

# An Appraisal of the Plate Tectonic Forces: Role of Gravitational Potential Energy (GPE) in the Deformation of Indo-Eurasian Collision Zone

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## ABSTRACT

Concording with the plate tectonic theory, lithosphere consists of several tectonic plates moving in different directions and stimulating various tectonic processes and consequencing mountains, earthquakes, volcanoes, mid-oceanic ridges and oceanic trenches. It is excogitated that three main plate tectonics driving forces viz. ridge push, slab pull and trench suction together with resistance force viz. collisional resistance, basal drag etc. maneuvering deformation in Indo-Eurasian collision region. But these forces acting in tandem are not sufficient in explaining the discrepancies in regional surficial lithospheric deformation pattern explicitly. Hence, we invoke Gravitation Potential Energy (GPE) derived deviatoric stress in explaining the deformation pattern of Indo-Eurasian collision region. We also provide explanation for the occurrence of  $M_w$  7.3 aftershock following the 2015  $M_w$  7.9 Nepal earthquake construing the GPE as an important proxy to the deviatoric stress field.

**Key words:** Tectonic forces, Topography, GPE, Indo-Eurasian, Himalaya, deformation.

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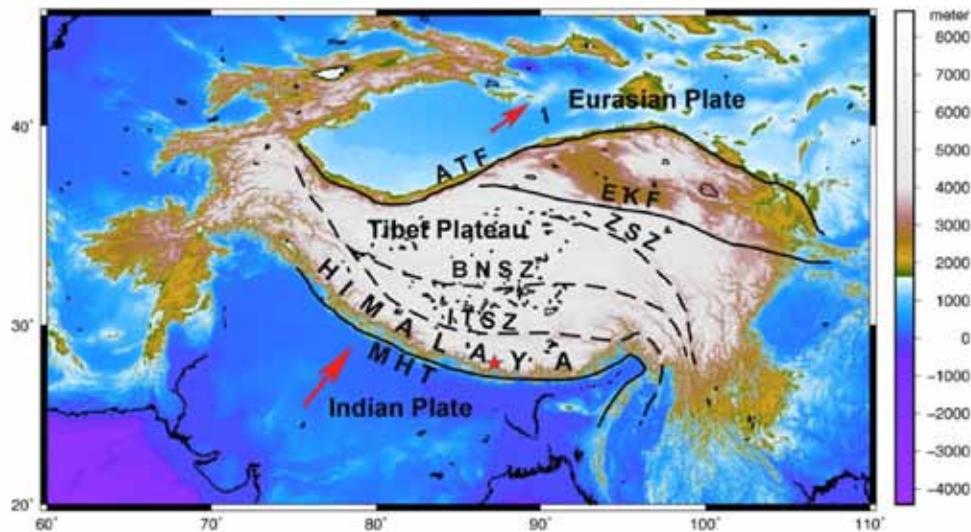
## INTRODUCTION

Wegener, (1912), by compiling and analyzing large amount of data from various disciplines (viz. fossil, meteorological similarities in the America, Africa and parts of Northern Europe), proposed the theory of continental drift. He had surmised that the continental drift was powered by the centripetal force pertinent to rotation of the earth. However, it was soon realized that this force was too small to drive the continental movement. Later on, it was suggested that the driving mechanism for these plate motions is linked to mantle convection, i.e. convective motion in the asthenosphere that exert a drag to the over lying lithosphere there by driving plate motion, and mantle convection in turn is powered by the heat in the interior of the earth generated by radioactive decay (Holmes, 1928). During 1950s and 1960s, new geological and geophysical techniques viz. radiometric dating, bathymetric mapping of the seafloor produced a wealth of new data, which led to the development of the theory of plate tectonics (tectonic is derived from  $\tau\epsilon\chi\tau\omicron\nu\kappa\eta$ , which designated in ancient Greek the art of building) (e.g. Dietz, 1961; Hess, 1962). As per the plate tectonic theory, the earth's outer shell called lithosphere consists of several plates moving in different directions and stimulating various tectonic processes, manifesting as earthquakes, mountain building etc., and providing explanations for various geological observations. The theory of plate tectonics revolutionized the perception of

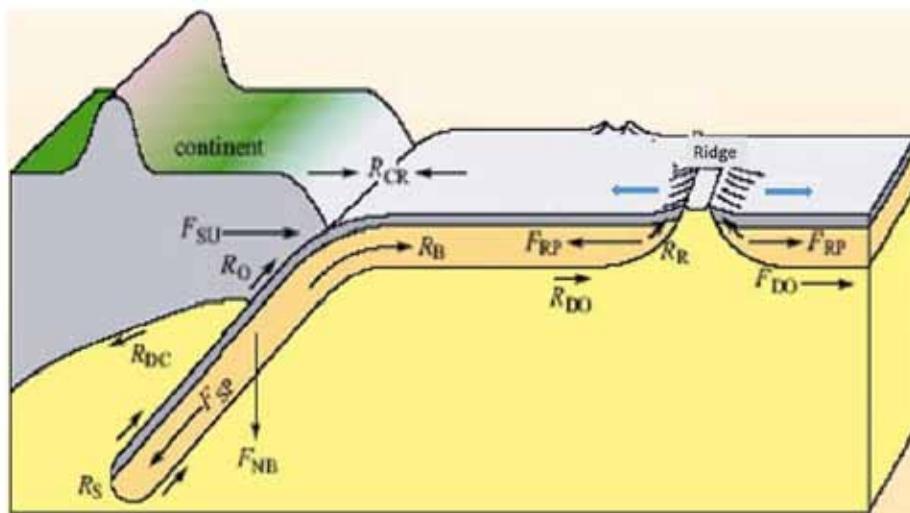
geophysicists and geologists on the geodynamics of the earth. It should be noted that like any scientific theory, the theory of plate tectonics has its own limitations and cannot account for all the observable facts.

What forces drive the plates remain enigmatic and one of the intriguing problems in the theory of plate tectonics. Though, it is proposed that mantle convection drives movement in the interior but is not the major driving mechanism to move the plates. Forsyth and Uyeda, (1975), Solomon et al., (1975) and Chapple and Tullis, (1977) proposed that the plates are driven by forces that are applied at plate boundaries. The main driving forces were thought to be the slab-pull force (Cloos, 1993), where the slabs would pull the trailing subducting plates to which they are attached towards the trench, and the ridge push force (Lister, 1975; Meijer and Wortel, 1992), where the plates on either side of a spreading ridge are pushed away from these ridges. A third force, the trench suction force, was also proposed, which resulted from slab sinking and would drive overriding plates towards the subduction zone (Lithgow-Bertelloni and Gynn, 2004). On the other hand, the main resisting forces are collision resistance, basal shear/ drag. As all these forces collectively are not able to explain the deformation pattern in Himalaya collision region, it is proposed that the GPE (Bucher, 1956; England and Molnar, 2005; Flesch et al., 2001) induced force arising due to lateral density variations along with the topography playing significant role. All these aspects are discussed in the context of Indian subcontinent/ Himalaya regions.

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**Figure 1.** Indo-Eurasian collision and adjacent regions with important tectonic features superposed on topography. The red star indicates Mount Everest.



**Figure 2.** Forces acting upon a plate.  $F$  denotes a driving force, whereas  $R$  denotes a resisting force (Bott, 1982). Ridge push ( $F_{RP}$ ), Slab pull ( $F_{SP}$ ), Negative Buoyant force, ( $F_{NB}$ ), Collisional Resistance ( $F_{CR}$ ), Bending Resistance ( $R_B$ ), Slab Resistance ( $R_S$ ), Over riding place Resistance ( $R_O$ ), Ridge Resistance ( $R_R$ ), Trench Suction ( $F_{SU}$ ), Basal Drag ( $R_{DO}$ ).

### Tectonic Forces

Theory of plate tectonics revolutionized our understanding of earth science, in particular provided a unified explanation for the processes of earthquakes, volcanoes, and mountain building. The forces capable of deforming the lithosphere have three possible sources: (i) mantle convection, (ii) plate tectonic processes, and (iii) lateral variations in GPE.

**Mantle convection:** In the mantle convection process, the tectonics plates are driven by the internal heat energy within the earth. This comprises the heat left over from the initial formation of the earth and heat from the radioactive decay of the minerals inside the earth. Heat from the earth's lower mantle rises as plumes towards the upper mantle

where cooling occurs. The plumes spread out, then sink back into the interior, known as **mantle convection**. These convection currents seem to propel the motion of plates.

**Plate tectonic processes:** Plate tectonic processes are responsible for most geographical and geological features of the earth, in particular, those that are associated with natural hazards such as volcanoes and seismic zones. The tectonic forces arising from various tectonic processes (as discussed below) can be further divided as plate driving forces (e.g. ridge push, slab pull, slab suction, plume push) and plate resistance forces (e.g. collisional resistance, basal drag). These aspects are explained below in detail.

**GPE:** Potential Gravity Theory (PGT) studies show that surface topography and lateral variations in crustal

thickness and composition may lead to significant gravity-induced horizontal stresses (e.g., England and Molnar, 2005; Flesch et al., 2001). Pressure variations associated with topography and Moho undulations may reach 10–75 MPa (e.g. 1000 m of local topography or 5000 m of Moho depression produce 20–30 MPa pressure difference) (Tesauro et al., 2011). Stress changes associated with surface elevation as well as sub-surface density distribution are referred to as topographic deviatoric stress or more simply the GPE (Bucher, 1956). The gravitational collapse leads to reduction of lateral differences in GPE causing the neighboring lithospheric columns to undergo compression or extension (e.g., Artyushkov, 1973; Fleitout and Froidevaux, 1982). Thus, the variation in GPE is an important proxy to the deviatoric stress field and is estimated in Himalaya collision region (Figure 1).

### Plate Driving Forces

Stress field in Indo-Eurasian collision region is sensitive to various tectonic forces, boundary conditions, geophysical parameters and lithospheric rheology. In particular, the driving mechanism for the Indian plate has been a source of controversy since the advent of the plate tectonics theory (Ghosh et al., 2006). Below, we address some of the major tectonic (plate driving and resistive) forces that are operative in Indian subcontinent and Himalaya region. Figure 2 gives all these forces. It should be noted that plate tectonics is a thermodynamic engine and can be calculated as such (Swedan, 2015).

### Ridge Push

Ridge push results from the elevated position of the oceanic ridge, which causes slabs of lithosphere to slide down the flanks of ridge and acts perpendicular to the ridge axis. Here, we address the ridge push force  $F_{RP}$  acting along the Central Indian ridge between the borders of Somalia and Indian plate. The expression for the ridge push is given by the relation (Turcotte and Schubert, 2002) as

$$F_{RP} = \rho_m g \alpha_v (T_m - T_o) \left[ 1 + \frac{2\rho\alpha(T_m - T_o)}{\pi(\rho_m - \rho_w)} \right]$$

where  $\rho_m$  is density of the mantle (3300 kg/m<sup>3</sup>),  $g$  is the acceleration due to gravity (9.8 m/s<sup>2</sup>),  $\alpha_v$  is the thermal expansion coefficient ( $3 \times 10^{-5}$  /K),  $(T_m - T_o)$ , the temperature difference between mantle and surface (1200 K),  $\rho_w$  is the density of water (1000 kg/m<sup>3</sup>), thermal diffusivity ( $kd$ ) can be taken as 1 mm<sup>2</sup>/s and  $t$  is the age of lithosphere in seconds. The magnitude of this force is calculated based on the mean age of 20 Ma for this oceanic lithosphere. This force is applied as pressure of magnitude  $7.5 \times 10^{12}$  N/m distributed along the entire oceanic lithosphere and acts normal to the strike of the ridge.

### Slab Pull

The slab-pull force results from the negative buoyancy of the subducting slab compared with the surrounding sub-lithospheric mantle. Slabs are negatively buoyant due to their higher average density compared to the ambient mantle (~80 kg/m<sup>3</sup> for 80 Ma oceanic lithosphere; Cloos, 1993) and hence sink like a rock. As these slabs sink into the asthenosphere, they pull the trailing plate along. The slab pull force is proportional to the excess mass of the cold slab in relation to the mass of the warmer displaced mantle. The force contribution can be given by the relationship (Turcotte and Schubert, 2002):

$$F_{SP} = \left( 2\rho_m g \alpha_v b (T_c - T_o) \left( \frac{\kappa \lambda}{2\pi u_o} \right)^{\frac{1}{2}} \right) + \left( \frac{2(T_c - T_o) \gamma \Delta\rho_{os}}{\rho_m} \left( \frac{\kappa \lambda}{2\pi u_o} \right)^{\frac{1}{2}} \right)$$

where  $b$  = slab length,  $\lambda$  = 4000 km,  $u_o$  = 50 mm/yr,  $\gamma$  = 4 MPa/K, and  $\Delta\rho_{os}$  = 270 kg/m<sup>3</sup>, with the remaining parameters identical to those in the equation used for ridge push. For example, a 700 km long, 100 km thick 80 Ma slab (with density contrast  $\Delta\rho$  = 80 kg/m<sup>3</sup>) has a negative buoyancy force of  $5.5 \times 10^{13}$  N per meter trench length. However, most of the negative buoyancy is thought to be absorbed by shear forces and slab-normal forces in the mantle resisting subduction and sinking of the slab (Forsyth and Uyeda, 1975).

For fast moving plates (5–10 cm/yr) the subducting slab attains a ‘terminal velocity’ where forces related to the negative buoyancy of the slab are balanced by viscous drag forces acting on the slab as it enters the mantle and the net force experienced by the horizontal plate is quite small (Forsyth and Uyeda, 1975). The amount of net force actually transferred to the horizontal plate, however, is still quite controversial. Schellart, (2004) suggests that as little as 8%–12% of slab pull force is transferred to the horizontal plate while Conrad and Lithgow-Bertelloni, (2002) suggest that as much as 70%–100% may be transmitted.

### Slab Suction

Slab pull occurs when detached slabs that descend into the mantle, excite viscous flow that might exert traction on the base of the lithosphere, thereby sucking plates along. Attached slabs also create suction. Slab suction forces are one of the major plate tectonic driving forces. This driving force is important when the slabs (or portions thereof) are not strongly attached to the rest of their respective tectonic plates. They cause both the subducting and overriding plate to move in the direction of the subduction zone.

Slab suction is the weakest of the three major forces involved in plate motion, the others being slab pull (the strongest) and ridge push (Conrad and Lithgow-Bertelloni, 2002). They further suggest that slab-pull forces account

for around half of the driving force of plate tectonics, with a nearly equal contribution from subduction suction induced by subducting slabs. However, both attached and detached portions of lithosphere that descend beneath the 660 km deep mantle transition zone probably do not transmit stresses into higher-level slabs, and only their suction effect adds to plate motions.

### Plume Push

Plume push force is pertinent to non-tectonic plumes. Plume rises through the mantle from well beneath the lithosphere, and consequently, logically can expect a vertically upwards force, while the ridge push, slab pull, slab suction cause horizontal movement of the plates. Based on modeling of the geophysical data from the Indian Ocean, Müller, (2011) suggested that a mantle-plume head might have coupled the motions of the Indian and African tectonic plates, and determined their velocities. While the Indian plate was accelerated, African plate was slowed, which is explained by a push exerted in the same direction of Indian plate motion (i.e. in NE direction) while it opposed the African plate motion moving in same direction. Thus, it became clear that the motion of the Indian and African plates were synchronized and the Réunion hotspot was the common source of force.

The enigmatic question is how did a mantle plume exert such a force ?. It may be (i) because plume push caused a local bulge from which the plates slid, or (ii) the mantle motion associated with the mushroom-like structure of the horizontally growing plume head might exert viscous drag on the overlying plates (Müller, 2011). Cande and Stegman, (2011) further provided the evidence that such mantle plume "hot spots", which can last for tens of millions of years and are active today at locations such as Hawaii, Iceland and the Galapagos, may work as an additional tectonic driver, along with ridge push and slab pull forces.

### Plate Resistance Forces

#### Collisional Resistance

Collisional resistance arises when a plate collides with another plate boundary (as is the case with Indian and Eurasian plates). It directly resists all the driving forces associated with plate tectonics. It is observed that at the collision boundary along Himalayas, the Indian plate converges at an average rate of 50 mm/yr (Bilham et al., 1998). The resistance arising along the Himalayan plate boundary where the Indian plate converges under Eurasian is referred to as the continental collision force  $F_{cc}$ . Coblenz et al., (1998) estimated a force of  $2 \times 10^{12}$  N/m for the Himalayas and hence applied as pressure along this boundary. In spite of high velocities, the collision

forces in Himalayas are lower than the slab pull force in the subduction zone.

#### Basal Shear/ Drag Force

Basal shear stresses, the second major class of stresses are those applied at the base of the lithosphere. The drag force operates on almost all parts of a moving lithospheric plate. This force was initially considered to be the main reason why Wegner's theory of continental drift was discarded, i.e. the forces required to force a continent around the globe was simply too large. As seen, this is not true considering the large shear zone created by the asthenosphere that allows lithospheric plates to slide around the earth. However, the basal drag force still acts to resist plate motion at the interface between the lithosphere and upper mantle.

Among all the above driving forces, it is observed that only ridge push is a numerically well-known force that depends on the age of the lithosphere. However, the estimates of slab pull and collision forces are subjected to large number of uncertainties in the subduction zones (Scholz and Campos, 1995).

### Theoretic Background of GPE and Deviatoric Stress

Lithosphere is considered to be composed of the elastic part of the crust and the viscous part of the upper mantle. Here we consider the entire lithosphere as a fluid, which is floating on the asthenosphere and obeying Navier-Stokes equation, which is consequence of Newton's second law of motion.

$$\rho \frac{Dv}{Dt} = -\nabla p + \nabla T + f$$

where  $\frac{D}{Dt} = \frac{d}{dt} + v \cdot \nabla$ ,  $p$  is the pressure,  $T$  is the stress tensor,  $f = \rho g$  is the downward force per unit volume and  $v$  is the flow velocity.

Assuming a specific viscous rheology and steady state, the above equation can be re-written as

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g \hat{z}_i = 0 \quad (1)$$

where  $\hat{z}_i$  is the unit vector in vertical direction,  $\sigma_{ij}$  is the total stress and  $x_j$  is the  $j^{th}$  coordinate direction. In the above equation summation notation is used, where  $i$  is given values of  $x$ ,  $y$ , and  $z$  and the repeated index  $j$  is used to represent the summation over  $x$ ,  $y$ , and  $z$ .

Equation (1) can take the form

$$\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \sigma_{xx}}{\partial x} - \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0 \quad 2(i)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{xx}}{\partial y} + \frac{\partial \tau_{yy}}{\partial y} - \frac{\partial \tau_{xx}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0 \quad 2(ii)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = -\rho g \quad 2(iii)$$

If the horizontal gradients in shear traction  $\tau_{xy}$  and  $\tau_{yz}$  are small compared to  $\rho g$  i.e.

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} \ll \rho g$$

then above equation can be expressed as

$$\sigma_{zz}(z) = - \int_{-h}^z \rho(z') dz' \quad (3)$$

The vertically averaged equations 2(i) and 2(ii) from the surface at  $z = -h$  to the base of the lithosphere at uniform depth  $z = L$ , where  $h$  is the surface elevation and  $L$  is the base of the lithosphere

$$\frac{\partial \overline{\tau_{xx}}}{\partial x} - \frac{\partial \overline{\tau_{zz}}}{\partial x} + \frac{\partial \overline{\tau_{xy}}}{\partial y} = - \frac{\partial \overline{\sigma_{zz}}}{\partial x} - \frac{1}{L} \tau_{xz}(L)$$

$$\frac{\partial \overline{\tau_{xy}}}{\partial x} - \frac{\partial \overline{\tau_{zz}}}{\partial y} + \frac{\partial \overline{\tau_{yz}}}{\partial y} = - \frac{\partial \overline{\sigma_{zz}}}{\partial y} - \frac{1}{L} \tau_{yz}(L)$$

where  $\tau_{xz}(L)$  and  $\tau_{yz}(L)$  are the traction applied to the base of the lithosphere that fall out the vertical integrals ( $\tau_{xz}(-h)$  and  $\tau_{yz}(-h)$  are zero).

The vertically averaged stresses  $\overline{\tau_{ij}}$  and  $\overline{\sigma_{zz}}$  obtained by dividing the corresponding depth integrals by reference lithosphere thickness  $L$  are defined as

$$\overline{\tau_{ij}} = \frac{1}{L} \int_{-h}^L \tau_{ij} dz \quad (4)$$

$$\overline{\sigma_{zz}} = - \frac{1}{L} \int_{-h}^L (L-z) \rho(z) g dz \quad (5)$$

The vertically averaged vertical stress defined in equation (5) is equivalent to  $1/L$  times the GPE per unit area defined by the reference level at the base of the lithosphere at depth  $L$ . The GPE per unit area of a column of material  $U$  above a given depth  $z$  is given by the integral of the vertical stress  $\sigma_{zz}$  from the  $L$  to the surface  $h$  (Molnar and Lyon-Caen, 1988)

$$U = \int_h^L \sigma_{zz}(z') dz' = \frac{g}{L} \int_h^L dz' \int_h^{z'} \rho(z') dz' \quad (6)$$

where  $\rho(z)$  is the density,  $L$  is the depth of the lithosphere,  $h$  is the topography elevation and  $g$  is the acceleration due to gravity. The horizontal stresses can be directly related to the vertical density distribution (Dahlen, 1981).

$$\sigma_{xx} = \frac{g}{L} \int_h^L \Delta \rho(z) dz \quad (7)$$

where  $\sigma_{xx}$  is the horizontal stresses averaged over the thickness of the lithosphere, relative to a reference state against which the  $\Delta \rho$  is measured. Using the definition of GPE in equation (6) the horizontal stress can be expressed in terms of the potential energies

$$\sigma_{xx} = \frac{\Delta U}{L} \quad (8)$$

where  $\Delta U$  is the difference between the potential energy of the lithosphere column  $U_l$  and the potential energy of some others reference column  $U_r$

$$\Delta U = U_l - U_r \quad (9)$$

### Estimation of GPE for Indo-Eurasian Collision Region

Himalayas, the most active seismo-tectonic collision orogeny belt in the world, resulted from collision of the Indian plate  $\sim 50$  Ma ago and characterized by large mountain ranges. Schellart and Rawlinson, (2010) detail convergent plate margin dynamics from structural geology, geophysics and geodynamic modeling perspective. The deformation and stress field in Himalaya collision zone is difficult to explain using the plate boundary driving/resistive forces previously explained. Speculating that the GPE derived forces significantly affect the stress field/strain rate in the lithosphere (although other local stress sources may also be an important factor in explaining the observed stress field in this region), we attempted to estimate GPE in Himalaya collision region.

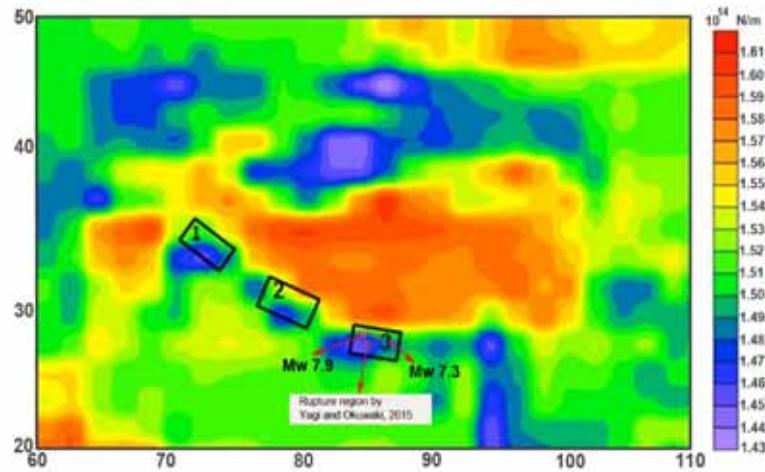
In this study, we considered the Indo-Eurasian collision region confined by  $60^\circ$ - $110^\circ$  E and  $20^\circ$ - $50^\circ$  N, the Mount Everest and Eastern Himalaya Syntaxis (EHS) with adjacent regions. Laterally heterogeneous lithosphere has been assigned a uniform thickness of 100 km, since beyond this depth there exists almost uniform density. The GPE difference is estimated considering satellite altimetry data ETOPO5 and crustal thickness model CRUST2.0 (Laske et al., 2001). The seismic crustal thickness considered here is more accurate representation of the GPE as it is constrained by seismic data set (Bassin et al., 2000; Mooney et al., 1998). Assuming constant crustal and mantle densities of  $2750 \text{ kg/m}^3$  and  $3300 \text{ kg/m}^3$  respectively and assuming the lithosphere to be in Airy isostatic compensation, we calculated GPE (Figure 3) and its associated deviatoric stress field at each grid point ( $5' \times 5'$  grid spacing) using the formulation described above. Thus estimated GPE and deviatoric stress distribution are shown in Figures 3 and 4 respectively.

### DISCUSSION

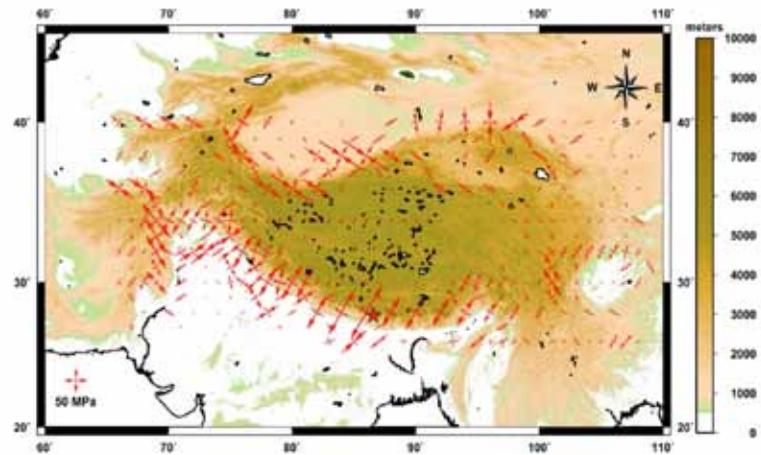
The acting forces on the lithospheric plate have three possible sources: (i) mantle convection, (ii) plate tectonic processes e.g. ridge push, slab pull, and (iii) lateral variations in GPE. The state of dynamic equilibrium of the plate can be mathematically defined as

$$\nabla \cdot \sigma + f = \rho \ddot{u} + c \dot{u} \quad (10)$$

where  $\sigma$  is the stress tensor and  $f$  denotes the body force,  $\rho$  is the density of the plate,  $c$  is the coefficient of damping,  $\ddot{u}$  and  $\dot{u}$  are the plate accelerations and velocities (Jayalakshmi and Raghukanth, 2017). In the equation (10), the terms on the RHS represent the forces due to inertia and damping. Presently, Indian plate decelerates



**Figure 3.** GPE per unit area distribution in the Himalaya collision and contiguous region. The rectangles 1,2 and 3 represent high GPE gradients in Indo-Gangetic Plains (IGP) (Shrivastava et al., 2013).



**Figure 4.** Vertically averaged horizontal deviatoric stresses derived from the GPE distribution shown in figure 3 superposed on the topography. The star indicates the location of the Mount Everest (Shrivastava et al., 2013).

at very slow rate of few millimeters per year (Harada and Hamano, 2000; Bowin, 2010), the first term on RHS can be neglected. The damping force is the resistance induced by the plate due to mantle drag force (shown in Figure 2), which is caused by the viscous couplings between the plate and the mantle beneath.

The total stress tensor at any point in the lithosphere can be considered to be composed of isotropic part and the anisotropic “deviatoric” part. The isotropic part of the stress tensor is an invariant quantity corresponding to the mean normal pressure of magnitudes of the order of 20-40 MPa averaged over a 100 km thick lithosphere (e.g. Batchelor, 1967; Jaeger, 1979; Coblenz et al., 1998), whereas an anisotropic “deviatoric” part is dynamic part causing deformation and changes in shape. The present study concerns estimation of “deviatoric” stresses within the lithosphere that are associated with GPE differences. It should be noted that the parts of lithosphere whose vertically-averaged strength exceeds the

stresses generated by gravity acting on density differences behave as rigid blocks, whereas weaker lithosphere deforms pervasively (Coblenz et al., 1998).

The deviatoric stresses associated with GPE in combination with plate boundary forces are the powerful tools to trace and explain the first order deformation patterns in active collision/subduction zones (Flesch et al., 2007; Liu et al., 2002; Ghosh et al., 2006; Fleschet et al., 2001). Though the Indo-Eurasian collision took place ~65–50 Ma ago, the convergence still continues. However, slab pull as the driving force may be minimal. Further, as the basal tractions discussed previously are not intrinsic to lithosphere, hence this component can also be ignored. Thus, the deviatoric stress pattern derived here from inversion of GPE fields calculated using topography and available knowledge of crustal structure and density variation should be sensitive pointer and thus could be used to trace present day pictures of deformation in Indo-

Eurasian collision zone. The estimated GPE values are found to vary in the range  $1.4 - 1.6 \times 10^{14}$  N/m, where the maximum value  $1.6 \times 10^{14}$  N/m corresponds to the Mount Everest ( $\sim 8850$  m high, see Figure 1). In the calculation of GPE stress in Indo-Eurasian collision region, we have not considered dynamic topography and some plate boundary forces. Nevertheless, it is interesting to note that the estimated deviatoric stresses are corroborated well with that of stress and strain rates obtained by inverting the focal mechanism solutions of large earthquakes and GPS derived plate motions. It should be noted that the GPS estimated strain rates are sensitive to near-surface deformation, whereas the GPE derived deviatoric stresses provide depth integrated value for the full thickness of the lithosphere (Hsu et al., 2009). This aspect is clearly observed in much smaller region i.e. in Shillong plateau region of EHS (Baruah et al., 2016). They noted that due to higher topography and density heterogeneities, the western edge of the Shillong plateau shows a dissimilar GPE variation with respect to that in the eastern edge. The strain rate measured by the GPS measurements has not shown any EW disparity in stress pattern.

Another interesting aspect of GPE derived stress pertains to 2015  $M_w$  7.9 Nepal earthquake. It is surmised that the large aftershock  $M_w$  7.3 on May 12, 2015 following the April 25, 2015 Nepal earthquake seems to have occurred due to imploding stress due to very high topography of the Mount Everest. It should be noted that, as a balancing act, the GPE produced stress is countered by the stress in the adjoining region. In the event of this stress being weakened by the after shock activity as is the case consequent to  $M_w$  7.9 earthquake, the imploding stress field can bring the fault regions that are critically stressed, to rupture. This may be the reason why  $M_w$  7.3 after shock occurred at the outer periphery of the after shock clustered region (Shrivastava et al., 2017).

## CONCLUSIONS

In this study, we have provided description of various tectonic driving and resistance forces and GPE and deviatoric stress estimation. These tectonic forces are of the order: ridge push force  $7.5 \times 10^{12}$  N/m, slab pull  $5.5 \times 10^{13}$  N/m, collisional resistance  $2.1 \times 10^{12}$  N/m, GPE derived stress  $12 \times 10^{12}$  N/m<sup>2</sup>. We must note that these estimates are subjected to large number of uncertainties. These forces generate first-order stress fields inflicting lithospheric perturbations on the scales of more than 500 km, nevertheless, failing to explain the deformation in Himalaya collision region. The deviatoric stress field associated with GPE explicates this discrepancy, and explained satisfactorily (i) the stress distribution in Indo-Eurasian collision region, and (ii) the occurrence of  $M_w$  7.3 after shock following the 2015  $M_w$  7.9 Nepal earthquake.

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## Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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