

## Reconciling lithospheric deformation and lower crustal flow beneath central Tibet: COMMENT and REPLY

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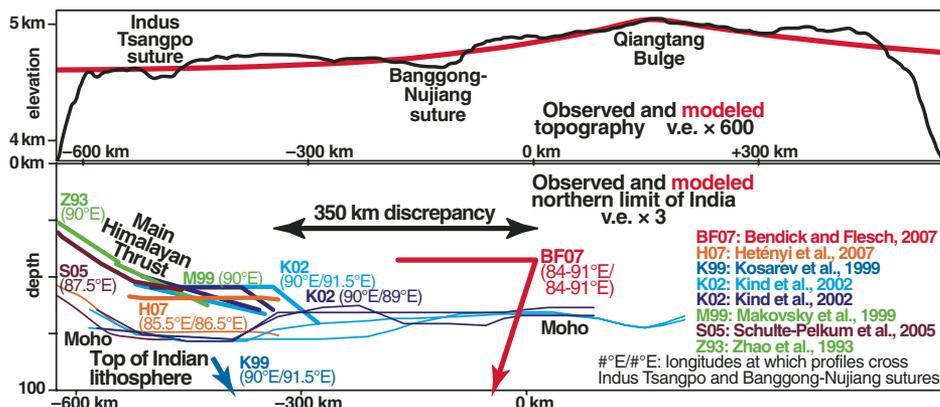
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Bendick and Flesch (2007) model a band of high topography in northern Tibet (Qiangtang Bulge, Fig. 1) as caused by a high-viscosity (rigid) lower-crustal indenter present below 45 km depth (their Fig. DR4) that extends 120 km north of the Banggong-Nujiang suture (their Fig. DR3). They explicitly describe this rigid indenter as Indian crust (their Fig. 2A). I do not argue with their theoretical model, but I disagree with their geologic interpretation of the rigid indenter because of the ~350 km discrepancy between their claimed northern limit of Indian crust and all published interpretations based on seismic imaging. Although Bendick and Flesch state that “the exact indenter shape has very little effect on the topography”, the northern limit of their indenter is a key parameter in matching the topography of the Qiangtang Bulge (their Fig. DR3). Thus the “prow” shape (their Fig. 2; “BF07” in my Fig. 1) is not required, but the northerly limit of rigid crust (0 km in Fig. 1) is a prediction and a test of their model.

Figure 1 locates seismic images of the top of subducting, rigid Indian basement (Main Himalayan thrust) from seismic reflection (Zhao et al., 1993), refraction (Makovsky et al., 1999), and receiver-function data (Kind et al., 2002; Schulte-Pelkum et al., 2005; Hetényi et al., 2007). All these data indicate a >300 km discrepancy with Bendick and Flesch’s northern limit of a rigid Indian indenter. Nor can the Bendick and Flesch indenter be the northern limit of Indian mantle lithosphere, even if the indenter top was twice as deep as the 45 km they model; receiver-function images (Kosarev et al., 1999) place the northern limit of Indian lithosphere >400 km south of the Bendick and Flesch indenter tip (Fig. 1).

Data in Figure 1 span 85.5°–91.5°E and, though most data are from the eastern part of the swath modeled by Bendick and Flesch (84°–91°E), the remarkably good agreement between seismic images spanning 5° of longitude suggests the northern limit of rigid India trends west-east, parallel to the Indus Tsangpo and Banggong-Nujiang sutures. Certainly “the front of the Indian indenter may have a complicated shape, probably varying in position both with



**Figure 1. Top: Observed and modeled topography of Tibet (after Bendick and Flesch, 2007). Bottom: Cross section of seismic images of Main Himalayan Thrust (northern limit of underthrust rigid Indian basement; thick lines south of -300 km) and Moho (thin lines); and Bendick and Flesch (2007)-predicted northern limit of rigid India (at 0 km).**

depth and along strike” (Bendick and Flesch, 2007), but currently no seismic images claim to show Indian basement north of the Banggong-Nujiang suture at mid-crustal levels.

Possibly seismologists have misinterpreted their images, though the collinearity of the Main Himalayan thrust identified by modern seismicity (top of subducting Indian basement) (Zhao et al., 1993) with the various images of a seismic reflector/refractor/converter at depths increasing northward from 20 km to the Moho makes this a difficult argument to sustain. Or possibly the Qiangtang Bulge is simply inherited topography from an older thrust belt or magmatic arc (P. Kapp, personal comm., 2007). More likely, the viscosity contrast inferred by Bendick and Flesch is not the northern limit of Indian basement, but a different boundary, possibly the northern limit of the Lhasa terrane that is sutured to northern Tibet along the Banggong-Nujiang suture. Such an interpretation in no way negates the Bendick and Flesch paradigm of Tibet (following many others, cf. Klemperer, 2006) as divided into a southern part underlain by rigid lower crust/upper mantle, and a northern part underlain by low-viscosity lower crust/upper mantle, but is important in any discussion of the degree of underthrusting and convergence that has taken place in the Himalayan orogen.

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Foremost in response to Dr. Klemperer's Comment (2008), we wish to emphasize that neither the position nor the origin of a rigid indenter beneath Tibet is the primary object of our research. Rather, the general nature of mechanical layering through the Tibetan lithosphere, and the implications of those properties on vertical coupling, are our fundamental results.

Given that caveat, we acknowledge the spatial discrepancy between the location of the maximum in intermediate-wavelength topography, taken as an indicator of the northward indenter limit, and the limit of Indian crustal material imaged by a variety of seismic methods. There are several possible factors, which both mitigate this discrepancy and decrease our model constraints on complex structures at depth. They are (not in order of importance):

1. Spatial uncertainty in seismic inversions: Tomographic techniques vary in lateral resolution based on which particular phases are used, azimuthal distribution of arrivals, geometry of the seismometer array, depth of the velocity anomaly, and a variety of other factors. Klemperer (2008) does not provide formal uncertainties on his reported slab positions,

although the scatter of positions in his Figure 1 probably reflects an appropriate uncertainty.

2. Along-strike geometry: Our model consists of a two-dimensional approximation to a strongly three-dimensional problem. This approach suffices to address the questions of mechanical coupling and crustal dynamics that constitute our primary research target, but does not provide an accurate spatial mapping of the indenter in three dimensions. Any change in the position of the indenter front with longitude in our targeted region would result in smearing and flattening of the topographic bulge that we take as a marker for the indenter position. As Klemperer notes, one approximation for the indenter front is parallel to the Himalayan arc itself, implying that the indenter front does have a strongly curved shape not considered in our methodology.

3. Vertical geometry: The reported model is also fairly insensitive to vertical geometry of the indenter. We find no difference in surface topography or stress coupling for a flat-fronted indenter or a prow-shaped indenter. However, these two different shapes would give very different results for different seismic observations, since the position of the indenter would then vary with depth, such that different seismic arrivals would map different positions for the slab.

4. Very low topographic slope: One of the most notable characteristics of our modeling results is the relatively low viscosity of the Tibetan middle and lower crust. The very low slope of the topographic bulge associated with flow requires this low viscosity. Although the low slope is critical to our inversion for viscosity, it also means that the position of the bulge maximum is relatively poorly constrained. That is, a stiffer material would produce a narrow, localized bulge given the same dynamics. Such

a material would narrowly constrain the position of the indenter front. However, because our primary result is the low viscosity of the Tibetan crust, we inevitably lose spatial resolution of indenter position, especially when combined with factors 2 and 3, above.

5. Nonlinear dynamic effects: We have modeled the crustal flow dynamics using the simplest possible approximation of a Newtonian fluid. This method does not include any more complicated effects seen in nonlinear fluids, such as asymmetry and forward deflection of a "bow wave" structure, or complicated responses to indenter geometry. Any of these effects might serve to offset the topographic maximum from the actual spatial position of the rigid indenter.

6. The Lhasa block hypotheses: Our modeling exercise makes absolutely no attempt to explore the genetic origin of the rigid indenter. One possibility proposed by Klemperer is certainly possible, that the indenter front is stiff Tibetan upper and middle crust, rather than Indian upper and middle crust. Because we consider only the mechanical properties of the indenter, and not its history, any origin for the indenter is allowed.

To summarize, we emphasize that the primary result of this work is a mechanical and dynamic model for the central Tibetan Plateau, not a structural or evolutionary model. Dr. Klemperer's observations about the nature of a rigid indenter at depth in the crust beneath Tibet do not change the fundamental results relating to vertical coupling in Tibet determined in our study.

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