Linking plate tectonics and mantle flow to Earth's topography

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It has long been known that solid-state convection within Earth's mantle should result in deformation of its surface (Pekeris, 1935), a phenomenon referred to as dynamic topography. This topography is relatively elusive: it is transient over time scales of 1–10 m.y., it occurs over spatial scales covering a few hundred to a few thousand kilometers, and its amplitude is on the order of 1 km at long wavelengths. This amplitude is small in comparison to the secular bimodal topography of Earth (the average elevation contrast between oceans and continents is ~4.5 km), mostly because of thickness and density contrasts at crustal and lithospheric depths, that is modulated by tectonic processes, resulting in mountain belts up to several kilometers high.

To illustrate the effect of mantle flow on present-day topography (Fig. 1A), the residual topography (the non-isostatic part of topography that is thought to be of dynamic origin) proposed by Steinberger (2007) has been removed from observed topography in Figure 1B. While point measurements (Winterbourne et al., 2014) and global models (e.g., Steinberger, 2007) of residual topography depend on which data and assumptions are used to evaluate isostatic topography, some features are common across global estimates (Flament et al., 2013) and are apparent in Figure 1B. In the absence of mantle flow, continental elevations would be lower in eastern and southern Africa (Conrad and Gurnis, 2003), and higher in Australia, South America, eastern North America, and eastern Europe. The Indian Ocean would be shallower between Australia and Antarctica (Gurnis et al., 1998), and the Pacific Ocean would be deeper to the northeast of Australia (Davies and Pribac, 1993). As for the South Atlantic Ocean, it would be shallower to the east of Argentina (Shephard et al., 2012) and deeper to the west of southern Africa (Nyblade and Robinson, 1994)—in other words, the South Atlantic would not be as asymmetric (Flament et al., 2014).

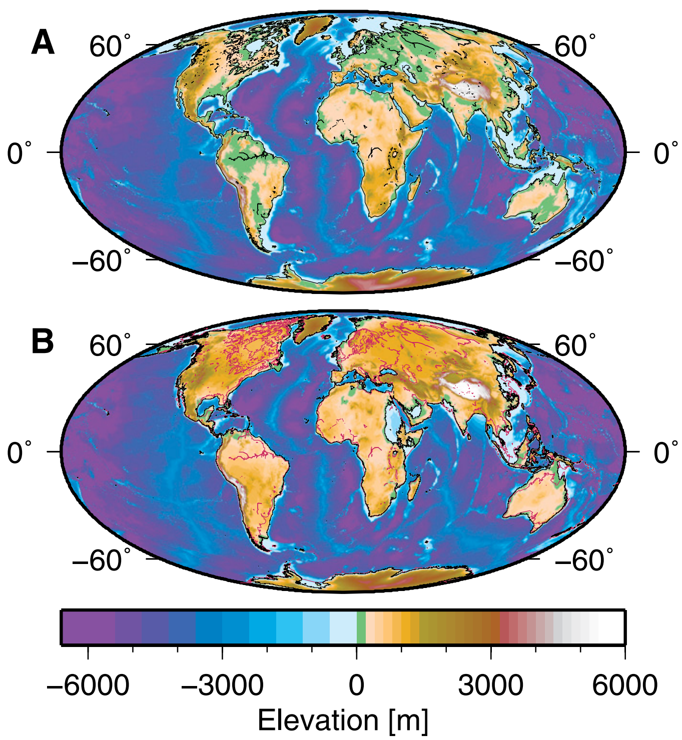

Figure 1. A: Earth's topography (Amante and Eakins, 2009; including ice, here plotted as land). B: What Earth *might* look like in the absence of mantle flow (see text for details). Actual coastlines are shown in black in A, and in maroon in B, and hypothetical coastlines are shown in black in B.

Because a large portion of Earth's continents lies at low elevations (as reflected by the difference between the equal-area arithmetic mean, 529 m, and median, 178 m, of elevations above −200 m), changes in long-wavelength dynamic topography cause significant shifts in coastlines despite the small amplitude of the signal. In Figure 1B, this is reflected by the emergence of continental shelves around Australia, South and North America, and eastern Europe, and by the flooding of eastern Africa. The topography and coastlines in Figure 1B are both illustrative and should not be taken at face value, because of the uncertainties associated with residual topography, and because the smaller isostatic correction due to water redistribution was ignored for simplicity. Nonetheless, the link between mantle flow and shifting coastlines is now well established for several "stable," low-lying continental platforms, including Cretaceous North America (Liu et al., 2008) and Australia (Gurnis et al., 1998), and Cenozoic South America (Shephard et al., 2010).

In this issue of *Geology*, Husson et al. (2014, p. 839) take a different approach and investigate the influence of mantle flow on the evolution of the topography of Earth's largest and highest mountain belt, where isostatic topography is greatest. Indeed, negative residual topography is also relatively large under the Himalayas and the Andes, mountain ranges that would each be $\lesssim$ 800m higher in the absence of mantle downwellings (Fig. 1). Husson et al. use seismic tomography and simplified tectonic reconstructions to design idealized snapshots of the Indian slab subducting under Eurasia in 10 m.y. increments for the past 30 m.y. In their scenario, as the Indian plate moved north, the slab at its leading edge was overturned from north-dipping to south-dipping (Van der Voo et al., 1999) at ca. 15 Ma. Solving the instantaneous Stokes flow for each of these snapshots, Husson et al. attribute to dynamic topography ≤900 m of uplift in the Higher Himalayas between 25 and 15 Ma (early Miocene) and >3 km of subsidence in the foreland basin since ca. 12.5 Ma (mid-Miocene). Their study challenges archetypal lithospheric models of mountain belt evolution. Firstly, it suggests that the interplay between plate motion and mantle flow could explain the early- to mid-Miocene uplift of the Himalayas and Tibetan Plateau (e.g., Molnar and Stock, 2009), without the need to invoke lithospheric delamination (Molnar et al., 1993). Secondly, it implies that estimates of the elastic thickness of the Indian plate (e.g., Jordan and Watts, 2005) should be revised because mantle flow significantly contributes to the long-wavelength subsidence of the Siwalik foreland basin. Thirdly, it emphasizes that the effect of dynamic topography is not limited to tectonically stable areas, and calls for the topographic evolution of tectonically active areas to be revisited considering mantle flow (Flament et al., 2014).

The deliberately simple approach used by Husson et al. also underlines the challenges and uncertainties in linking plate motion and mantle flow to Earth's topography. For instance, determining the convergence history between India and Eurasia requires constraints on the past motion of several other plates. Interestingly, although the increasing resolution of the magnetic data constraining recent plate motion suggests that the Indian plate might have been slowing down over the past 20 m.y. (Molnar and Stock, 2009), this result may be an artifact for the past 10 m.y. due to noise in the magnetic data (Iaffaldano et al., 2013). For earlier times, the

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conventional scenario of a collision between India and Eurasia at ca. 55 Ma (e.g., Klootwijk et al., 1992) has also been challenged, with the alternative proposition that an intra-oceanic arc (Van der Voo et al., 1999) first collided with Eurasia in the early Eocene, followed by the India-Eurasia collision around the Eocene-Oligocene boundary (Aitchison et al., 2007).

As for geodynamics, explicitly modeling the large-scale interactions between tectonic plates and the mantle is challenging because of the computational cost and numerical complexities of solving this multiscale problem. Nevertheless, such models are important because comparing their predictions to observations helps constrain both the uncertain physical properties of the solid Earth, and plate tectonic reconstructions. For example, fully dynamic global mantle flow models have been used to constrain the rheology of the mantle based on present-day plate velocities (Stadler et al., 2010) and to attribute the triangular shape of the age distribution of the ocean floor (in plots of area per age [km^2/yr] versus seafloor age [Ma]), a characteristic feature of plate tectonics for the past 140 m.y. (Seton et al., 2009), to the existence of continents (Coltice et al., 2012). In addition to fully dynamic models, several strategies have been designed to impose plate tectonic reconstructions as boundary conditions of mantle flow models (see Flament et al., 2013, for a review): backward advection models that are based on mantle tomography and may be valid for the past 50–75 m.y. (Conrad and Gurnis, 2003), forward models that are based on uncertain initial conditions but can be used deep in geological time (Zhang et al., 2012), and "adjoint" models that combine both approaches and are applicable to the past 100 m.y. (Liu et al., 2008).

Forward mantle flow models may help constrain tectonic reconstructions that become increasingly uncertain back in geological times (Torsvik et al., 2010). This can be achieved by implementing alternative tectonic scenarios as boundary conditions (Zahirovic et al., 2012) and comparing the predicted continental vertical motions (Zhang et al., 2012) and continental flooding (Gurnis, 1993) to the geological record. To succeed, this modeling effort will have to be accompanied by a parallel effort in acquiring and compiling large-scale geological observations, including paleogeography (e.g., Golonka et al., 1994) and thermochronology data.

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