Gravitational potential energy of the Tibetan Plateau and the forces driving the Indian plate

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ABSTRACT

We present a study of the vertically integrated deviatoric stress field for the Indian plate and the Tibetan Plateau associated with gravitational potential energy (GPE) differences. Although the driving forces for the Indian plate have been attributed solely to the mid-oceanic ridges that surround the entire southern boundary of the plate, previous estimates of vertically integrated stress magnitudes of ~6–7 × 10^{12} N/m in Tibet far exceed those of ~3 × 10^{12} N/m associated with GPE at mid-oceanic ridges, calling for an additional force to satisfy the stress magnitudes in Tibet. We use the Crust 2.0 data set to infer gravitational potential energy differences in the lithosphere. We then apply the thin sheet approach in order to obtain a global solution of vertically integrated deviatoric stresses associated only with GPE differences. Our results show large N-S extensional deviatoric stresses in Tibet that the ridge-push force fails to cancel. Our results calibrate the magnitude of the basal tractions, associated with density buoyancy driven mantle flow, that are applied at the base of the lithosphere in order to drive India into Tibet and cancel the N-S extensional stresses within Tibet. Moreover, our deviatoric stress field solution indicates that both the ridge-push influence (~1 × 10^{12} N/m) and the vertically integrated deviatoric stresses associated with GPE differences around the Tibetan Plateau (~3 × 10^{12} N/m) have previously been overestimated by a factor of two or more. These overestimates have resulted from either simplified two-dimensional approximations of the thin sheet equations, or from an assumption about the mean stress that is unlikely to be correct.

Keywords: gravitational potential energy, plate tectonics, Indian plate, deviatoric stress, basal tractions, driving forces.

INTRODUCTION

The driving mechanism for the Indian plate has been a source of controversy since the advent of the plate tectonic theory. The Indian plate velocity relative to Eurasia slowed from 10 cm yr^{-1} to ~5 cm yr^{-1} upon impact with Eurasia ca. 50 Ma (Molnar and Tapponnier, 1975; Molnar et al., 1993). The Indian plate continues its northward movement relative to Eurasia at a present-day rate of ~3.5 cm yr^{-1} (Kreemer et al., 2003). The Tibetan Plateau, which formed as a result of the collision between India and Eurasia, has the largest gravitational potential energy (GPE) signal on Earth. However, there is no complete dynamic explanation for this large GPE of the Tibetan Plateau and the relatively fast movement of the Indian plate. There is no apparent downgoing slab attached to the Indian plate that might assist in driving the plate into Eurasia through the slab pull mechanism (Gripp and Gordon, 1990). Because the plate is surrounded along its entire southern margin by mid-oceanic ridges, the motion of the Indian plate has been attributed to the ridge-push force, the deviatoric stress that results from differences in vertically integrated vertical stresses between elevated ridge and older oceanic lithosphere (Richardson, 1992; Cloetingh and Wortel, 1985, 1986; Sandiford et al., 1995; Coblentz et al., 1998). However, the ridge push, or vertically integrated deviatoric stress magnitude, which is ~3 × 10^{12} N/m (Richardson, 1992; Harper, 1975; Lister; 1975; Parsons and Richter, 1980), is not sufficient to satisfy inferred stress magnitudes of 6–7 × 10^{12} N/m that result from GPE differences between the Tibetan Plateau and the surrounding lowlands (Molnar and Lyon-Caen, 1988). An additional force is required to explain the disparity between the excess GPE of Tibet relative to that of the mid-oceanic ridges.

Lithospheric density variations associated with the support of the high topography of the Tibetan Plateau give rise to lithospheric body forces and hence stresses. Although the sources of stress that drive plate motions have been ascribed to many parameters (Forsyth and Uyeda, 1975), from the point of view of stress continuity and force balance, the stresses that drive lithospheric motion arise from two sources: (1) gravity acting on density variations within the lithospheric shell on Earth, and (2) gravity acting on density variations deeper than the lithospheric shell. The latter gives rise to tractions (radial and tangential) that act on the base of the lithosphere, affecting the stress field of the lithosphere and producing dynamic topography. The former involves density variations associated with support of nondynamic components of topography. The goal of this paper is to quantify the first of these in order to understand the role of density buoyancy variations within the lithosphere in driving India into Eurasia. This is important because such a calculation of the role of lithospheric sources calibrates

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the magnitude of a density buoyancy driven flow below the lithosphere. Moreover, if ridge push is the only driving force for India's motion, then the distribution of stresses associated with the high GPE of Tibet together with the GPE of ridges and surrounding ocean basins should explain the entire lithospheric stress field across Tibet and surrounding collision zone (Zoback, 1992).

METHODS

Plate tectonics enables us to approximate the upper 100–125 km of Earth as a thin shell. A thin sheet approach has been used by many previous authors (England and McKenzie, 1982; England and Houseman, 1986; England and Molnar, 1997; Lithgow-Bertelloni and Guynn, 2004) to solve for the stresses associated with internal horizontal density variations within this thin shell (e.g., crustal thickness contrasts, elevation differences, cooling of oceanic lithosphere). We also take the thin sheet approach to solve for the stresses associated with density variations intrinsic to the lithosphere. In order to avoid boundary condition problems, we compute stress response for the entire Earth's surface using a global grid of 2.5×2.5 degrees resolution. We incorporate weak plate boundaries by assigning relative viscosities to plate boundary zones. These viscosities are inversely proportional to the rate of strain (Kreemer et al., 2003). We make the plates two orders of magnitude higher viscosity than that of a mid-oceanic ridge with a moderate spreading rate (e.g., the Indian Ocean). A model with three orders of magnitude strength contrast between plates and plate boundary zones was also investigated (see GSA Data Repository[1]).

We use a finite element method to solve the three-dimensional (3-D) force balance equations for vertically integrated deviatoric stress for the spherical case. The deviatoric stress field solution is the mathematically unique solution that balances the body force distribution (GPE differences) and provides a global minimum in the second invariant of stress (Flesh et al., 2001). For this methodology, the magnitudes of deviatoric stresses depend on the magnitudes of the body force distributions and relative viscosity contrasts; the deviatoric stress magnitudes are independent of absolute magnitudes of viscosity. We calculate the vertically integrated vertical stress ($\bar{\sigma}_{zz}$), which is the negative of GPE per unit area, as:

$$\bar{\sigma}_{zz} = -\int_{-h}^{L}\left[\int_{-h}^{z}\rho(z')g\;dz'\right]dz = -\int_{-h}^{L}(L - z)\rho(z)g\;dz \qquad (1)$$

(Jones et al., 1996), where $\rho(z)$ is the density, L is the depth to the base of the thin sheet taken to be 100 km, h is the topographic elevation, and g is acceleration due to gravity. We calculate GPE using the Crust 2.0 data set (Laske et al., 2001). We neglect the basal traction terms in the force balance equations in order to quantify only the contributions to deviatoric stresses that are intrinsic to the lithosphere. Because radial tractions applied to the base of the lithosphere affect topography, they also influence GPE. We have therefore calculated GPE distributions and associated stress field solutions for a compensated model (uniform pressure at the base of lithosphere) (see footnote 1). The conclusions drawn for the Indian plate are the same whether or not the model is compensated. However, the uncompensated model provides deviatoric stress magnitudes that are everywhere 10%–20% higher than for the compensated model (see footnote 1). Cooling of the oceanic lithosphere is introduced by incorporating the plate model into our calculation (based on ocean-floor age data from Müller et al., 1997) using the revised parameters given by Stein and Stein (1992).

[1]GSA Data Repository item 2006063, supplemental data, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

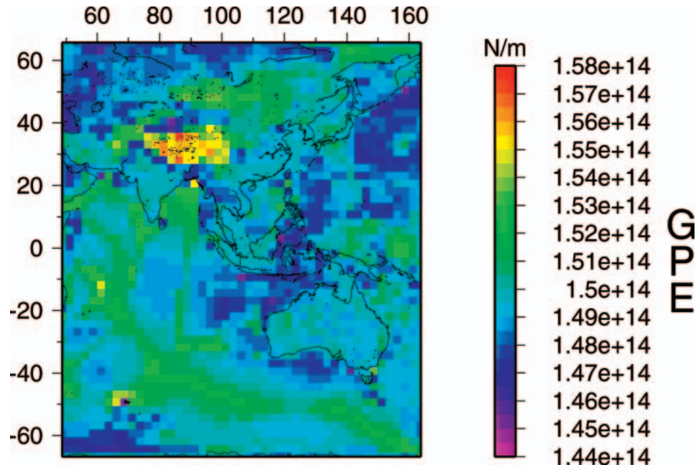

Figure 1. Gravitational potential energy (GPE) distribution for Indian and Eurasian plates. Topographically high areas like Tibet and mid-oceanic ridges have higher GPE than other areas.

RESULTS

The force balance associated with the global GPE distribution (Fig. 1) yields deviatoric extension along the mid-oceanic ridges and compressional deviatoric stresses in lower elevation regions of the oceans as well as the continents (Fig. 2). For the compensated model, the vertically integrated stress field in the Indian plate is dominated by NE-SW deviatoric compression of $\sim 2.5–3 \times 10^{12}$ N/m close to the collisional boundary. However, these compressional stresses decrease in magnitude farther south. The magnitude of stresses associated with GPE differences between Tibet and low-elevation regions in our compensated model is $\sim 2.5 \times 10^{12}$ N/m, while the mid-oceanic ridges exert a force of only $\sim 1 \times 10^{12}$ N/m. Moreover, our results show a predominant N-S deviatoric extension at the Tibetan Plateau, in addition to a much lower E-W deviatoric extension, in contrast to active faulting patterns that allow only for E-W extension. Our results for the Indo-Australian plate are in agreement with the SH_{max} directions of the World Stress Map (Zoback, 1992) and those derived by Sandiford et al. (1995).

DISCUSSION AND CONCLUSION

Our results indicate that the vertically integrated deviatoric stresses associated with elevated ridge and cooling of the lithosphere ($\sim 1 \times 10^{12}$ N/m) are not sufficient to cancel the large N-S extensional deviatoric stresses ($\sim 2.5 \times 10^{12}$ N/m) associated with the large GPE contrasts of Tibet and the surrounding regions. It is clear that something is missing as a driving force that does not have its source within the lithospheric shell. For example, substantial focusing of the ridge-push torque along the northern collisional boundary (Coblentz et al., 1998; Sandiford et al., 1995) has been proposed to support the ridge-push theory as the sole mechanism for driving the Indian plate. However, our results show that such focusing, while important for defining stresses within the Indo-Australian plate, is not enough to cancel out the N-S deviatoric extension in Tibet. Sandiford et al. (1995) suggested that the excess potential energy of the plateau at ~4 km elevation (England and Molnar, 1991) provides the right magnitude of the potential energy that can be supported by the ridge-push force, as there is a transition from reverse to normal faulting at that elevation. However, the normal faulting observed at an elevation higher than ~4 km involves E-W extension (Molnar et al., 1993), whereas our calculations demonstrate that a N-S extension would be expected if GPE is the only source of deviatoric stress operating on the lithosphere. Therefore, an additional long-wavelength N-S compressive stress of $\sim 2–3 \times 10^{12}$ N/m is required in our model to cancel out these N-S extensional de-

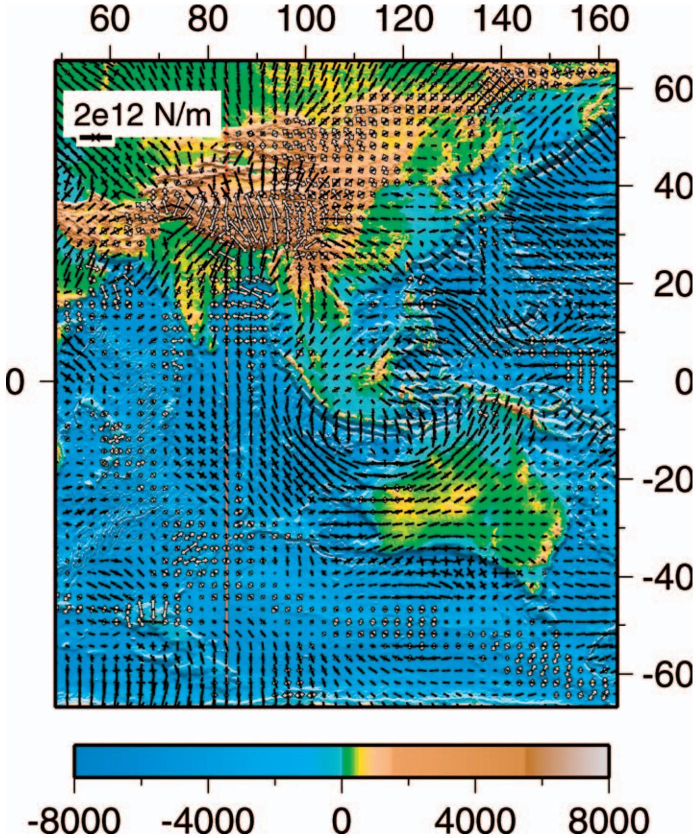

Figure 2. Distribution of vertically integrated horizontal deviatoric stresses for Indian and Eurasian plates. Extensional stresses are shown by white arrows and compressional stresses are shown by black arrows. Lengths of arrows are proportional to magnitudes of deviatoric stresses. Strike-slip regions are indicated by one tensional and one compressional pair of arrows. Areas having high gravitational potential energy (GPE) are in deviatoric extension, like Tibet and mid-oceanic ridges, and those having low GPE are in deviatoric compression, like rest of oceans. Plate boundaries are assigned variable viscosities depending on their relative strengths, inferred to be inversely proportional to strain rate (Kreemer et al., 2003). Reference viscosity of 0.01 is used for moderately spreading mid–Indian Ocean ridges; plates have viscosity of 1. Profile in Figure 3 is taken along N-S extending red line. Topography is in meters.

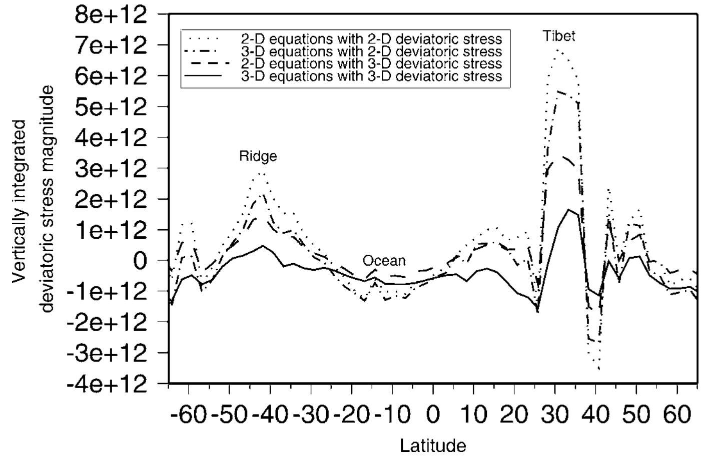

Figure 3. Comparison of different methods of solving force balance equations along N-S profile through 83.75°E. Axes (x-y) show vertically integrated deviatoric stress magnitudes projected along y-axis ($\bar{\tau}_{yy}$) and latitude, respectively. Solid line indicates our results. Reference gravitational potential energy (GPE) equal to GPE at sea level has been subtracted from actual GPE values. 2-D, 3-D—two dimensional, three dimensional, respectively.

viatoric stresses in Tibet (leaving only E-W extension) (Flesch et al., 2001).

The most compatible driving mechanism that would explain such a long wavelength compressional intraplate stress field distribution is the driving shear tractions associated with coupling of density buoyancy driven flow (e.g., Lithgow-Bertelloni and Guynn, 2004). These tractions arise due to the 'slab suction' force induced by the surrounding mantle on the base of the surface plate (Conrad et al., 2004). The contribution to lithospheric stresses associated with these shear tractions inferred from self-consistent mantle circulation models can be added to the deviatoric stress field shown in Figure 2 to obtain the full stress field solution. Therefore, one important result in our study is the absolute magnitudes of deviatoric stresses associated with GPE differences (Fig. 2) because they calibrate the magnitudes of deviatoric stresses ($\sim$2–3 $\times$ 10^{12} N/m) associated with the driving tractions applied to the base of the lithosphere in the Indian plate region. The density buoyancy distribution responsible for these driving tractions is most likely related to the long history of subduction of the Indian and Australian plates (Lithgow-Bertelloni and Richards, 1995; Wen and Anderson, 1997).

Our calculations show vertically integrated deviatoric stress magnitudes a factor of two lower than that proposed by Molnar and Lyon-Caen (1988) and Molnar et al. (1993) for Tibet as well as for the mid-oceanic ridges (Richardson, 1992; Harper, 1975; Lister, 1975; Parsons and Richter, 1980). We argue that deviatoric stress magnitudes resulting from ridge GPE as well as those calculated at the Tibetan Plateau have previously been overestimated. Previous overestimates arise from two factors: (1) a two-dimensional (2-D) approximation of the thin sheet equations, applied along a single profile, and/or (2) a 2-D definition of deviatoric stress, as opposed to a 3-D one (Dalmayrac and Molnar, 1981; Molnar and Lyon-Caen, 1988). A 2-D definition of deviatoric stress, $\tau_{ij} = \sigma_{ij} - \sigma_{zz}\delta_{ij}$, as opposed to a 3-D one, $\tau_{ij} = \sigma_{ij} - 1/3\ \sigma_{kk}\ \delta_{ij}$, replaces the 3-D constraint $\bar{\tau}_{xx} + \bar{\tau}_{yy} + \bar{\tau}_{zz} = 0$ with the constraint $\bar{\tau}_{zz} = 0$ (Flesch et al., 2001). As pointed out by Engelder (1994), in the 2-D definition the lithostatic stress, σ_{zz}, is set equal to the mean stress, $1/3\sigma_{kk}$. This is entirely a special case, unlikely to apply in many regions. The relationship between the 2-D and the 3-D stresses is given by:

$$\bar{\tau}_{xx}^{2\text{-D}} = 2\bar{\tau}_{xx}^{3\text{-D}} + \bar{\tau}_{yy}^{3\text{-D}}, \tag{2}$$

$$\bar{\tau}_{yy}^{2\text{-D}} = 2\bar{\tau}_{yy}^{3\text{-D}} + \bar{\tau}_{xx}^{3\text{-D}}, \quad \text{and} \tag{3}$$

$$\bar{\tau}_{xy}^{2\text{-D}} = \bar{\tau}_{xy}^{3\text{-D}}, \tag{4}$$

where the bars indicate depth integration over the entire plate thickness. We use horizontal deviatoric stresses projected along a N-S profile ($\bar{\tau}_{yy}$) of 83.75°E to demonstrate how the different ways of solving the force balance equations as well as the use of different definitions of deviatoric stress have led to different results, and possible misunderstandings, for deviatoric stress magnitudes (Fig. 3). This profile is chosen because it passes through the Tibetan Plateau, the deeper Indian Ocean, and the mid-oceanic ridge. The largest estimates of deviatoric stresses arise from solving simplified 2-D thin sheet equations, applied along a single profile, along with the use of the 2-D definition of deviatoric stress. As such, the horizontal force balance equations reduce to $\partial\sigma_{yy}/\partial y = 0$, which gives $\bar{\tau}_{yy} = -\bar{\sigma}_{zz} +$ a constant C, as a solution to the force balance equation. With a 2-D definition of deviatoric stress, vertically integrated deviatoric stress magnitudes are 6–7 $\times$ 10^{12} N/m for the Tibetan Plateau and 3–4 $\times$ 10^{12} N/m for the mid-oceanic ridge (dotted line in Fig. 3), which were predicted by Molnar and Lyon-Caen (1988). Use of the 3-D definition of deviatoric stress reduces these stress magnitudes by half (dashed line in Fig. 3), as predicted by equation 3. If the full 3-D thin sheet equations for vertically integrated deviatoric stresses are solved, but the 2-D definition of deviatoric stress is used, stress magnitudes (dash-dot line, Fig. 3) are slightly lower than the solution computed for a single profile (with the 2-D definition of deviatoric stress) because some of the potential energy differences are absorbed into other nonzero terms ($\bar{\tau}_{xx}$, $\bar{\tau}_{xy}$). The smallest magnitudes are obtained for solutions to 3-D force balance with 3-D definition of deviatoric stress (solid line in Fig. 3) because differences in GPE are absorbed not only into all of the horizontal terms, but $\bar{\tau}_{zz}$ as well.

Our calibration of the vertically integrated deviatoric stress magnitudes and directions associated with GPE variations has other implications. Molnar et al. (1993) argued that the rapid uplift of Tibet ca. 10–11 Ma resulted in an increased GPE of Tibet that produced increased compressional stresses in the Indian Ocean ($\sim 8 \times 10^{12}$ N/m), which was hypothesized to be sufficient to buckle the lithosphere there. These estimates are based on a 2-D approximation of the thin sheet equations, applied along a single profile, with the 2-D definition of deviatoric stress. We show here that deviatoric stresses associated with GPE differences between the elevated ridges, the deeper Indian Ocean, and the elevated Tibetan Plateau are much lower than predicted by Molnar et al. (1993), suggesting that the uplift of Tibet is unlikely to be the single factor for the onset of folding and reverse faulting that is occurring in the Indian Ocean.

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