From Continental Collision to the Earth's Deep Water Cycle

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While there is a general consensus that the Himalayan-Tibetan orogen is a consequence of collision between the Asian continent and the Indian shield, a broad array of different tectonic models have been proposed. Mantle dynamics is important in all these models, but processes in the mantle are not explicitly addressed in most cases. Here we address this important issue emphasizing new methodology and high-resolution, broadband seismic array data that are readily available in the public domain. The latter aspect is critical in that our results are independently verifiable – a basic tenet of any scientific endeavor.

Combining results from a variety of seismic methods and additional constraints from plate motions, mineral physics, geodesy, and petrology, the current configuration of overlapping lithospheres is constrained down to depths above the lower mantle (Fig. 1). We then reconstruct position of the Indian lithospheric mantle relative to Asia back to 15 Ma ago or the onset of the latest magmatic activity in Tibet. By then the leading (northern) edge of the Indian lithospheric mantle (Indian mantle front, IMF) has advanced sub-horizontally past the entire Lhasa terrane (now southern Tibet), and thickened the lithospheric mantle of the Qiangtang terrane (now central Tibet). Rayleigh-Taylor instability ensued, causing widespread but small volume of magmatic activity in northern Tibet (Fig. 1). Meanwhile, detached lithospheric mantle foundered quickly through the upper mantle and now rests at the bottom of the mantle transition zone (MTZ) just above the lower mantle. The remnant of detached lithospheric mantle of the Qiangtang terrane manifests itself as a large-scale seismic anomaly of high compressional wave speed (V_P) but curiously is undetectable through shear-waves.

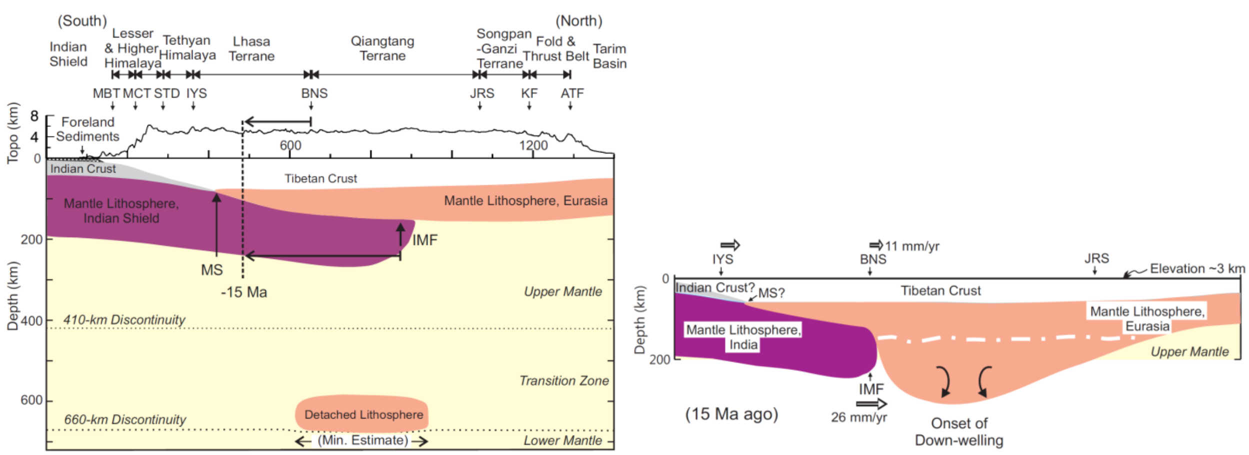

Figure 1. (Left panel) A north-south trending cross section showing our interpretation of the current configuration of lithospheres. The detached lithosphere in the MTZ is inferred from the minimum lateral extent of seismic anomaly of high V_P. The dashed vertical line marks the reconstructed position of the IMF and the BNS at 15 Ma ago. (Right panel) A schematic cross section showing reconstructed positions of the IMF and the BNS at 15 Ma ago when the IMF is near the southern edge of thickened Qiangtang terrane. (Chen and Tseng, 2007; Tseng and Chen, 2008; Chen et al., 2013).

The discordant results between *P*- and *S*-waves indicate that the foundered lithospheric mantle is rich in hydroxyls, a conclusion supported by other evidence including hydrous minerals in recent volcanic rocks found in northern Tibet. Since olivine and its high-pressure polymorphs, all nominally anhydrous

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minerals, can hold ~1 wt% of water throughout the upper mantle and the MTZ, foundering of thickened lithospheric mantle caused by continental collision is an unappreciated but effective pathway for water to enter the deep mantle. In fact, the global distribution of deep earthquake foci is inconsistent with the traditional notion that subduction of oceanic lithosphere is the major pathway for recycling water into the Earth's deep interior (Green et al., 2010).

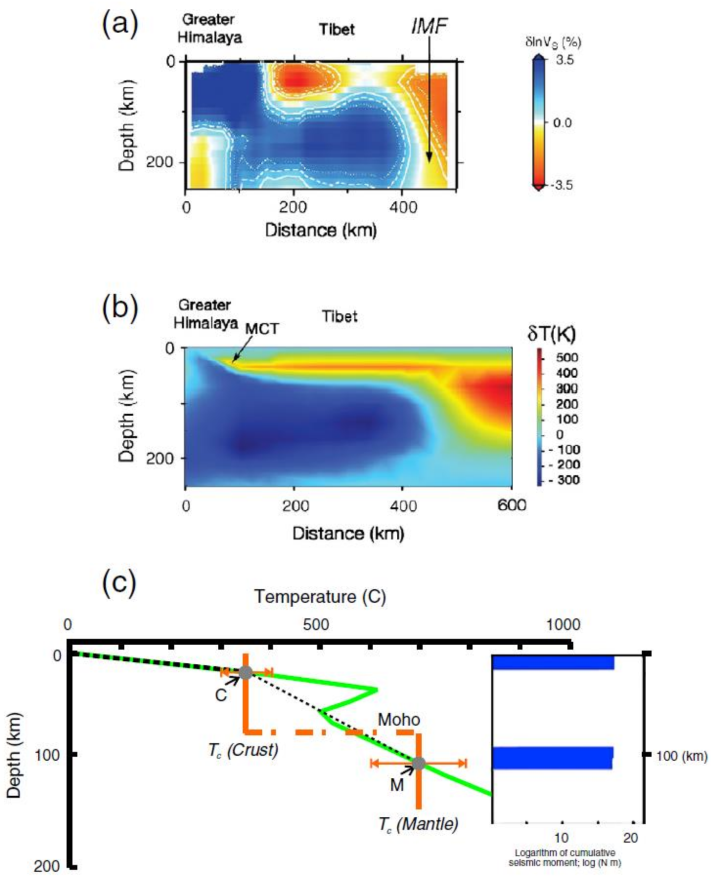

Figure 2. (a) North–south trending, vertical cross-section of V_S anomalies (Hung et al., 2011). (b) Simulated temperature anomalies (relative to an average continental geotherm) beneath Tibet along the same cross-section as in (a) (Wang et al., 2013). (c) Temperature as a function of depth beneath southern Tibet where the distribution of focal depths is bimodal (inset). The step-function (in orange) shows limiting temperatures for seismicity in crustal and mantle materials, giving two constraints in temperature from focal depths (near points "C" and "M"): Shallow crustal earthquakes indicate a high geotherm in the upper crust, while mantle events specify a low temperature of only about 700°C at a depth of approximately 100 km (dashed lines). The green curve is predicted temperature from numerical simulations by Wang et al. (2013); where the combined effect of cooling by underthrust Indian plate and viscose shear heating along the top of the Indian plate results in a temperature inversion in the now thickened lower crust of southern Tibet.

Currently, a clear, subhorizontal seismic anomaly of high V_P and V_S (but low V_P/V_S) in the upper mantle can be traced from under northern India all the way to beneath part of the Qiangtang terrane (Figs. 1 & 2a). This configuration of the "Greater India" (GI), or the submerged, northern portion of the Indian shield, is a vast heat sink that readily explains why the upper mantle is cold under southern Tibet, including the occurrence of large, sub-crustal earthquakes (down to depths about 100 km) where the temperature is below about 700 ± 100°C (Fig. 2b). Yet the upper crust of Tibet is hot, including crustal earthquakes that are no deeper than about 15 km where the temperature is above ~350 ± 100°C. Based on results of numerical simulations, we attribute the high temperature there to the self-limiting, localized nature of shear heating along the top of GI (Fig. 2c).

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