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Palaeo-altimetry of Tibet

Arising from: D. B. Rowley & B. S. Currie *Nature* 439, 677–681 (2006).

The determination of palaeo-elevation has emerged in the past 15 years as an important tool for constraining physical processes that govern the formation of mountain belts. Rowley and Currie[1] report palaeo-elevations for the Lunpola basin within the Tibetan plateau and claim that these elevations are incompatible with 'mantle-thickening models' for mountain formation. We show here that their data do not support this conclusion and, indeed, are consistent with its opposite. The Tibetan plateau could have risen by a kilometre or more as its dense lower lithosphere sank into the underlying mantle.

If continental lithosphere is thickened to form a mountain belt, the lower part of the lithosphere, which is inherently unstable because it has higher density than its underlying mantle, may abruptly sink and be replaced by mantle that is less dense[2,3]. Depending on the thickness of lithosphere that is replaced, the Earth's surface can rise by 1,000 m to perhaps 2,500 m (refs 2,3). (In this communication, all references to elevation are to the height of the land surface above sea level; change in sea level between 35 Myr and the present is negligible in this context.) The essence of Rowley and Currie's argument is that, because their inferred elevations for the Lunpola basin at about 35 Myr (4,850 m (+1,630/−1,435 at 95% confidence), 4,260 m (+1,480/−1,420), and 4,050 m (+1,420/−1,220)) are similar to its present-day elevation (4,567–4,718 m), the surface of the Tibetan plateau cannot have risen appreciably after 35 Myr, and that convective removal of lower lithosphere could not have occurred.

Rowley and Currie's[1] argument assumes that the elevation history of the Lunpola basin, which forms only a very small part of the Tibetan plateau, is representative of the whole. The position of the basin renders that assumption doubtful: it lies close to the northern edge of the Lhasa block, which was part of an Andean margin through late Cretaceous and early Tertiary time, and probably achieved a high elevation much earlier than the rest of the plateau[4–6].

Rowley and Currie's[1] argument also neglects the influence of crustal thinning on the surface height of the plateau since 35 Myr ago. Extensional faulting began on the plateau at about 8–15 Myr[3,7,8], and summation of moment tensors of earthquakes suggests that roughly half of the present-day rate of east–west extension in Tibet represents vertical thinning[9,10]. Because of isostasy, crustal thinning causes the surface elevation to drop. The present rate of thinning is about 4×10^{-9} per yr; if this rate had operated for the past 8–15 Myr, then the crust would have thinned by 2.5–5 km and, in the absence of other processes, the height of the land surface would have decreased by about 500–1,000 m (refs 2, 3). Because crustal thinning extracts gravitational potential energy from the plateau[2,3], the present-day rate of thinning is probably lower than the average rate, so the total decrease in surface height may have been greater than we estimate.

The average of Rowley and Currie's[1] three estimates of palaeo-elevation, at 35 Myr, for sites in the Lunpola basin is about 250 m lower than the present-day elevation of the basin and, at 8–15 Myr, surface heights in the plateau were higher than they are now by about 500–1,000 m. Thus, ignoring uncertainties, Rowley and Currie's[1] palaeo-altitudes are consistent with a rise of the Lunpola basin by about 750–1,250 m at some time between 35 ± 5 Myr and the onset of crustal thinning at around 8–15 Myr. Accounting for departures from assumptions in Rowley and Currie's estimates[1] (such as differences in initial $\delta^{18}O$, in paths of moisture transport, in evaporation of precipitation, and so on) could make the uncertainties larger than quoted, and permit greater surface uplift. Thus, Rowley and Currie's results do not disprove 'mantle-thickening models' for the formation of the plateau: indeed, when combined with the effect of crustal thinning on the surface elevation of the plateau in the past 15 Myr, the data offer support for the idea that convective removal of mantle lithosphere contributed to the high surface elevation of the present-day Tibetan plateau.

Peter Molnar*, Gregory A. Houseman†, Philip C. England‡
*Department of Geological Sciences and Cooperative Institute for Research in Environmental Science (CIRES), University of Colorado, Boulder, Colorado 80309-0399, USA
e-mail: molnar@cires.colorado.edu
†Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
‡Department of Earth Sciences, Oxford University, Oxford OX1 3PR, UK

1. Rowley, D. B. & Currie, B. S. *Nature* **439,** 677–681 (2006).
2. England, P. & Houseman, G. *J. Geophys. Res.* **94,** 17561–17579 (1989).
3. Molnar, P., England, P. & Martinod, *J. Rev. Geophys.* **31,** 357–396 (1993).
4. England, P. C. & Searle, M. *Tectonics* **5,** 1–14 (1986).
5. Murphy, M. A. *et al. Geology* **25,** 719–722 (1997).
6. Kapp, P., Yin, A., Harrison, T. M. & Ding, L. *Geol. Soc. Am. Bull.* **117,** 865–878 (2005).
7. Harrison, T. M., Copeland, P., Kidd, W. S. F. & Yin, A. *Science* **255,** 1663–1670 (1992).
8. Blisniuk, P. M. *et al. Nature* **412,** 628–632 (2001).
9. Molnar, P. & Chen, W.-P. *J. Geophys. Res.* **88,** 1180–1196 (1983).
10. Molnar, P. & Lyon-Caen, H. *Geophys. J. Int.* **99,** 123–153 (1989).

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Rowley & Currie reply

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Molnar *et al.*[1] question our conclusion on the role of convective destabilization of thickened mantle lithosphere in determining the surface elevation history of the Tibetan plateau. The primary argument depends on our interpretation[2,3] of oxygen-isotope-based estimates of palaeo-elevation of the Lunpola basin, a locality in the centre of the plateau.

Molnar *et al.*[1] raise the questions of whether the Lunpola basin is representative of the plateau and whether our data are incompatible with an increase of 1 km to 2.5 km in the surface elevation[4]. Regarding their first point, it is not known how representative the Lunpola basin is of the central Tibetan plateau, nor whether it was topographically high before the date of our oldest samples. However, Molnar *et al.* may be carrying the Andean analogy to extreme: for example, present-day Java is comparably 'Andean' but elevations in the back-arc extend to below sea level, despite contractional deformation in this region. Although evidence from Cretaceous–early Tertiary shortening in central Tibet has provided insight into the regional extent of pre-collision shortening[5], the magnitude of crustal thickening, and its corresponding effect on Tibetan palaeo-elevations, is unresolved.

Continuous convergence of India and Asia since collision began requires either storage of intrinsically negatively buoyant mantle lithosphere above the asthenosphere, or continuous advective removal of mantle lithosphere from both the Indian and Asian sides of the orogen into the underlying mantle, or some