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Comment on "Rapid Uplift of the Altiplano Revealed Through 13C-18O Bonds in Paleosol Carbonates"

T. Sempere, *et al.*

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Comment on "Rapid Uplift of the Altiplano Revealed Through ^{13}C-^{18}O Bonds in Paleosol Carbonates"

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Based on stable isotope measurements, Ghosh *et al.* (Reports, 27 January 2006, p. 511) concluded that the Bolivian Altiplano uplifted 3 to 4 kilometers between ~10.3 and ~6.7 million years ago as a result of gravitational loss of dense lithosphere. This result stands at odds with current geological knowledge of the Central Andes, and we propose a test for the reliability of the paleoaltimetry method.

Ghosh *et al.* (*1*) reconstructed the elevation history of the Altiplano plateau in the Bolivian Andes using a thermometer based on the temperature-dependent binding rate of ^{13}C and ^{18}O isotopes in carbonate minerals. Their measurements indicate that the Altiplano lay between –400 and 0 m from 11.4 to 10.3 million years ago (Ma) and rose to its current altitude at an average rate of 1.03 ± 0.12 mm per year between ~10.3 and ~6.7 Ma. Ghosh *et al.* concluded that such a rapid uplift was likely to have been produced by gravitational loss of dense lithosphere to the asthenosphere (delamination), but this scenario disagrees with current geological knowledge of the Central Andes.

The idea that part of the Bolivian Altiplano was at or below sea level as late as ~11 Ma disagrees with the common view that Andean orogeny started in western Bolivia either ~26 Ma (*2*) or ~40 Ma (*3*, *4*), and with geomorphic evidence that the volcanic highlands west of the Altiplano were above 2000 m as early as 20 to 17 Ma (*5*). Furthermore, forearc strata document that these highlands underwent uplift between ~40 and 10 Ma (*6*). The fault-bounded Corque Basin displays high compacted sedimentation rates [970 m per million years (My) between 12 and 9 Ma (*7*), decreasing to 337 m/My between 9 and 6 Ma (*8*)] and can be seen as a pull-apart basin (*9*) whose surface was at a substantially lower altitude than surrounding highlands. Therefore, generalization of paleoaltitudes reconstructed in the basin (*1*) to the entire Altiplano may be inappropriate.

Ghosh *et al.* (*1*) argued that their proposed uplift history is consistent with paleobotanical evidence (*10*). However, the current paleoaltimetry method based on fossil leaf morphology systematically underestimates high altitudes (*11*). Therefore, Low Miocene paleoaltitudes reported for Andean Bolivia using this method (*10*) may also be underestimations and cannot be invoked to support the results in (*1*).

Crustal thickening in the Central Andes is widely believed to have been caused by tectonic shortening (*12*). On the contrary, Ghosh *et al.* (*1*) contend that this process is too slow to account for the rapid uplift of the Altiplano implied by their results. Instead the authors suggest crustal delamination, removal of dense lower crust and/or mantle lithosphere, as a more plausible mechanism. However, this process can only occur when the lower part of the lithosphere has become gravitationally unstable as a result of thickening (*13*). Delamination below the Altiplano (*1*) should thus have been a consequence of thickening. However, if the Corque Basin was indeed at or below sea level at ~11 Ma (*1*), the crust—which is now ~55 km thick (*14*)—had not been thickened by then. Because an unthickened crust implies an unthickened lithosphere, it is difficult to explain why the lower lithosphere would start to delaminate before thickening. Even if thickening of the Altiplano crust started at 10.3 Ma with simultaneous "slow" delamination, it is unclear what process triggered thickening at that time.

Can soil paleotemperatures, and hence paleoaltitudes, be securely deduced from isotope-geochemical measurements? Ghosh *et al.* (*1*) assumed that the carbonate nodules they analyzed were devoid of diagenetic signal, yet they reported one sample (04BL69) from the 10.3 to 11.4 Ma interval that yielded an apparent paleotemperature of 50.3° ± 4.9°C and acknowledged that this was likely due to cryptic recrystallization during burial. The samples from this interval were subject to minimum burial depths of between 2200 and 3400 m (*8*) and thus to temperatures of 60° to 90°C (adopting a conservative estimate of 30°C/km for the geothermal gradient). We believe it unlikely that only one sample was selectively affected by burial metamorphism and that samples above and below were not.

We propose a simple test to determine whether a burial heating component is indeed present in the geochemical signal. The ~11.4 to 5.8 Ma, ~3.5-km-thick section analyzed by Ghosh *et al.* (*1*) [and (*8*)] is only the uppermost part of the ≥12-km-thick (*15*), 55.5-Ma continental succession that crops out in the Corque syncline. A ~4.7-km-thick part of this succession, partly overlapping with the former (*1*, *8*), was reliably dated 14.5 to 9.0 Ma by magnetostratigraphy (*7*) and displays facies, including carbonate nodules, somewhat similar to the ~11.4 to 5.8 Ma succession. Collecting samples down-section and processing them by the method used by Ghosh *et al.* (*1*) would show whether apparent paleotemperatures keep growing down-section or not, and thus refute or validate their method.

Because isotopic resetting may occur during burial diagenesis of paleosol nodules, the geochemical methods used by Ghosh *et al.* (*1*) should have been robustly validated by thorough down-section sampling before drawing conclusions about the history and mechanisms of uplift in the Central Andes. If burial is proved to have modified the geochemical signal as we predict, the reported paleoaltitude estimates from at least the 11.4 to 10.3 Ma interval will need to be reevaluated and the rapid and late Andean uplift proposed by Ghosh *et al.* reconsidered.

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References

1. P. Ghosh, C. N. Garzione, J. M. Eiler, *Science* **311**, 511 (2006).
2. T. Sempere, G. Hérail, J. Oller, M. G. Bonhomme, *Geology* **18**, 946 (1990).
3. S. Lamb, P. Davis, *Nature* **425**, 792 (2003).
4. B. K. Horton, *Tectonics* **24**, TC3011 10.1029/2003TC001619 (2005).
5. M. Sébrier, A. Lavenu, M. Fornari, J.-P. Soulas, *Géodynamique* **3**, 85 (1988).
6. M. Farías, R. Charrier, D. Comte, J. Martinod, G. Hérail, *Tectonics* **24**, TC4001 (2005).
7. P. Roperch, G. Hérail, M. Fornari, *J. Geophys. Res.* **104**, 20415 (1999).
8. C. N. Garzione, P. Molnar, J. C. Libarkin, B. J. MacFadden, *Earth Planet. Sci. Lett.* **241**, 543 (2006).
9. S. Rousse, S. Gilder, M. Fornari, T. Sempere, *Tectonics* **24**, 10.1029/2004TC001760 (2005).
10. K. M. Gregory-Wodzicki, *Geol. Soc. Am. Bull.* **112**, 1091 (2000).
11. E. A. Kowalski, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **188**, 141 (2002).
12. B. L. Isacks, *J. Geophys. Res.* **93**, 3211 (1988).
13. R. W. Kay, S. M. Kay, *Tectonophysics* **219**, 177 (1993).
14. S. L. Beck *et al.*, *Geology* **24**, 407 (1996).
15. P. Rochat, G. Hérail, P. Baby, G. Mascle, O. Aranîbar, *C. R. Acad. Sci. Paris* **327**, 769 (1998).

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Response to Comment on "Rapid Uplift of the Altiplano Revealed Through 13C-18O Bonds in Paleosol Carbonates"

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Response to Comment on "Rapid Uplift of the Altiplano Revealed Through ^{13}C-^{18}O Bonds in Paleosol Carbonates"

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Clumped-isotope thermometry measurements of carbonate samples deposited in the Bolivian Altiplano as early as 28.5 million years ago and buried up to ~5000 meters deep exhibit no relationship between burial depth and apparent temperature, and largely yield temperatures within error of plausible Earth-surface conditions. These results counter the predictions of Sempere *et al.* and support our previous conclusions regarding the uplift of the Altiplano.

Sempere *et al.* (*1*) suggest that the temperatures recorded by carbonate clumped-isotope thermometry in 11.4 to 10.3 million-year-old soil nodules from the northern Altiplano (*2*) reflect partial resetting during burial rather than deposition at low altitude. Their arguments include a testable prediction: If the soil carbonates in question underwent partial resetting during burial, then more deeply buried samples from the same or related sections should be even more strongly reset, yielding apparent temperatures above any plausible depositional temperature.

Figure 1 presents the results of carbonate clumped-isotope thermometry analyses for 32 soil and lacustrine carbonates from the northern Altiplano. These data include those in (*2*) as well as new measurements that are part of a broader ongoing study of modern and ancient carbonates [generated using the same analytical methods described in (*2*)]. This expanded suite includes soil carbonates deposited between 28.5 and 0 million years ago (Ma) and buried between 0 and ~5000 m deep, as well as lake carbonates of similar age and burial depth. Age estimates for the new measurements are based on recently published magnetostratigraphy (*3*) and previously published $^{40}Ar/^{39}Ar$ dates (*4*) of tuffs within the Corque and Tambo Tambillo sections, and on magnetostratigraphy (*5*) within the Salla section. We estimated maximum burial depths for each sample based on our own measured sections near Callapa (*3*) and estimated section thicknesses in the Tambo Tambillo and Salla areas (*4*, *6*).

The data presented in Fig. 1 exhibit no systematic relationship between apparent growth temperature and burial depth, are generally within analytical uncertainty of earth-surface temperatures [the only noteworthy exception was reported and discussed in (*2*)], and include relatively low temperatures in samples far older and more deeply buried than those reported by (*2*)—i.e., the temperatures of 16.9°C and 21.5°C found in 23.6- to 23.7-Ma soil carbonates that were buried to ~5000 m. Moreover, we observe no systematic difference between surface-deposited carbonates of different types (i.e., soil versus lacustrine). Variations in temperature within this suite stem from a variety of factors, including primary differences in paleoaltitude and paleoclimate [discussed for many of the Callapa samples in (*2*)], unusual diagenetic resetting [e.g., the one high-temperature Callapa sample discussed in (*2*)], and analytical uncertainties. It is beyond the scope of this reply to discuss all of these issues in detail. Nevertheless, these data contradict the predictions of Sempere *et al*. and, more generally, lend no support to the suggestion that burial metamorphism has systematically reset the growth temperatures of Altiplano soil carbonates. For this reason, we maintain that the difference in average apparent temperature between 11.4 and 10.3 Ma and post-6.7-Ma soil carbonate suites reported in (*2*) reflects a difference in their temperatures of deposition and thus constrains paleoaltitudes using methods (and with uncertainties) that have already been discussed (*2*).

Sempere *et al*.'s geomorphic and stratigraphic arguments against a late Miocene date for uplift of the northern Altiplano are relevant but contain no quantitative paleoaltitude determinations and say nothing specific about the mid- to late-Miocene paleoaltitude of the Altiplano. Sempere *et al*. recognize that the Western Cordillera could have extended to higher altitudes than the Altiplano (as they do today); we suggest it is also possible that mid-Miocene altitudes in any or all of these regions might have been higher or lower than Oligocene and early Miocene altitudes. It will be difficult to know how to evaluate these issues until there is a quantitative database documenting temporal and spatial variations of paleoaltitudes across the Andean orogen.

Sempere *et al*.'s critique of paleoaltimetry based on fossil leaf assemblages has no direct

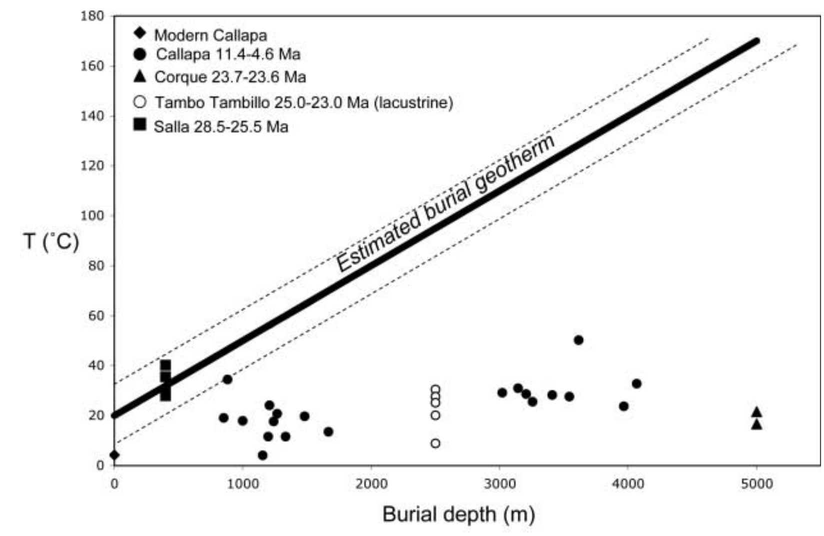

Fig. 1. Apparent growth temperatures for various Altiplano carbonates based on clumped-isotope thermometry plotted as a function of estimated maximum burial depth. Symbols discriminate among soil carbonates from sections near Callapa, Corque, and Salla and lacustrine carbonates from near Tambo Tambillo, as indicated by the legend. The heavy solid line indicates an estimated burial geotherm, assuming a surface temperature of 20°C and a gradient of 30°C per km. The dashed lines define a ±10°C offset from this trend, which we consider a reasonable estimate of its uncertainty. Carbonates deposited on or near the surface of the Altiplano within the past 28.5 million years and buried to 5000 m or less exhibit no systematic relationship between apparent temperature and burial depth and show no evidence for pervasive resetting of deeply buried samples.

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bearing on the Ghosh *et al*. study (*2*). Although we noted that clumped-isotope thermometry results broadly agree with paleobotanical altimetry, our central arguments do not depend on this issue.

We do not agree with Sempere *et al*. (*1*) that removal of mantle lithosphere requires previous crustal thickening beneath the Altiplano. The Eastern Cordillera preserves the largest documented shortening in the Andes (*7*, *8*) and is the most plausible candidate for the locus of development of an unstable lower-crustal and/or lithospheric-mantle root. Gravitational removal of this material could have led to simultaneous surface uplift of the eastern Altiplano and Eastern Cordillera and lower crustal flow from the Eastern Cordillera to the Altiplano, thickening the crust beneath the Altiplano. This scenario is only one of several that cannot be discounted using existing constraints. Nevertheless, it is an example of a process that is consistent with both the paleoaltitude reconstructions of (*2*) and the physics that govern convective removal of lithosphere, crustal thickness, and isostasy.

References and Notes

1. T. Sempere, A. Hartley, P. Roperch, *Science* **314**, 760 (2006); www.sciencemag.org/cgi/content/full/314/5800/760b.
2. P. Ghosh, C. N. Garzione, J. Eiler, *Science* **311**, 511 (2006).
3. C. N. Garzione, P. Molnar, J. C. Libarkin, B. J. MacFadden, *Earth Planet. Sci. Lett.* **241**, 543 (2006).
4. L. Kennan, S. Lamb, C. Rundle, *J. S. Am. Earth Sci.* **8**, 163 (1995).
5. R. F. Kay, B. J. MacFadden, R. H. Madden, H. Sandeman, F. Anaya, *J. Vert. Paleontol.* **18**, 189 (1998).
6. B. J. MacFadden *et al.*, *J. Geol.* **93**, 223 (1985).
7. N. McQuarrie, *Geol. Soc. Am. Bull.* **114**, 950 (2002).
8. K. Elger, O. Oncken, J. Glodny, *Tectonics* **24**, 10.1029/2004TC001675 (2005).

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