear regression to these data is:

$$h = -472.5\delta^{18}\mathrm{O}_{\mathrm{mw}} - 2645 \qquad (2)$$

with an $R^2 = 0.95$. We choose a linear regression because their weighted mean data set is not sufficient to merit a polynomial fit. Although more rainfall data would increase confidence in this regression, surface water data collected over two years from small tributaries along the Coroico River (our unpublished data, Fig. 1) corroborate the weighted mean values observed in the sparse rainfall data set and show a similar isotopic gradient to Eqs. (1) and (2). Eq. (2) produces elevation estimates of: 400–2200 m in carbonates deposited before 10.3 Ma, 2000–3800 m in carbonates deposited between 7.4 and 6.8 Ma, and 4000–4700 in carbonates deposited since 6.8 Ma. This reanalysis of the data based on weighted mean precipitation not only yields essentially the same amount of surface uplift (2.5 to 3.6 km of surface uplift), but it also brings the calculated elevations for the oldest part of the section into a reasonable range, with all values above 400 m. Although there may be a systematic bias associated with not knowing the starting values for meteoric water before it ascends the eastern flank of the Andes, the similar slopes of the $\delta^{18}\mathrm{O}_{\mathrm{mw}}$ vs. altitude regression for both surface water and rainfall data suggest that estimates of surface rise or fall are reasonable.

5. Conclusions

In reviewing the comments of Hartley et al., we find the evidence for rapid surface uplift between 10 and 7 Ma to be, if anything, stronger than they were in our original paper. We therefore appreciate this opportunity to respond to Hartley et al. and to correct the typographic error in Garzione et al. (2006).

We would like to reiterate that we acknowledged the limitations of oxygen-isotope paleoaltimetry and have taken care to account for potential systematic biases such as evaporation. For this reason, we documented environments of deposition and evaluated which sedimentary carbonates are most representative of the oxygen isotopic composition of local rainfall. We integrated paleoaltimetry data with existing structural, sedimentological, magmatic, and other geologic data, but we did this with an understanding of the definition of surface uplift and how it differs from other measures, such as structural relief and exhumation. The integration of surface elevation estimates

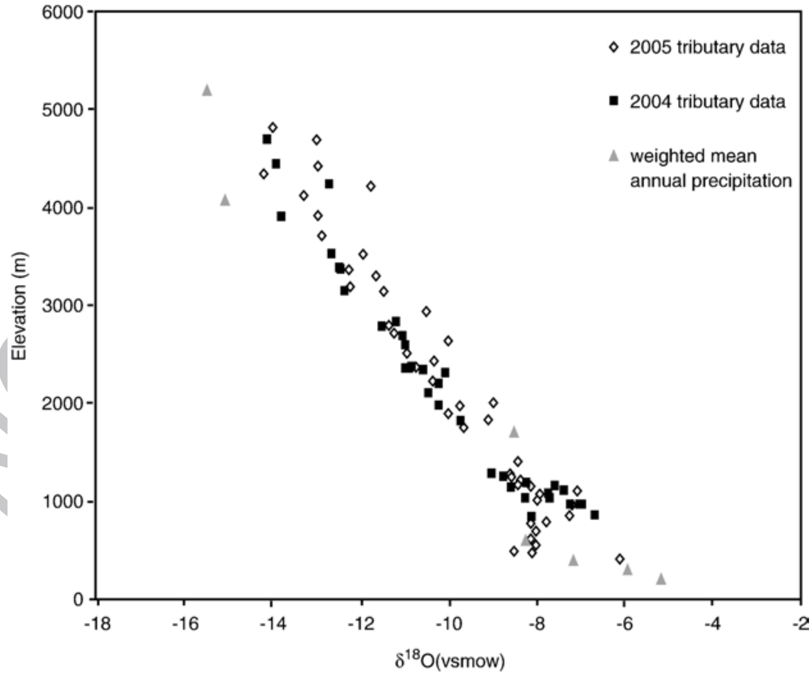

Fig. 1. δ^{18}O (relative to Vienna standard mean ocean water, VSMOW) of rainfall and surface waters across the Eastern Cordillera. Rainfall data represent the weighted mean isotopic composition (1983–1985) from Gonfiantini et al. (2001). Tributaries to the Coroico river were sampled in late May 2004 and early May 2005 and are plotted relative to the sampling elevation. A linear regression to the rainfall data (grey triangles) defines Eq. (2).

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with these other quantifiable variables has enabled us to evaluate the processes that elevated the Andean plateau.

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