Isostasy can't be ignored

To the Editor — In an elegant analysis of landslides following the 2008 Wenchuan earthquake in Sichuan, China, Parker *et al.*[1] showed that estimates of the mass of material in landslides exceeds by two to six times the mass of material that moved upwards during the earthquake. With the sensible logic that the material within the landslides soon will be transported out of the Longmen Shan Mountains, they use this discrepancy to argue that erosion seems to remove mass faster than geodynamic processes supply it to the Longmen Shan. I applaud their analysis, but I think that they overlooked an aspect that renders this deduction only plausible at best, and quite likely false. That aspect is isostasy, Archimedes' principle applied to the Earth, which, when generalized to include an elastic surface layer, calls for equal pressure at any depth in the underlying mantle beneath the elastic layer[2].

As Wager[3] and Holmes[4,5] recognized long ago, the isostatic compensation of mass removed from the surface of the Earth requires a net upward flux of mass, with respect to sea level, so that the creation of high peaks follows from the incision of deep valleys. If the mass removed is given by ΔM, the upward displacement of mass is $\Delta M\rho_c/\rho_m$, where ρ_c and ρ_m are the densities of crust and mantle, respectively. The factor of ρ_c/ρ_m arises because the mass removed, with crustal density, occupies a larger volume than the mass of mantle material that replaces it. With $\rho_c = 2800$ Mg m^{-3} and $\rho_m = 3300$ Mg m^{-3}, a compensating mass of $0.85\Delta M$ should rise in response to the removal of ΔM. Thus, removal of about 5–15 km^3 of erodible material in landslides[1] implies that when it is transported out of the Longmen Shan, about 4.2–12.8 km^3 of rock should move upwards with respect to sea level, on the timescale over which isostasy responds to rapid unloading. If the net upward mass transport that Parker *et al.* associate with faulting during the earthquake (2.6±1.2 km^3) is added to these estimates, only with a conspiracy of values would more material be removed than replaced by the combination of tectonic processes and isostatic compensation: about 6.4–15.2 (±1.2) km^3 is obviously indistinguishable from about 5–15 km^3.

A few caveats should be noted. First, Parker *et al.* pointed out that their estimate of around 5–15 km^3 is a minimum estimate; hence their contention, and that of Godard *et al.*[6], that the Longmen Shan is diminishing in size could still be right, even allowing for isostatic compensation of yet more mass removal. Second, both my analysis and that of Parker *et al.* ignore interseismic vertical movement, which could contribute additional upward mass flux. Third, although a finite flexural rigidity of the lithosphere will not alter the amount of isostatically compensated upward movement of mass, it will spread that upward displacement over an area wider than that of the landsliding. A sufficiently large value for the flexural rigidity might cause the compensating upward movement to occur so far from the Longmen Shan as to be irrelevant to the growth of that mountain belt. A sufficiently large flexural rigidity, however, seems unlikely, especially given the absence of a flexural basin southeast of the Longmen Shan. Finally, because of viscous flow in the underlying mantle, isostatic compensation is not instantaneous. The viscous response to an instantaneous redistribution of mass will exponentially approach an isostatically compensated state. Characteristic e-folding relaxation times of a few thousand years[7] deduced from post-glacial rebound, however, suggest that isostatic compensation will occur on timescales comparable to recurrence intervals of Wenchuan-like earthquakes.

Although most Earth scientists appreciate the importance of isostasy in maintaining high terrain, many forget that present-day rock uplift owes its existence mostly (~85%) to isostatic compensation of material that has been eroded and transported outside that terrain, and not to active tectonics. ❐

References

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Authors' reply — We thank Peter Molnar for his interest in our work[1], and for graciously (and quite correctly) pointing out the potential role of isostasy in the long-term volume balance of the Longmen Shan orogen. However, his point does not affect the primary message of our paper, which was to assess the instantaneous competition between erosional and tectonic processes associated with the earthquake. Instead, isostasy is yet another reason, in addition to those we previously presented, why this instantaneous imbalance we describe might not hold over long timescales — that is, over multiple earthquake cycles and viscoelastic response times (>10^3 years). Indeed, we suggested in our paper that long-term rock uplift is unlikely to be a simple function of the 2008 coseismic displacements; it is produced by a combination of tectonic activity and flexural-isostatic deformation, but the relative importance of each component was not the focus of our study.

Molnar calculates the isostatic response to an eroded mass ΔM, assuming that the lithosphere has no flexural rigidity, and asserts that a non-zero effective elastic thickness (T_e) would not change the overall magnitude of the erosionally driven compensating mass. He also notes, however, that non-zero values of T_e will cause the flexural-isostatic response to be distributed more widely across the plateau margin and adjacent Sichuan Basin, thus decreasing the amount of erosionally driven rock uplift directly underneath the Longmen Shan. Estimates of T_e in the Longmen Shan and western Sichuan Basin range from 20 to 45 km (refs 2–4), indicating that the response calculated by Molnar is most likely an overestimate. To evaluate this, we performed approximate deflection calculations using the simple linear model of Jordan[5]. Assuming a T_e of 20 km (ref. 2) and spatially averaged