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Discussion

A comment on "Rapid late Miocene rise of the Bolivian Altiplano: Evidence for removal of mantle lithosphere" by C.N. Garzione et al. [Earth Planet. Sci. Lett. 241 (2006) 543–556]

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1. Introduction

Garzione et al. (2006) measured oxygen isotope compositions of Miocene paleosol carbonate nodules and lacustrine and palustrine limestones deposited in the northern Bolivian Altiplano. They suggested that these compositions record an increase in elevation which indicate that the Altiplano surface was uplifted by 2.5–3.5 km between ~10.3 and ~6.8 Ma. They further suggested that the rapidity and magnitude of this uplift could only be accounted for by crustal delamination. There are, however, alternative ways of interpreting these data which do not require such rapid uplift and are not at odds with other geological data from the Central Andes.

2. Oxygen isotope data and paleoelevation estimates

Garzione et al. (2006) sampled the upper part of a ≥8 km thick section of continental sediments present in the Corque Syncline of the northern Altiplano of Bolivia. They presented oxygen isotope data for 79 carbonate samples spread over a 11.54–5.46 Ma stratigraphic interval. They assumed that the measured $\delta^{18}O$ values from pedogenic, palustrine and lacustrine limestones accurately represent the composition of the paleo–meteoric water from which they precipitated based on the relationship between $\delta^{18}O$ values of meteoric water and altitude (Gonfiantini et al., 2001). They observed a 3–4‰ change to increasingly negative $\delta^{18}O$ values between 10.3 and 6.8 Ma interpreted to represent a 2500–3500 m increase in altitude during this time interval. However, seasonal variations in $\delta^{18}O$ values between 10 to 15‰ occur in modern meteoric waters on the Altiplano and evaporative enrichment can account for a shift in $\delta^{18}O$ values of up to 2‰ (Ghosh et al., 2006). The possibility therefore that the $\delta^{18}O$ values presented by Garzione et al. do not accurately record paleo–meteoric water should be considered, particularly as the likely impact of fractionation on the older samples is to significantly underestimate paleoelevation.

The $\delta^{18}O$ values for specific time intervals reported by Garzione et al. (2006) are −9.5‰ to −13.3‰ between 11.5 and 10.3 Ma, −8.3‰ to −14.1‰ between 7.6 and 6.8 Ma, and −13.8‰ to −15.3‰ between 6.8 and 5.3 Ma (excluding outliers). The $\delta^{18}O$ values for the 11.5–10.3 Ma and 7.6–6.8 Ma time intervals show complete overlap (Fig. 1) indicating no significant shift

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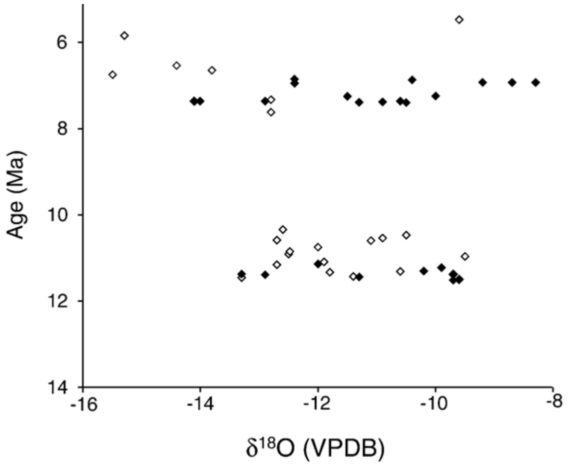

Fig. 1. Redrawn Fig. 4 of Garzione et al. (2006) showing $\delta^{18}O$ values (taken from their Table 1) of carbonate *versus* stratigraphic level. Open diamonds are palaesol carbonates, closed diamonds are palustrine carbonates. Data from the lacustrine interval (10.33 to 7.6 Ma) and sandstone cements have been excluded in order to simplify the diagram. These data were interpreted by Garzione et al. (2006) to indicate a 3–4‰ shift to more negative $\delta^{18}O$ values between 10.3 and 6.8 Ma.

to more negative $\delta^{18}O$ values and therefore no change in paleoelevation. Indeed, the abrupt shift to more negative values at ~6.8 Ma would then suggest that almost instantaneous uplift occurred at this time.

Garzione et al. (2006) estimated paleoelevation from the $\delta^{18}O$ values of paleo–meteoric water from the carbonates for different time intervals. Using their uncertainties the 11.5–10.3 Ma samples were deposited between elevations of −1700 m and +2400 m, the 7.6–6.8 Ma samples between 700 and 3900 m, and the 6.8–5.4 Ma samples between 3000 and 4700 m. Given these error limits uplift between 10.3 and 6.8 Ma can only be objectively constrained to be somewhere between 600 m and 6400 m. Garzione et al. (2006) supported their results by claiming that the uplift rates they determined were compatible with those based on fossil leaf morphology [*e.g.* Gregory-Wodzicki, 2000]. However, in Bolivia and East Asia, the current leaf morphology method systematically underestimates altitudes when these are high (as it reconstructs mean annual temperatures in error by as much as 15 °C), because applying equations generated from forests in North America to unrelated forests is inaccurate (Kowalski, 2002). Low Miocene paleoaltitudes estimated by fossil leaf morphology in Andean Bolivia are therefore likely to be serious underestimations.

3. Evidence for surface uplift

Garzione et al. (2006) used the work of Kennan et al. (1997) to suggest that widespread incision of 1.5–2.0 km affected paleosurfaces in the Eastern Cordillera beginning at 6.5 Ma. The geomorphological evidence suggests that 2.0–2.5 km of uplift relative to the foreland has affected the Eastern Cordillera since 10 Ma, but only 800 m of dissection occurred between 10 and 3 Ma. On the western slope of the Altiplano, the timing of valley incision appears to be controlled by (1) the eventual "breaking" of the sealed ignimbrite surfaces at some critical time (Thouret et al., 2003), (2) increased runoff around 7 Ma, a period when climatic conditions were distinctly less arid than today (Gaupp et al., 1999), and (3) the onset of glaciation and increased runoff from about 3 to 4 Ma (Clapperton, 1993). In addition, geomorphic evidence suggests that the volcanic highlands on the western flank of the Altiplano were above 2000 m between 20–17 Ma (Sébrier et al., 1998). In summary, geomorphological evidence for post 6.5 Ma incision generated by widespread regional surface uplift at this time across the Central Andes is at best ambiguous.

It is clear from structural studies that a significant amount of shortening took place before 10 Ma along the western flank of the Altiplano (Victor et al., 2004), within the Altiplano–Puna plateau (Elger et al., 2005), and in the Eastern Cordillera (McQuarrie et al., 2005). 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, and elevation estimates suggest that the Altiplano was bounded by mountain ranges up to 2000 m-high by 9 Ma (Hartley, 2003). Evidence for significant tectonic shortening (and implied uplift) prior to 10 Ma is overwhelming and supported by paleomagnetic data that provide ample evidence that large scale rotation and oroclinal bending of the Andean forearc region occurred prior to eruption of the plateau forming ignimbrites in southern Peru and northern Chile, *i.e.* between 20 and 35 Ma (Roperch et al., 2006). Additional evidence for uplift of the Altiplano is provided by the presence of up to 2500 m of conglomerates deposited between 25 and 10 Ma in the forearc and derived directly from the uplifting western edge of the Altiplano [*e.g.* Victor et al., 2004; Wörner et al., 2002]. In Southern Peru and Northern Chile, this sediment wedge has been covered by extensive plateau ignimbrites with volumes exceeding 1000 km^3 (Wörner et al., 2000). The age of these ignimbrites just west of the Garzione et al. study area shows a narrow range around 19 Ma and suggests a short period of extensive crustal melting (Wörner et al., 2002, 2000). This melting is difficult to envisage in thin continental crust and indicates the combined thermal effects of advective heat input into the lower crust and crustal scale convection after crustal thickening (Wörner et al., 2002, 2000; Babeyko et al., 2002). The timing of these plateau ignimbrites then argues