

Present-day kinematics at the India-Asia collision zone: COMMENT and REPLY

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Lucy Flesch

Department of Earth and Atmospheric Sciences, Purdue University,
550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051, USA

Rebecca Bendick

Department of Geosciences, University of Montana, 32 Campus Drive
#1296, Missoula, Montana 59812-1296, USA

The recent publication, “Present-day kinematics at the India-Asia collision zone” (Meade, 2007), attempts to address an ongoing controversy about the dynamics of the Tibetan Plateau by finding block models for the region that correctly reproduce the kinematics from many global positioning system (GPS) observations. A closely related paper (Thatcher, 2006) undertakes a similar exercise, using a subset of velocity observations and different assumptions about the elastic energy cycle in the uppermost crust. The conclusions of both authors note that these block models allow slow slip rates on some large Tibetan faults. They argue, therefore, that a regional velocity field dominated by the interactions among nearly rigid crustal blocks cannot be ruled out for Tibetan tectonics, even though these slow slip rates have previously been used to argue for continuous deformation of the plateau.

In fact, a comparison of both papers hints at an opposite possibility: that the bulk mean rheology of Tibetan lithosphere behaves viscously, and deformation of a highly viscous material is best able to reproduce Tibetan kinematics at large length scales. Such a continuous viscous material is simply a body with a continuously varying strain function (no discontinuities), which may or may not contain lateral strength variations; this treatment is appropriate for Tibet only if one considers the integrated anomalously thick crust (60–70 km), rather than just the seismogenic layer, which indisputably hosts discontinuous strain in the presence of faults.

Figure 1 shows an approximate superposition of the block models and velocity fields from Meade (2007) and Thatcher (2006). Two important points can be made by this figure: 1) the best agreement occurs at the Tarim basin, which has greater mechanical rigidity than the main plateau, and 2) the worst agreement occurs where the largest number of GPS observations are available (on the eastern plateau boundary). Indeed, Shen et al. (2005) provide yet another, even more complicated, block geometry for the eastern plateau.

In Meade’s (2007) and in Thatcher’s (2006) studies, the uppermost crust is certainly brittle, and deforms elastically during interseismic intervals. What matters for continental dynamics at the largest scales is whether the interaction between these brittle blocks or viscous flow at greater depth drives the surface velocity and deformation fields. In block models and in fluids with non-zero viscosity, point velocities are correlated with neighboring velocities relative to their distance. In a fluid, the correlation is a function of distance determined by the viscosity and the thickness of the elastic lid. Therefore, a kinematic model of rigid crustal blocks, where the block size is comparable to this correlation distance, and a continuous viscous model with the appropriate viscosity will both yield a good fit to discrete velocity data. For example, Flesch et al. (2005) provide a continuous kinematic model that fits the observed GPS velocities as well as the data of Meade (2007) and Thatcher (2006). In a block approximation of a continuous-velocity field, only the scale of blocks and not their exact geometry determines the goodness of fit. The block boundaries are non-unique (McKenzie and Jackson, 1986). The observation that two different

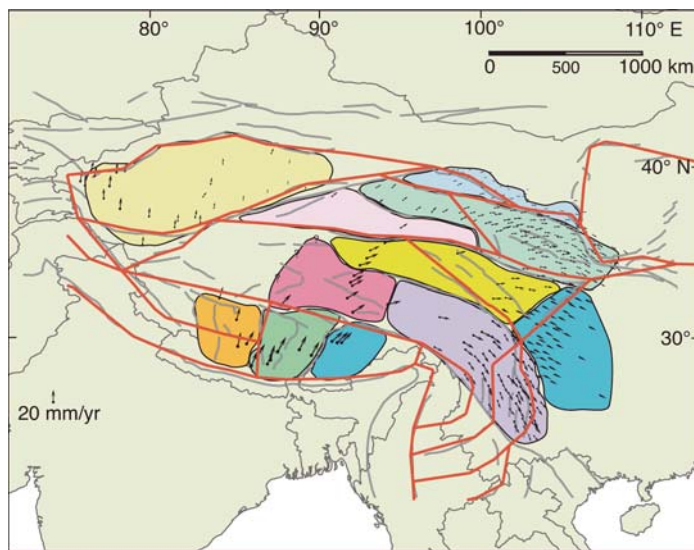


Figure 1. Superposition of Tibetan block boundaries in Meade (2007) (red lines) and block boundaries from Thatcher (2006) (colored polygons) shows differences in these boundaries between two kinematic models that both fit existing GPS data (black vectors).

configurations of blocks, both with comparable scaling, do good jobs of reproducing observed velocities in eastern Tibet (Fig. 1) suggests that the velocity field may be dominated by a highly viscous material, rather than the interaction of unique blocks. Because block models with small blocks approach a continuous approximation, and continuum models with very high bulk viscosity approach a block approximation, new and better velocity observations may not suffice to resolve this question.

No one disputes that the uppermost crust is rigid and brittle. Understanding the temporal and spatial distribution of strain at the scale of individual crustal structures mandates a rigid block formulation. The question is whether the strength of this uppermost crust dominates the total regional dynamics, or whether the rheology of the bulk lithosphere is more important.

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Brendan Meade

Harvard University, Earth and Planetary Sciences, 20 Oxford Street, Cambridge, Massachusetts 02138, USA

I welcome the Comment by Flesch and Bendick (2007) regarding my model and interpretation of global positioning system (GPS) velocities at the India-Asia collision zone (Meade, 2007), as well as the opportunity to further discuss the interpretation of GPS velocities in general. To be clear, it appears that this Comment represents an emerging discussion. With regard to my block model, Flesch and Bendick agree that this approach is “required” for “understanding the temporal and spatial distribution of strain at the scale of individual crustal structures...” Further, they do not state any disagreement nor note errors with any quantitative estimate presented in my paper. Instead, the Comment from Flesch and Bendick focuses on “an ongoing controversy about the dynamics of the Tibetan Plateau,” and, in particular, the role of a “bulk mean rheology of Tibetan lithosphere.”

My work (Meade, 2007) does not attempt to contribute to parameterizations of the bulk rheology of lithosphere such as that mentioned in the Flesch and Bendick Comment. The focus of my work is the development of a block model of the elastic upper crust that is constrained by geodetic data and compared with geologic estimates of fault slip rates and seismic moment release rates. This model can be interpreted in the context of layered viscoelastic (Maxwell body) models (Savage and Prescott, 1978; Savage, 2000) if the viscosity of the lower crust or upper mantle exceeds 10^{19} Pa·s, and if the characteristic earthquake recurrence intervals are less than 500 yr (e.g., Savage, 2000). Also, I do incorporate a simple earthquake cycle model, and consider the short-term moment balance; there is no explicit consideration of the “energy cycle in the uppermost crust.” However, this is still a vertically layered treatment of the upper lithosphere rather than the “very high bulk viscosity” parameterization discussed by Flesch and Bendick.

As pointed out in my paper, several theoretical studies have demonstrated that steady-state surface velocities provide no diagnostic information about the distribution of viscous deformation throughout the lithosphere below the elastic layer (Hetland and Hager, 2004; Li and Rice, 1987; Savage, 2000; Zatman, 2000). These results preclude the determination of steady-state lithosphere kinematics in viscous or visco-elastic layers below the elastic upper crust from observations of steady-state surface motions (e.g., GPS velocities). Thus, as has been discussed by previous authors, steady-state geodetic observations primarily provide information about the behavior of the upper crust and, in particular, the effects of interseismic elastic strain accumulation. However, transient GPS velocities following large earthquakes have been used to constrain the rheology of the lower crust and upper mantle (e.g., Hetland and Hager, 2003).

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