Reconciling lithospheric deformation and lower crustal flow beneath central Tibet

R. Bendick
Department of Geosciences, University of Montana, Missoula, Montana 59812-1296, USA

L. Flesch
Department of Earth & Atmospheric Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051, USA

ABSTRACT

A viscous region with deformable boundaries is used to model simultaneous crustal flow and lithospheric coupling in northern Tibet. This model suggests that (1) the deformation of northern Tibet is different from that of southern Tibet because of structural differences between the regions; (2) the viscosity contrast between the crust and the mantle lithosphere is relatively small beneath northern Tibet; and (3) crustal flow is compatible with crust-mantle coupling under these conditions.

Keywords: continental dynamics, crustal flow, mantle anisotropy, Tibet.

INTRODUCTION

Several recent dynamic models of the Tibetan Plateau (Bird, 1991; Royden, 1996; Clark and Royden, 2000; Vanderhaeghe et al., 2003; Beaumont et al., 2004) use channel flow solutions to describe Tibetan crust. Such models, because they involve a sandwich of weak lower crustal material between stronger layers, imply decoupling of the upper crust and the mantle lithosphere. Alternatively, strong seismic anisotropy in the Asian mantle lithosphere beneath central and northern Tibet is characterized by correlation between the fast polarization direction and the surface direction of maximum shear, requiring mechanical coupling of the lithosphere there (Flesch et al., 2005). We present a dynamic model of the plateau that allows both flow in the crust and vertically coherent deformation of the crust and mantle, thus satisfying constraints from a large number of independent observations of the Indian-Asian collision.

Thin viscous sheet models (e.g., England and McKenzie, 1982; England and Houseman, 1986) address continuous deformation of the lithosphere by providing vertically averaged stress and strain fields for mean homogeneous rheology. They therefore calculate the largest scale of continuous deformation in the Indian-Asian collision. However, structural and geophysical information indicates that the equivalent mean rheology of these solutions actually consists of stronger and weaker regions that control lithospheric dynamics at smaller scales.

Based on this additional information, we divide the Indian-Asian collision into three distinct segments: the Himalayan wedge, southern Tibet, and northern Tibet (Figs. 1 and 2). The Himalayan wedge, between the southernmost frontal thrusts and the Indus suture, contains only material derived from India, and is dominated by horizontal maximum stresses and slip on a small number of large thrust faults (Ni and Barazangi, 1984). The Indian lower crust underplates the Himalaya and southern Tibet without significant internal deformation (Schulte-Pelkum et al., 2005; Kumar et al., 2006).

In southern Tibet, between the Indus-Tsangpo and the Banggong sutures, topography (Fielding et al., 1994), coherence of the Bouger anomaly with the topography (Jin et al., 1994), a variety of seismic observations (Alsdorf et al., 1998; Makovsky and Klemperer, 1999; Tian et al., 2005; Yuan et al., 1997; Rapine et al., 2003), and electrical conductivity (Wei et al., 2001) are all interpreted as evidence for a weak layer in the middle crust, underlain by a strong Indian indenter (Nelson et al., 1996) with negligible seismic anisotropy (Sandvol et al., 1997). We approximate this segment as a low-viscosity layer channelized between the strong uppermost crust and the strong Indian lithosphere (Fig. 2). Channel flow solutions for the dynamics are appropriate, in the sense that large viscosity contrasts confine most, if not all, deformation to the weak layer and force the velocity field to be horizontal.

The surface trace of the Banggong suture approximately coincides with the termination of Indian lithosphere, and therefore the crustal channel, at depth because channel flow solutions are only appropriate where large rheological contrasts occur at all channel boundaries. The front of the Indian indenter may have a complicated shape (Fig. 2), probably varying in position both with depth and along strike (Sandvol et al., 1997; Huang et al., 2000; Tilmann et al., 2003; Kumar et al., 2006; Hauck et al., 1998; Solon et al., 2005; Tian et al., 2005; Zhao et al., 2001).

Northern Tibet, north of this indenter and beneath a strong lid, hosts Eurasian lithosphere with monotonically increasing seismic velocity (Rapine et al., 2003) and maximum seismogenic thickness of 25 km (Langin et al., 2003). Both the Moho and the base of the lithosphere are approximately flat through the northern plateau, and lithospheric thickness...
that crustal stresses can be transmitted through the lithosphere, changing viscosity contrast (less than an order of magnitude) at the Moho such that mountain building (Silver, 1996; Sandvol et al., 1997; Huang et al., 2000) are best fit by the directions of maximum shear of the deformation field determined from Quaternary fault and global positioning system data (Holt, 2000; Flesch et al., 2005), suggesting that the surface and the mantle are deforming in a vertically coherent manner (Zhang and Karato, 1995).

Because deformation through the Tibetan lithosphere is the result of a combination of tectonic boundary forces (India-Eurasia collision), which are applied throughout the lithosphere, and gravitational body forces (lithospheric density difference due to the high topography of Tibet), which are contained within the upper crust (Flesch et al., 2001), vertical coherence requires that the lithosphere is mechanically coupled and transmits the vertical normal stresses associated with gravitational collapse into the mantle (Flesch et al., 2005). The requirement of mechanical coupling through the lithosphere precludes true channel flow in the north Tibetan crust, in agreement with the structural argument. However, the lack of strong indentor material allows a smaller viscosity contrast (less than an order of magnitude) at the Moho such that crustal stresses can be transmitted through the lithosphere, changing the form of the crustal flow and generating correlated deformation. A finite region of viscous crust that acts as a fluid enclosed by deformable boundaries (McKenzie et al., 2000) incorporates this transmission of normal stresses throughout the lithosphere coincident with the continuous deformation of the viscous region (Fig. 2).

**MODEL DESCRIPTION**

We initially calculate the pressure everywhere in such a viscous region. This entails solving Stokes’ equation for a Newtonian fluid on a finite element mesh, omitting inertial terms and enforcing incompressibility, in a two-dimensional section with the indenter geometry shown in Figure 2. Vertical boundaries are either rigid and undeformable, such that both vertical and horizontal velocities are specified, or stress free, such that \( \nabla^2 \psi = 0 \), where \( \psi \) is the stream function:

\[
(u, w) = \left(-\frac{\partial \psi}{\partial z}, \frac{\partial \psi}{\partial x}\right)
\]  

(1)

The horizontal boundaries are rigid and deformable (McKenzie et al., 2000), so that horizontal (boundary parallel) velocities and vertical (boundary normal) stresses are specified. This condition is that of a fluid of constant viscosity enclosed in a deformable film; pressure gradients in the fluid deform the shape of the horizontal boundaries, where normal stresses are balanced. This formulation assumes that the strength contrast across the bottom horizontal boundary is sufficiently small that stresses large enough to deform the viscous fluid also deform the neighboring region. On the upper boundary, the uppermost crust is thin enough to deform flexurally at the long wavelengths of the dynamic topography. Rigid, deformable solutions also include continuous isotasy. In all cases, short-wavelength topography relaxes rapidly by flow in the viscous region, consistent with very low relief in northern Tibet, while longer wavelength dynamic topography grows. The exact indentor shape has very little effect on the topography.

The pressure field within the viscous region (GSA Data Repository Fig. DR1) includes both a large lithostatic component and a perturbation due to flow. Flow-related deviatoric stresses are finite but small compared to stresses associated with the lithostatic component (Fig. DR2). In the numerical problem, the form of the solution depends only on the Argand (Ar) number (a dimensionless ratio of gravitational body forces to viscous forces):

\[
Ar = \frac{gh^2}{\mu U^2}
\]  

(2)

where \( p \) is the density of the viscous region, \( g \) is gravitational acceleration, \( h \) is the thickness of the viscous region, \( \mu \) is its viscosity, and \( U \) is the convergence velocity. We choose the best dimensionless solution based on the scale of high elevation in the Changtang region of Tibet (Fig. DR3). Appropriately rescaled, this solution corresponds to deformation in a 60-km-thick region with a viscosity of \(~10^{20}\) Pa s, although all parameters included in the Argand number trade off. Viscosity is the most poorly known of these. Maximum pressure perturbations in the best solution are \(~12\) MPa (Fig. DR1) Because the viscous region is not channeled, these pressure perturbations stimulate a velocity field (Fig. DR4) that drives displacements of both the upper boundary, resulting in surface topography, and the lower boundary, resulting in correlated deformation of the crust and mantle lithosphere.

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GSA Data Repository item 2007222, Figures DR1–DR4, illustrating the pressure, velocity, topography, and stress conditions associated with collision of a weak crustal region with a strong crustal region, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 2. Top: Section of the lithosphere in the two-dimensional region. ITS—Indus-Tsangpo suture; BNS—Bangong-Nujiang suture; ATF—Altyn Tagh fault. Bottom: Rigid deformable boundary conditions specify a horizontal velocity and balanced vertical normal stresses on the horizontal boundaries of constant viscosity region in the crust. For Tibet, this viscous region collides with the rigid, undeformable indenter of Indian lithosphere. Here, the velocity vector is \((u, w)\), \(U\) is the convergence velocity in a frame fixed to the indenter, \( p \) is the lithostatic pressure, and \( \mu \) is the viscosity; \( x = 0 \) is fixed to the indenter front (see text). The indenter has a prow shape to approximate the complicated shape of the indenter front, although the shape of this front in the model has little effect on the stress field or dynamic topography.
This numerical model provides a plausible mechanism for simultaneous crustal flow and lithospheric coupling; therefore we investigate how stresses due to flow influence the Tibetan deformation field. The model of Flesch et al. (2001) uses the thin sheet approximation described above with the exception that it does not require the knowledge of a lateral viscosity or rheology distribution. The minimum deviatoric stresses averaged over the vertical extent of the lithosphere are determined by solving the force balance equations using estimates of gravitational potential energy per unit area as inputs, equal to the depth integral of pressure at a 100 km depth reference level. Because the force balance equations are linear in stress we can combine and solve for numerous deviatoric stress fields to isolate the effect of lower crustal flow. Therefore, we separately integrate pressure perturbations associated with lower crustal flow to incorporate vertical rheology variations (Fig. DR2). This method allows us to solve for the absolute magnitude of stress resulting from the viscous flow that can then be directly compared to stresses associated with gravitational collapse and the Indian-Eurasian collision. We input estimates of the vertically averaged pressure between 82°E and 96°E to avoid boundary effects for the region of interest, but limit our interpretation to the swath between 84°E and 91°E, where the collision is nearly normal to the strike of the indenter front (Fig. 1), so the assumption that the pressure field from flow does not vary in the third dimension (E-W) is reasonable. The resulting vertically averaged deviatoric stress field associated with viscous flow (Fig. 3A) is an order of magnitude smaller than the deviatoric stress field associated with gravitational collapse (Fig. 3B) (Flesch et al., 2001). This result is consistent with the initial model formulation of pressure in the viscous region as a large lithostatic component and a small perturbation due to flow.

To assess the impact this stress field associated with viscous flow has on the overall deformation field for Tibet, we consider two cases: case 1 combines stress field boundary conditions associated with the India-Eurasia collision and the deviatoric stress field associated with gravitational collapse (Fig. 3C); case 2 also considers the deviatoric stress field associated with the pressure from viscous flow (Fig. 3D). The total deviatoric stress field is the sum of the two (Fig. 3C) or three (Fig. 3D) fields. Both solutions shown are similar to that of Flesch et al. (2001) and are virtually identical to each other. Inclusion of the pressure term associated with viscous flow in the lower crust does not play any significant role in driving the observed deformation in Tibet, generating only tens of meters of additional elevation atop the ~5-km-high plateau. However, the rigid, deformable mode of viscous flow is vital to mechanically coupling the vertical stresses within Tibet.

RESULTS

A collision between a strong indenter and a weaker region of continental crust stimulates flow in the weak region. If that region is bounded everywhere by much stronger materials, then this flow is channelized. However, if the strength (viscosity) contrast across one or both boundaries of the fluid region is relatively small, less than an order of magnitude, flow in the weakest region stimulates correlated deformation in neighboring regions as stresses are transmitted across boundaries rather than simply supported by stronger regions.

Because the response of the rigid, deformable viscous region to convergence and gravitational body forces is the mechanism of lithospheric coupling in this model, we observe that coupling occurs only about and north of the Banggong suture. Where strong Indian material underplates the low-velocity mid-crust in southern Tibet, no gravitational body forces are transmitted to the mantle lithosphere. Instead, high topography and the crustal channel are both supported by the strength of the Indian lithosphere. North of the northern limit of this Indian indenter, gravitational body forces are transmitted throughout the lithosphere, including the viscous Tibetan middle and lower crust and the Tibetan mantle lithosphere. Deviatoric stresses due to flow in the weakest part of the crust are an order of magnitude smaller than those associated with gravitational body forces or India-Eurasia collision that dominate the total regional deformation.

A reasonable model for the dynamics of the Tibetan plateau must simultaneously satisfy observations of low-viscosity crust and correlated crust and mantle deformation. One model that accomplishes this task is a viscous layer with rigid, deformable boundaries beneath the plateau north of the northern limit of Indian lithosphere. Such a viscous layer bounded by relatively weak surrounding material transmits the vertical normal deviatoric stress associated with gravitational collapse from the upper crust into the mantle without perturbing the overall deformation of the lithosphere, other than relaxing short-wavelength topography and stimulating low-amplitude, long-wavelength topography. Thus, at the surface and the mantle, both boundary and body forces drive the deformation field. The deformability of the Moho implies that, although the mantle lithosphere may be two or three times more viscous than the lower crust, the mantle cannot be many orders of magnitude more viscous. Such a condition would channelize crustal flow (as in south Tibet) and preclude coupling of vertical stresses. Likewise, the mantle may be as viscous as or less viscous than the upper crust but not more viscous, otherwise the transmission of the crustal body forces would not influence mantle deformation.
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REFERENCES CITED


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