J. Ind. Geophys. Union (July 2015)
v.19, no.3, pp:243-255

Thermo-mechanical structure of the Indian continental lithosphere

Ajay Manglik
CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad - 500007, INDIA
*Corresponding Author: ajay@ngri.res.in

ABSTRACT
Thermo-mechanical properties of the rocks constituting the lithosphere control the nature of lithospheric deformation at multi-scales. The oceanic lithosphere, being simple in terms of the crustal structure, composition, and the thermal structure, in general has a fairly well defined thermo-mechanical structure. Significant variations in the crustal thickness and composition, complex evolutionary history, and variations in the composition and viscosity of the mantle part of the lithosphere due to varying degree of depletion of incompatible elements lead to a very complex mechanical structure of the continental lithosphere. This paper presents a brief review of the modeling studies carried out to estimate the mechanical/ thermo-mechanical properties and structure of the Indian continental lithosphere. A synthesis of the results obtained by various approaches reveals two major inferences and the discrepancies in the estimates of the mechanical strength of the Indian continental lithosphere. First inference is that the Indian shield can be broadly sub-divided into the northern and the southern segments based on the mechanical strength of the lithosphere, with the Central Indian Tectonic Zone forming the contact between the two segments. Second inference is that there are variations in the mechanical strength of the northern Indian shield along the strike of the Himalayan collision belt. The observations of the lowest surface heat flow in the Archaean western Dharwar craton implying the thickest lithosphere in this region and the low effective elastic thickness for the southern shield obtained by the admittance and coherence analyses present an exciting paradoxical scenario having implications for the tectonic deformation of the Indian continental lithosphere in response to the plate boundary forces. An integration of the new geophysical images of the Indian continental lithosphere and thermo-mechanical modeling can help in resolving the discrepancy.

INTRODUCTION

The lithosphere, the outermost rigid broken shell of the Earth, participates in the geodynamical processes that shape the morphological features seen on the surface and controls natural hazards having origin internal to the planet such as those related to earthquakes and volcanoes. Here, the mechanical properties of the rocks constituting the lithosphere are very important as these determine the nature of lithospheric deformation either in the intraplate regions or at plate boundaries. A further complication is added by increasing pressure and temperature with depth within the lithosphere. Thus, the rocks have mechanical properties that depend on pressure, temperature, fluid content and interconnectivity of pores, and time-scale of deformation. The oceanic lithosphere, being simple in terms of the crustal structure, composition, and thermal structure has a fairly well behaved mechanical strength profile. The thickness of the mechanically strong oceanic lithosphere increases with age away from mid-oceanic ridges following the well-known √age relationship up to 80 million years of age. This is not true for the continental lithosphere. Significant variations in the crustal thickness and composition, complex evolutionary history, and even variations in the composition and viscosity of the mantle part of the lithosphere due to varying degree of depletion of incompatible elements (Carlson et al., 2005), lead to a very complex mechanical structure of the continental lithosphere.

A significant amount of work has been done globally to develop models of the mechanical strength of the continental lithosphere following different approaches such as constructing rheological profiles of lithosphere by extrapolating laboratory-scale deformation parameters to geological-scale models (Ranalli, 1995), forward modeling of flexural rigidity and admittance and coherence from gravity and topography data (Watts, 2001), post-glacial rebound, and post-seismic relaxation modeling. Here, I focus on the studies specifically carried out for the Indian continental lithosphere. Many of these studies focused on the Himalayan collision belt, this being one of the best examples of flexure of continental lithosphere. It is not an exhaustive review of all the work done on the Indian continental lithosphere but gives a glimpse of the kind of geophysical studies that have been carried out to estimate the thermo-mechanical structure and highlights the anomalies in the estimates of mechanical strength by various approaches. Information about the mechanical properties of the rocks can also be deciphered by geological studies, which are not discussed in this paper.

RHEOLOGICAL BRITTLE-DUCTILE STRUCTURE:

Both observational and modeling aspects have been pursued to delineate the rheological structure of the Indian shield. Geophysical observational aspects include identification of lower crustal reflectivity and dipping interfaces in deep

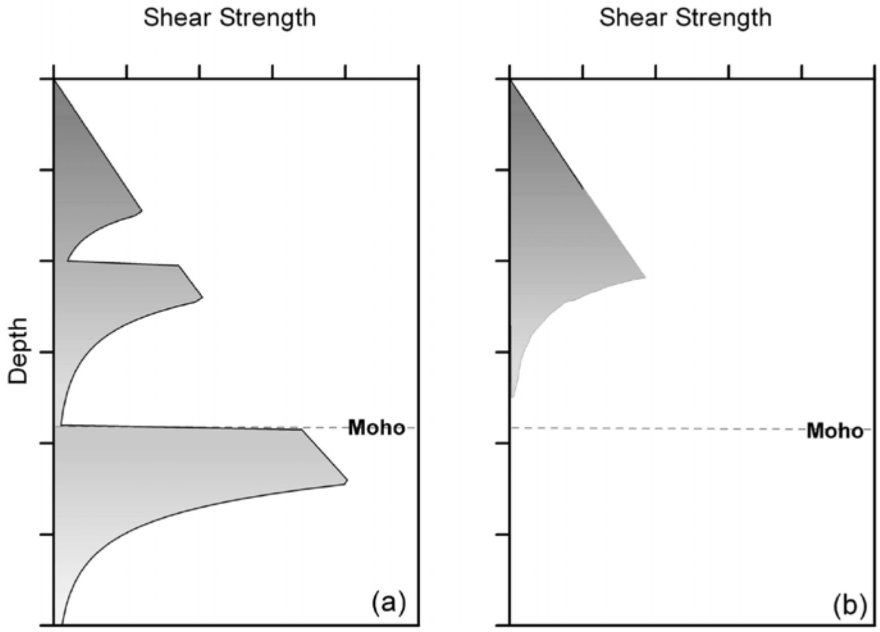

Figure 1A. Cartoon showing (a) jelly sandwich, and (b) crème-brûlée rheological models.

crustal seismic images of the Indian continental crust and distribution of focal depths of earthquakes as an indicator of brittle-ductile transition. Under modeling aspect, crustal and thermal structures of some regions were integrated with empirical rheological laws of representative rock types to construct layered brittle-ductile structure.

Observational Perspective:

Deep crustal seismic study along the Kavali-Udipi profile revealed a block-faulted structure (Kaila et al,1979) of the crust and dipping reflectors in the crust within most of the blocks. In contrast, the Moho reflector was delineated to be horizontal. Using this structural configuration Roy Chowdhury and Hargraves (1981) inferred that the Moho was at a probable temperature of 1000ºC, well above the olivine brittle-ductile transition temperature of about 750ºC, enabling ductile flow at the Moho level. Recently, Mandal et al. (2014) have applied the common reflection surface stack technique to the multifold deep seismic reflection data of the Nagaur - Jahazpur section of the Nagaur - Kunjer transect across the Aravalli-Delhi fold belt (Reddy et al., 1994; Tewari et al., 1997; Rajendra Prasad et al., 1998). They imaged the extension and the listric nature of the Jahazpur thrust at the Moho below the Sandmata complex as well as highly reflective nature of the lower crust beneath the Sandmata and Mangalwar complexes. The Moho marks the lower boundary of these sub-horizontal reflectors. The high reflectivity is an indicator of the ductile deformation during the evolution of this belt.

Based on the depth distribution of seismicity, Chen and Molnar (1983) inferred the presence of a low strength, aseismic, and ductile lower crust separating relatively high strength upper crust and mantle seismic regions for the Karakoram region. They found most of the crustal seismicity is confined to depths shallower than 25 km. Seismicity is also noticed then in the uppermost mantle below 70 km depth, with intermediate crustal section being mainly aseismic. This 'pine-tree' type (also named as 'jelly sandwich' model) of rheological structure was later disputed by Jackson (2002) as relocation of these events put mantle events into the crust, leading to the proposal of a 'crème-brûlée' model wherein the maximum strength resides in the crust and the continental mantle is mechanically weak. This opened a debate whether the continental lithosphere has a 'jelly sandwich' or a 'crème-brûlée' type rheological structure (Fig.1), each of this would lead to a very different nature of continental deformation when subjected to plate tectonic forces or topographic loads (Jackson, 2002; Burov and Watts, 2006; Handy and Brun, 2004).

Cermak et al. (1991) analyzed the depth distribution of seismicity in northeast India to construct probable rheological model of the region. They used focal depth data of 410 earthquakes of 3.5-7.5 magnitude that occurred during 1905-1988 in the depth range of 2-211 km. Depth distribution of seismicity (Fig.2) indicated an almost uniform distribution of seismicity down to the depth of 120-140 km, except one peak in the depth range of 30-40 km, which was related to the artifact due to the fixing of focal depth at 33 km in the algorithms used for the determination of focal depths. The distribution reveals

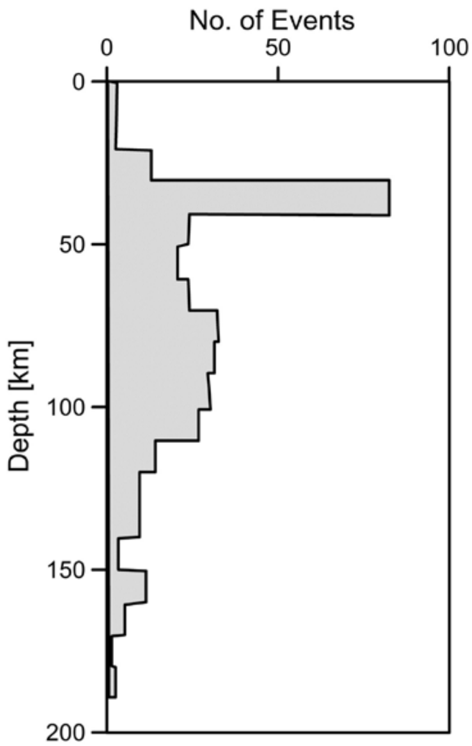

Figure 2. Depth distribution of seismicity in NE India (Cermak et al., 1991).

that the entire crust is seismically active, necessitating construction of a rheological model that can sustain brittleness up to the depth greater than 140 km. Cermak et al. (1991) performed rheological modeling and proposed that only "wet" rheological models with supra-hydrostatic pore-fluid pressure could explain the pattern of crustal seismicity. However, the proposed model was unable to correlate the seismicity distribution with the strength profile.

In more recent studies, Mandal et al. (2006) provided the depth distribution of seismicity for the Bhuj region and Srinagesh and Rajagopala Sarma (2005) for the Koyna - Warna region. Mandal et al. (2006) relocated 999 aftershocks that occurred within one year of 2001 Bhuj earthquake and another 250 aftershocks during 2002-2004 by using a joint hypocentral determination technique. The depth distribution (Fig.3a,3b) reveals that the long-term seismicity ceased at the depth of 40 km with the maximum events concentrated around 22 km. However, during 2001 the maximum concentration was at about 20 km depth and the seismicity cut-off depth reached to about 50 km. The 1-D seismic velocity model used by them in the above study put the Moho at 42 km depth with the crust between 25-42 km depth having relatively higher P-wave seismic velocity of 7.15-7.88 km/s. Thus, in their model, the seismicity is confined to the crust. Srinagesh and Rajagopala Sarma (2005) relocated 609 earthquakes using the double difference algorithm and attributed the variation in the maximum depth to the seismicity amongst North escarpment zone (NEZ), South escarpment zone (SEZ) and Warna seismic zone (WSZ) to the brittle-ductile transition. Accordingly, they delineated the brittle-ductile transition at 11 km depth in the NEZ and at 6-8 km in the SEZ and WEZ (Fig.3c) and related this variation to the geometry of the fault system. They used a 1-D crustal P-wave velocity model up to 16 km depth to relocate the events. Therefore, the inferred brittle-ductile transition remains within the upper crust.

Modeling Perspective:

In this approach, various geophysical datasets are integrated with the empirical friction and creep laws, and mathematical modeling to construct the mechanical structure of a continental lithosphere in the form of a stack of brittle and ductile layers. The crustal and mantle lithospheric seismic velocities and density structure, heat flow and heat generation data, strain rates, etc. are the inputs for rheological models. One needs to solve a second order heat advection-diffusion equation with boundary and initial conditions suitable for the tectonic model of the region and use temperature structure in the creep laws to construct rheological model. In general, old continental lithosphere is considered as thermally stable; hence only steady-state heat diffusion equation is used. Never-the-less, transient models have also been developed, especially for

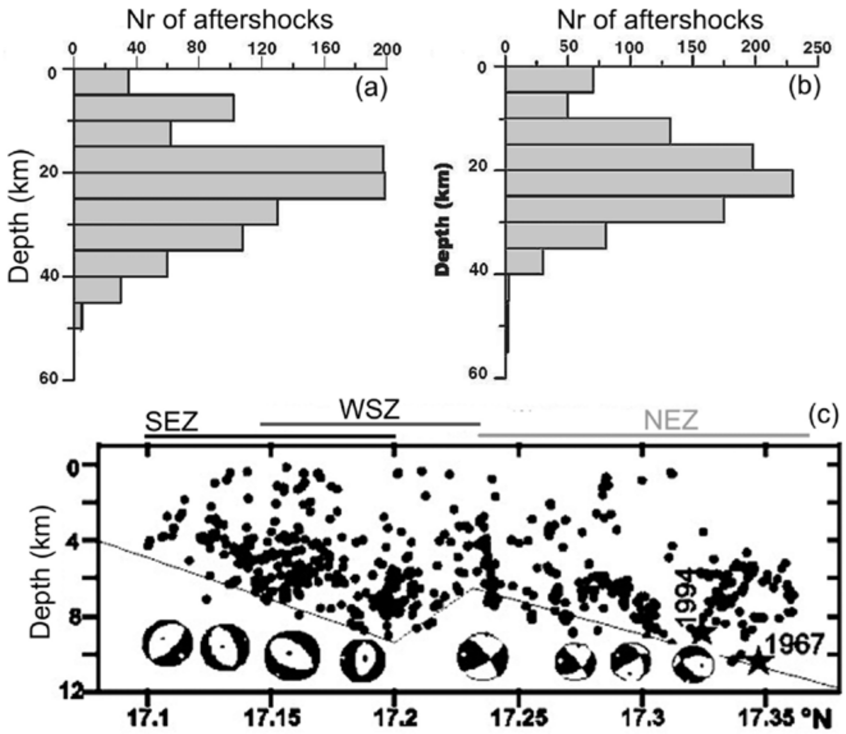

Figure 3. Depth distribution of seismicity in the Bhuj region after the 2001 earthquake (a) during 2001-02 and (b) during 2002-04 (Mandal et al., 2006), and the along-latitude variation of the seismicity depth in the Koyna – Warna region (Srinagesh and Rajagopala Sarma, 2005). NEZ- North escarpment zone, SEZ- South escarpment zone, and WSZ- Warna seismic zone.

tectonically active regions.

Initial studies to model rheologial structure of the Indian shield were carried out by Singh (1981) and Bhattacharya and Singh (1984) who estimated the shear strength of the Indian shield following rheological modeling approach and using surface heat flow and heat generation data of Khetri, Singhbhum, Kolar, and Karadikuttam. However, in their model only olivine rheology, appropriate for the sub-crustal lithosphere, was used ignoring the weak crustal rheology. Manglik and Singh (1991) included more realistic quartz and feldspar rheologies for the continental upper and lower crust respectively, besides olivine rheology for the lithospheric part of the mantle and developed rheological models for six sites in the Indian shield (Fig.4). Manglik and Singh (1992) estimated lithospheric strength profiles for the rheologically stratified models. These models provided the thickness of the mechanically strong rheological lithosphere as about 80 km and 65 km for the southern and the northern parts of the shield, respectively, for the strain rate of 10^{-14} s^{-1}. Manglik and Singh (1999) further included the effect of grain boundary diffusion in olivine in previously developed rheological models of the Indian shield and obtained about 28-30% reduction in the thickness of rheological lithosphere. Based on these results they inferred variations in the rheological thickness and strength of the Indian continental lithosphere, the southern part of the shield in general being mechanically stronger and thicker compared to the northern part of the shield.This was in agreement with the then prevailing understanding that Archaean cratons have thick low-density, high-viscosity roots and low heat flow and hence are expected to be mechanically very strong and non-deformable, an argument in support of the longevity of the cratons (Jordan, 1988). Manglik (2005) presented a synthesis of the rheological modeling approach and the results for the Indian continental lithosphere.

There are not many studies that deal with modeling of rheological evolution of the Indian continental lithosphere due to tectonic processes. In one study, Manglik and Singh (1995) analyzed the effect of crustal magma underplating at the Moho on rheological evolution of the overlying crust and underlying mantle lithosphere by solving magma solidification problem as a moving boundary problem. They concluded that the rheological weakening and subsequent strengthening of continental lithosphere as a result of magma underplating could have significant influence on the initiation of crustal deformation, generation of low angle faults and enhancement of lower crustal reflectivity.

A wealth of information on the crustal and lithospheric structure of the Indian continental lithosphere has been generated especially in the past one decade. There is a scope to develop evolutionary models of deformation of the Indian

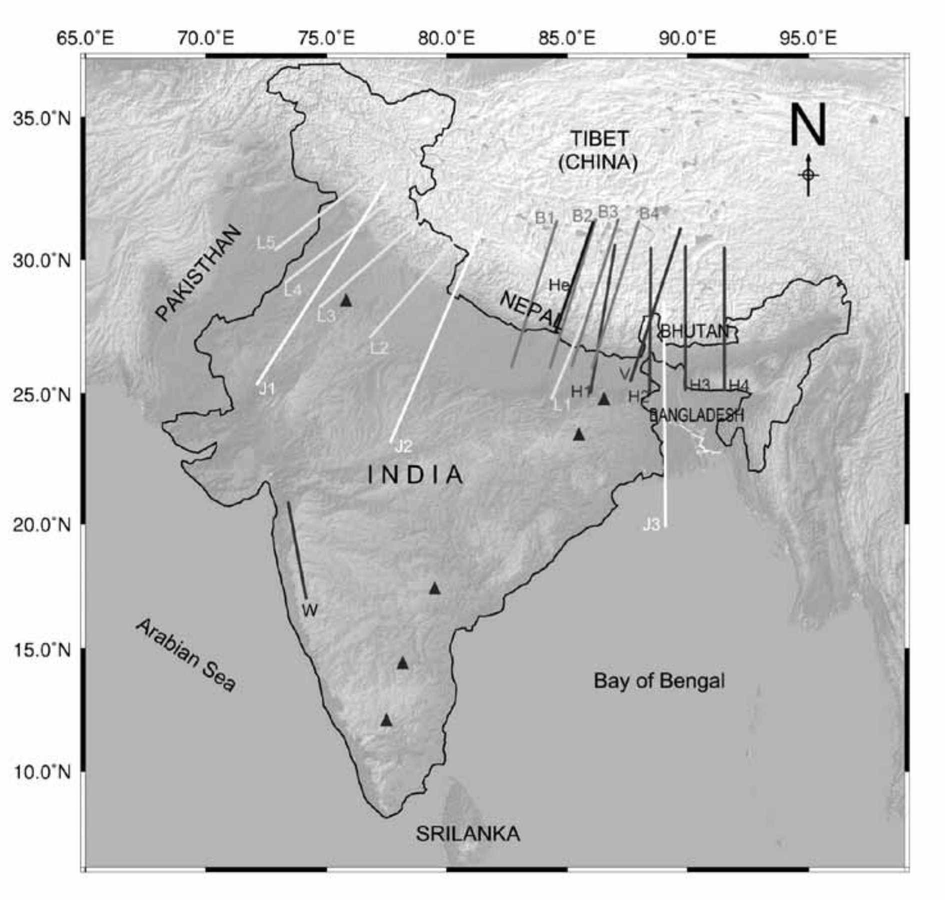

Figure 4. Profiles along which 1-D flexural modeling studies have been carried out by many researchers. L1-L5 (Lyon-Caen and Molnar, 1983), W (Watts and Cox, 1989), J1-J3 (Jordan and Watts, 2005), V (Tiwari et al., 2006), He (Hetényi et al., 2006), B1-B4 (Berthet et al., 2013), H1-H4 (Hammer et al., 2013). Triangles represent the heat flow sites used by Manglik and Singh (1991) for rheological modeling. Background is the topography map. Fig. is prepared by using gmt (http://gmt.soest.hawaii.edu/).

continental lithosphere by coupling these new geophysical images with numerical modeling techniques dealing with viscoelastic/ elasto-plastic media and temperature dependent physical and mechanical properties.

Integrating Rheological Modeling with depth of Seismicity:

The cut-off depth of seismicity has often been linked to the brittle-ductile (B/D) transition depth under the assumption that earthquakes nucleate at the B/D boundary. This argument has also been used to make distinction between "Jelly sandwich" and "Crème-brute" models. While the occurrence of earthquakes at a particular depth may be linked to the brittleness of the medium, their absence below the cut-off depth does not always imply ductile nature of the rocks below. It could be linked to either mechanically too strong or too weak underlying layer (Watts and Burov, 2003; Handy and Brun, 2004) making the correlation between the cut-off depth of seismicity and B/D transition unequivocal. In this respect, lower crustal seismicity is of special interest because rheological models for a normal crustal composition and moderate-to-high heat flow fail to explain brittleness at these depths. The region of the central Indian shield bounded between the Narmada-Son and Tapti lineaments (NSTL) offers one such opportunity to develop a model of the thermo-mechanical structure of the region using the constraint of deep crustal seismicity. Jabalpur (1997) and Satpura (1938) earthquakes occurred in the deep lower crust (>35 km) (Bhattacharya et al., 1997; Mukherjee, 1942). Manglik and Singh (2002) used focal depths of these earthquakes as a constraint for deriving thermo-mechanical structure of the continental crust of the central Indian shield. Based on rheological modeling, they inferred two plausible scenarios for the occurrence of deep crustal seismicity. In the first case, a sufficiently low heat flow from the mantle, similar to that of a cratonic-type, was required for the brittle regime to sustain at 30-38 km depth in the lower crust of typical feldspar-rich composition. In the second case, the brittleness at the lower crustal depth (>35 km) in a moderately hot crust could be achieved by incorporating rheologically high strength mafic underplating at the Moho. Gravity models have supported the presence of thick magmatic underplating in the Narmda-Son lineament region (Singh and Meissner, 1995). Thus, the rheological modeling with the lower crustal seismicity constraint suggested low-to-moderate mantle-derived heat flow for the region and excess surface heat flow was linked to the fluid advection in the upper crust.

The above model explains brittleness in the lower crust and by implications even stronger mantle lithosphere dominated by olivine rheology. Manglik et al. (2008) attempted a different approach to estimate the relative strength of the mantle lithosphere. They carried out finite element modeling for intraplate stresses along the Hirapur - Mandla profile (Murty et al., 2004) passing through the Jabalpur earthquake region and analyzed a series of models having different distribution of mechanical properties. They concluded that the model with a mechanically strong lower crust overlying a relatively weak sub-Moho layer was able to enhance the stress concentration in the hypocentral region, implying a weaker mantle in comparison to the lower crust for this region of central India. Manglik et al. (2009) analyzed the effect of the dome-shaped structure delineated by a deep crustal seismic study along the Nagaur - Jhalawar profile in NW India (Rajendra Prasad et al., 1998) following the finite element stress modeling approach to infer about the mechanical state of the crust and sub-crustal lithosphere of that region.

FLEXURAL STRENGTH – FORWARD MODELING APPROACH:

In the above approach of developing thermo-mechanical structure of continental lithosphere, extrapolation of experimentally determined parameters of the creep laws at high strain rates to geologically relevant low strain rate regime are considered to be a major source of uncertainty although success of rheological models in explaining lower crustal reflectivity and listric faulting despite large uncertainty has worked in favor of these models. Another major source of uncertainty is the thermal structure of the continental lithosphere. The general practice of constructing thermal structure by extrapolating surface heat flow and radiogenic heat generation data to depths suffers from large extrapolation errors as well as from the errors caused by ignoring variations in the physical properties. The layered models of the radiogenic heat generation in crust also take a simplistic view of the radiogenic heat elements concentration in different layers and dependence of physical properties, e.g. thermal conductivity, pressure and temperature. If these variations in radiogenic elements concentration and physical properties are included in models, the temperature at the Moho would have an uncertainty of a few hundred degree centigrade and it would be much larger at the lithosphere-asthenosphere boundary.

There are other alternate approaches to estimate the bulk mechanical properties of the continental lithosphere. One such approach is modeling of flexure of lithosphere in response to the load of topography. In this approach, a fourth order equation for deflection of plate is solved and Bouguer gravity anomaly of the resulting structure computed and compared with observed gravity anomaly. The flexural rigidity, the parameter that controls the deflection of a plate when subjected to a load, is thus determined. The elastic plate thickness is proportional to the cube root of the flexural rigidity. The Himalayan collision front, being one of the best examples globally for this purpose, has led to several studies (Fig.4) providing useful estimates of the mechanical strength and eventually the elastic thickness of the Indian continental lithosphere. Some of these are summarized below.

Lyon-Caen and Molnar (1983) estimated the flexural rigidity of the Indian plate along profiles (Fig.4) cutting across the Himalaya by using the Bouguer gravity anomaly and the geometry of the basement of the Ganga Basin as constraints. In their model, the flexural rigidity drops from $0.7\pm0.5 \times 10^{25}$ N.m beneath the Ganga Basin to $0.1 - 1.0 \times 10^{23}$ N.m beneath the Greater Himalaya. Karner and Watts (1983) extended the flexural modeling to six profiles covering a large portion of the Himalayan arc and obtained the elastic plate thickness(T_e) and the flexural rigidity of 82–104 km and $0.5 - 1 \times 10^{25}$ N.m, respectively. Jin et al. (1996) further extended these profiles (Fig.4) up to Tarim Basin by incorporating gravity data from the Chinese side with a data gap over Nepal and re-analyzed the effective elastic thickness of the lithosphere. Their study re-confirmed earlier results indicating high-rigidity of the Indian plate (T_e = 90 km) beneath the Ganga Basin and the Lesser Himalaya and weakening of the Indian plate beneath the Higher Himalaya. Further north, they suggested a moderately rigid Eurasian plate (T_e = 40-45 km) beneath Tibet and Tarim Basin. Tiwari et al. (2006) carried out flexural modeling along a profile across the Sikkim Himalaya and obtained T_e of 50 ± 10 km.

Jordan and Watts (2005) carried out 1-D flexural modeling along three profiles (Fig.4) passing through western (Kumaun - Garhwal), central (central Nepal), and eastern (Bhutan) sectors, respectively, of the Himalayan belt and concluded that there are significant along-strike variations in the elastic plate thickness. The central segment has T_e of 70 km whereas in the eastern segment it is 30 km and in the western segment it is 50 km. They further extended the 1-D flexural analysis to 2-D by following iterative flexure and gravity anomaly modeling technique and obtained largest T_e of 125 km in the foreland basin of the central profile. The results also suggested that a single T_e value of 40 km for the western and eastern profiles was able to explain the gravity anomalies but in the central segment a variations in the T_e from about 100 km beneath the foreland basin to about 40 km beneath the Himalayan load was required. Although, the estimates of T_e obtained by 1-D and 2-D approaches vary in terms of absolute values, these reveal a broader scenario that the central Himalayan foreland basin has a strong rigid block and the Indian plate in the eastern and western sectors is comparatively less rigid, which is a significant inference that has implications for the seismicity distribution along the Himalayan belt.

The above flexural modeling studies considered either a uniform elastic plate or a plate composed of horizontal blocks each having different flexural rigidity. However, as discussed in the rheological modeling section, the lithosphere consists of a stack of elastic (brittle) and plastic (ductile) layers and therefore the response of such a composite plate to the applied load would be different from that of a plate characterized by uniform flexural rigidity. The next development in forward flexural modeling of the Indian plate addressed this aspect through the application of the visco-elasto-plastic models of plate flexure to the Indian plate. Hetényi et al. (2006) considered a simple 3-layered model of the lithospheric plate consisting of rheologically different upper crust, lower crust, and upper mantle and a temperature distribution, corresponding to the moderate heat flow regime, that varies only with depth,to study its flexural response to a southward migrating load simulating the Tibet-India convergence. The Moho depths obtained by the receiver function analysis of Hi-CLIMB seismological data in central Nepal and basement depths of the foreland basin were used as geometrical constraints for plate flexure. The results yielded the effective elastic thickness (EET) of about 70 km beneath the Indian continent, dropping to 30-40 km thickness about 150-200 km south of the MFT and attaining the lowest value of 20-30 km beneath the Himalaya. Since temperature can be a vital parameter consideration of a laterally uniform temperature over such a long profile may be an oversimplification and major source of uncertainty. Berthet et al. (2013) applied the same technique to four profiles (Fig.4) covering a 350-km-wide area lying between the eastern and central Nepal with the Moho depth constraints from the HIMNT and Hi-CLIMB experiments. The results remain similar to those obtained by Hetényi et al. (2006) and indicate no major lateral variations in the strength of the Indian plate in this part of the Nepal Himalaya. Hammer et al. (2013) extended the analysis to the Bhutan Himalaya. Bouguer anomaly profile (Fig.4) across the Himalaya in this part shows short-wavelength flexure with a narrower and shallower foreland basin compared to the Nepal Himalaya. They obtained maximum EET of 25 km and the flexural rigidity of $\sim 5 \times 10^{22}$ N.m for Bhutan, which is significantly less than the maximum EET of 60-80 km and flexural rigidity of $\sim 10^{24}$ N.m in Nepal. Again a broad conclusion of these studies was that there are significant along-strike variations in the mechanical strength of the Himalayan belt between central Nepal and Bhutan.

Although, most of the flexural modeling studies related to the Indian continental lithosphere concentrated on the Himalayan collision front, a few flexural studies have also been carried out for other sections of the Indian shield. Watts and Cox (1989) used stratigraphy and dip of various basaltic flows along a N-S section (Fig.4) in the Deccan Volcanic Province (DVP) and computed flexural response of lithosphere to a migrating volcanic load. This yielded an elastic thickness of 100 km for the continental lithosphere. In contrast, the 2-D flexural modeling carried out by Jordan and Watts (2005) revealed a less than 10 km thick elastic plate for the western part of the DVP.

ELASTIC PLATE THICKNESS BY ADMITTANCE/ COHERENCE APPROACH:

In this approach, the thickness of the elastic plate (T_e) is estimated by spectral analysis of gravity and topography data, either by computing the transfer function between gravity and topography in the wave number domain (admittance approach) or by estimating statistical correlation between these datasets (coherence approach). There has been a debate on the values of T_e obtained by the method originally proposed by Forsyth (1985) and the values obtained from the spectral analysis of free air gravity anomaly and topography data as proposed by McKenzie and Fairhead (1997). This debate is not discussed here. Instead only the estimates obtained for the Indian shield by various researchers by this approach are presented. McKenzie and Fairhead (1997) suggested a T_e of only 24 km for the northern Indian shield. Tiwari and Mishra (1999) applied admittance and coherence analysis to the Bouguer gravity anomaly and topography data along three E-W profiles in the DVP (Fig.4) covering the locations of Killari and Koyna earthquakes and obtained the effective elastic thickness of 10±2 km. Stephen et al. (2003) obtained elastic plate thickness and mechanical strength of the Indian continental lithosphere by applying multi-taper (MTM) and mirrored peridogram (MPM) techniques to Bouguer gravity and topography data of the south Indian shield. MTM method yielded T_e of 12, 14, 11, and 15 km for the DVP, Godavari rift, Dharwar craton (DC), and Southern Granulite Terrain (SGT), respectively. The T_e values of 20, 31, 22, and 31 km obtained for these regions by MPM are consistently relatively large but the pattern remains mainly the same, with the DVP and DC having lower thickness than the Godavari rift and the SGT. Rajesh and Mishra (2004) covered also the northern part of the Indian shield and determined the relative mechanical strength by the multi-taper analysis. They obtained T_e values of 18 to 26 km for the northern Indian shield with the average thickness of 23 km and 12 to 16 km for the southern Indian shield with the average thickness of 14 km. Although counterintuitive to the general understanding of the cratonic regions, the result highlighted the contrast in the mechanical properties of the northern and southern parts of the Indian shield separated by the Central Indian Tectonic Zone (CITZ) with the Proterozoic northern domain presumably of relatively high heat flow regime having larger T_e compared to the Archaean Dharwar craton having low heat flow regime. Recently, Trivedi et al. (2012) and Ratheesh-Kumar et al. (2014) have revisited the work of Rajesh and Mishra (2004) by using the Morelet wavelet-based Bouguer coherence technique and obtained broadly the similar results. Interestingly, the mechanically strong block south of central Nepal, obtained by several earlier workers, has shifted to the eastern side in the T_e map of Trivedi et al. (2012) and to the western Himalayan sector in the T_e map of Ratheesh-Kumar et al. (2014). Both used the same gravity data and the same technique and yet found different results.

POST-SEISMIC VISCOUS RELAXATION:

There are other approaches to delineate the thermo-mechanical state of the crust/ lithosphere, e.g. post-glacial rebound, post-seismic relaxation, etc. Post-glacial rebound is not relevant in the context of the recent large-scale deformation of the Indian continental lithosphere. The co-seismic deformation by a large earthquake is normally followed by measurable post-seismic relaxation process that changes the stress state of the surrounding region. The magnitude and pattern of post-seismic deformation and stress changes depend strongly on the rheological structure of the crust and upper mantle, which in turn depends on composition, temperature and other controlling parameters. There are not many studies on these aspects for the Indian shield. In one such study, To et al. (2004) modeled the post-seismic deformation due to 1819 Kachchh and 2001 Bhuj earthquakes using a viscoelastic model with upper mantle viscosity of 1.5×10^{19} Pa.s.

ELASTIC STRUCTURE BY GEODETIC SEASONAL VARIATIONS:

In recent years, integration of seasonal variations of horizontal and vertical positions observed in GPS time series, seasonal variations of monsoon driven continental water storage estimated from satellite data, and geodetic deformation modeling has led to the estimation of the elastic structure of the Earth (Fu and Freymueller, 2012; Chanard et al., 2014). Chanard et al. (2014) have used seasonal variations of water load derived from Gravity Recovery and Climate Experiment (GRACE) data as input load to model geodetic deformation for elastic half-space and elastic layered models and constrained the model parameters to fit the observed geodetic variations records by positions time series of GPS stations mainly from Nepal and a few from India and China. They thus estimated a broad 1-D elastic model of the Himalaya and concluded that the seasonal strain seen in the Himalaya on the horizontal and vertical components of the GPS data is primarily due to surface load variations induced by continental hydrology.

DISCUSSION:

Some salient results have emerged from the above studies on the mechanical/ thermo-mechanical structure of the Indian continental lithosphere. First major inference is that the Indian shield can be broadly sub-divided into the northern and the southern segments based on the mechanical strength of the lithosphere, with the Central Indian Tectonic Zone (CITZ) forming the contact between the two segments. Second major inference is that there are variations in the mechanical strength of the northern Indian shield along the strike of the Himalayan collision belt. The western and the eastern sectors of the Himalaya and the adjoining foreland basin are mechanically relatively weak compared to the central sector, which appears to be constituted of a thick mechanically strong lithospheric block.

The nature of the first inference has changed over the past decade in view of the new estimates of the effective elastic thickness and the seismic tomography images of the northern Indian shield and the Himalayan collision belt. The observations of the lowest surface heat flow in the Archaean western Dharwar craton (WDC), lowest long-wavelength Bouguer gravity anomaly over this region, and thermo-mechanical modeling supported the globally perceived view that the WDC, being a cratonic nucleus, is mechanically the strongest segment of the Indian shield. Although only a few heat flow measurements are available from the northern shield, the dominance of relatively positive long-wavelength Bouguer anomaly north of the CITZ (Fig.5) could be explained by relatively high density and low-viscosity post-Archaean lithosphere (Mahadevan, 2013). However, the realization that the northern shield is almost double in thickness in terms of its elastic thickness has led to a paradoxical situation with mechanical strength reversal across the CITZ, which has serious implications for the deformation of the Indian continental lithosphere.

One consequence of the large effective elastic thickness (EET) is that the lithosphere of the northern shield is thicker than the southern shield. Seismic tomography images of the Himalayan collision belt and Tibet covering the northern Indian shield do indicate such a possibility. Li et al. (2008) developed a seismic tomography model of Tibet and surrounding regions(45 km x 0.35° x 0.35° block size down to 800 km depth and 45 km x 0.7° x 0.7° further deep) by using P-wave arrival time data (about 1

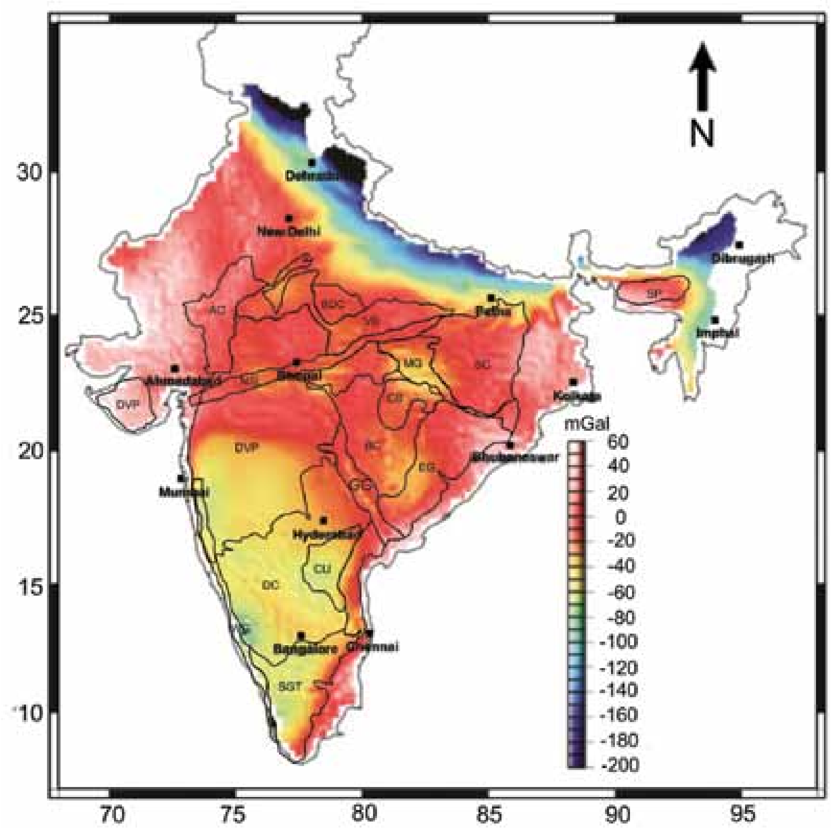

Figure 5. Boundaries of various cratons and other tectonic provinces superimposed on the long-wavelength Bouguer gravity anomaly map of India. Reprinted from Tiwari et al. (2011) with permission from Elsevier.

million P phases) from global, regional, and local networks. The model indicates the presence of a high velocity block with P-wave speed about 1.9% higher than the ‘ak135’ reference model even at 400 km depth in central Nepal and the adjoining Ganga basin. Fig.6 shows tomography images at 300 km and 400 km along with resolution test. Such high velocity blocks are not seen in the central part of the Indian shield. This result also supports the along-strike variations in the mechanical strength of the Indian continental lithosphere as the lithospheric thickness varies along the strike of the Himalaya. Li et al. (2008) also compared their model with the S-wave velocity model derived by Lebedev and van der Hilst (2008) by using fundamental and higher mode surface wave tomography. The S-wave tomography also reveals a high shear velocity block beneath the central Ganga basin at 100 km depth, which shifts to beneath central Nepal at 200 km depth. Thus, both studies support the presence of a high P- and S-wave velocity block in the central part of the northern Indian shield that can explain large EET in the northern part of the Indian shield.

While the above results strongly support the presence of thick, mechanically strong lithosphere, at least in the central part of the northern shield, whether they conversely imply a mechanically weak southern shield needs to be critically analyzed. The tomography images of Li et al. (2008) do not show the presence of high velocity blocks in the central and southern parts of the shield. However, the absence of high velocity anomalies need not imply that these regions have relatively low P-wave velocity. Checkerboard test (Fig.6) indicates that the ray coverage is relatively less in these areas of the shield leading to poor resolution of the structure. Kiselev et al. (2008) obtained the lithospheric S-wave velocity of about 4.5 km/s from the Moho to the depth of about 250 km for the Dharwar craton by joint inversion of P- and S- receiver functions and teleseismic P- and S- travel time residuals, which is lower than the 4.7 km/s velocity normally obtained for other cratonic keels implying the lack of the high velocity keel in their model of the Dharwar craton. In view of the low surface heat flow in this region, they attributed the low S-wave velocity to anomalous composition. Recent results of Kumar et al. (2013) on mapping of the lithospheric thickness across the Indian shield by using P- and S- receiver function techniques suggest a variation in the lithospheric thickness from ~70 km beneath the Dharwar craton to ~140 at the Himalayan front with undulations in between, which they have attributed to the buckling

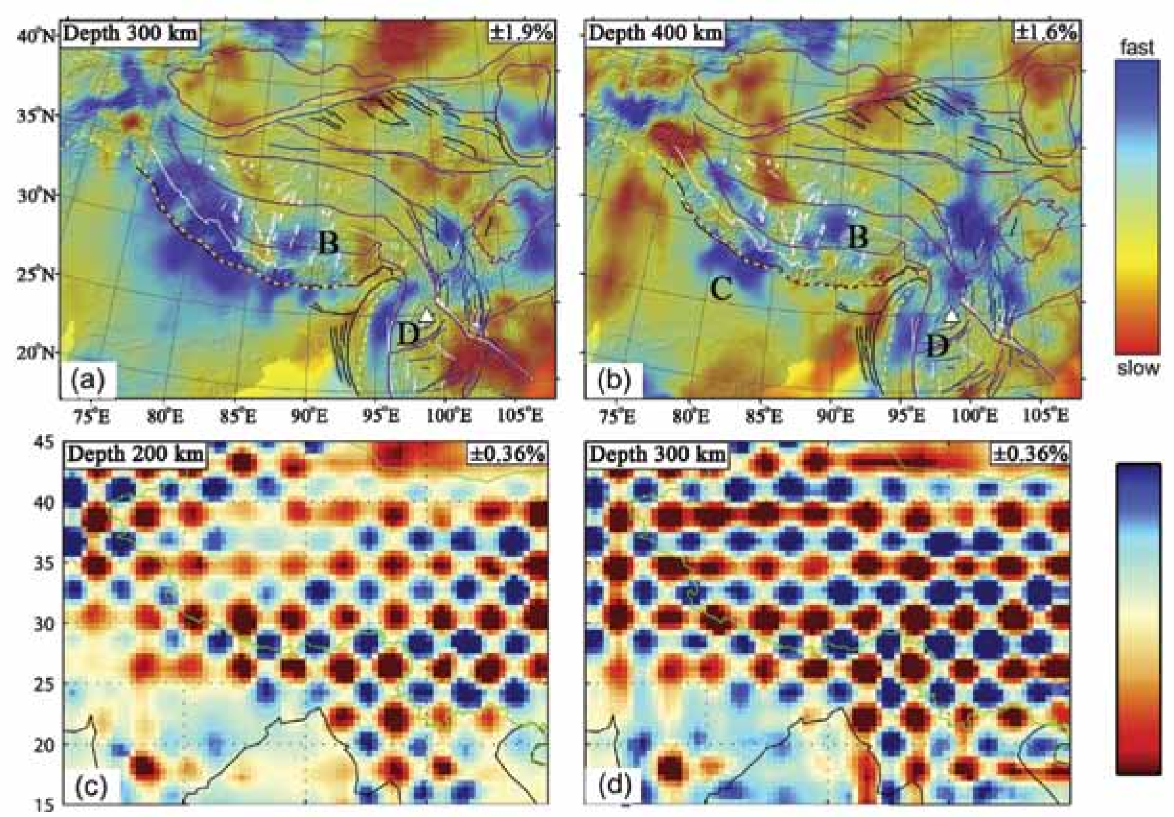

Figure 6. P-wave seismic tomography model of the Indian shield and the Himalayan collision belt at (a) 300 km, and (b) 400 km with corresponding checkerboard test results (c & d). Reprinted from (Li et al., 2008) with permission from Elsevier.

of the Indian lithosphere. This observation does support the mechanically weak nature of the southern shield. The lithosphere – asthenosphere boundary (LAB) image (Fig.13 of Kumar at el., 2013) reveals that the lithospheric thickness beneath the Southern Granulite Terrain (SGT) is more than 120 km, almost similar to that obtained at the Himalayan front and at the CITZ. This also raises an interesting question. How could a region affected by the Pan-African thermal event at ~550 Ma (Miller et al., 1996) and the impact of the Marion plume retain its antiquity especially when the lithosphere beneath the WDC got eroded by these and later thermal events. There are alternate views also invoking large thickness of the lithosphere beneath the Archaean Dharwar craton (Gupta et al, 2003).

A mechanically weak southern Indian shield warrants new explanations for the nature of the Archaean cratonic lithosphere whose longevity in the convecting mantle has been explained by invoking low-density buoyant root of several orders of magnitude and higher viscosity than the surrounding asthenosphere. Since this region also has the lowest surface heat flow (and hence lowest mantle heat flow) and thus low temperature at any given depth in comparison to the surrounding regions, a simple extrapolation to the northern shield with thick lithosphere would imply a still lower mantle heat flow beneath the northern shield. That can also explain relatively high shear wave velocity imaged by tomography. A mantle heat flow higher than that observed in the WDC is counter-intuitive, as it would imply a reduction in the shear wave velocity (Priestly and McKenzie, 2006). Expectations of a mantle heat flow lower than about 10-12 mW/m^2 in the northern shield could be an exciting observation. Alternatively one may invoke a compositional cause, a high-density lithosphere, which brings in its own inconsistency. The Indian plate underthrusts beneath the Himalaya at a low angle. A thick high-density lithosphere would be consistent with a steep angle subduction because of the large magnitude of the vertical force due to the gravity load to resist horizontal movement by plate boundary forces. Low temperature would also translate into high density but that change should be smaller than that caused by compositional changes.

To summarize, the Indian continental lithosphere offers an exciting scenario to re-visit the existing concepts for the genesis of the Archaean and Proterozoic lithospheres and assess their suitability in explaining new observations. Conversion of geophysical images of the subsurface into thermo-mechanical structure is the next step towards understanding the lithospheric deformation in various tectonics regimes.

ACKNOWLEDGEMENTS

I am thankful to Dr. K. Sain and Dr. P.R. Reddy for inviting me to write this article. Dr. R.N. Singh has critically reviewed the manuscript and provided valuable inputs. I am grateful to him for the same. I thank G. Pavan Kumar for preparing some Figures. Fig. 4 has been prepared by using GMT package (http://gmt.soest.hawaii.edu/). The work has been supported by the CSIR-NGRI projects MLP6107-28(AM) and PSC0204 (INDEX).

REFERENCES

Berthet, T., Hetényi, G., Cattin, R., Sapkota, S.N., Champollion, C., Kandel, T., Doerflinger, E., Drukpa, D., Lechmann, S., and Bonnin, M., 2013. Lateral uniformity of India Plate strength over central and eastern Nepal, Geophys. J. Int., v.195, pp: 1481–1493.

Bhattacharya, S., and Singh, R.N., 1984. Thermo-mechanical structure of the southern part of the Indian shield and its relevance to Precambrian basin evolution, Tectonophysics, v.105, pp: 103-120.

Bhattacharya, S.N., Ghose, A.K., Suresh, G., Baidya, P.R., and Saxena, R.C., 1997. Source parameters of Jabalpur earthquake of 22 May., 1997. Current Science, v.73, pp: 855-863.

Burov, E.B.,and Watts, A.B., 2006. The long-term strength of continental lithosphere: "jelly sandwich" or "crème brûlée"? GSA Today, v.16(1), doi: 10.1130/1052-5173(2006)016<4:TLT SOC>2.0.CO;2.

Carlson, R.W., Pearson, D.G., and James, D.E., 2005. Physical, chemical, and chronological characteristics of continental mantle, Rev. Geophys., v.43, RG1001, doi:10.1029/2004RG000156.

Cermak, V., Bodri, L., and Saikia, M., 1991. Geothermal and rheological implications of the crustal earthquake within and west of the Arakan-Yoma fold belt (Northeastern India), J. Geol. Soc. Ind., v.38, pp: 282-292.

Chanard, K., Avouac, J.P., Ramillien, G., and Genrich, J., 2014. Modeling deformation induced by seasonal variations of continental water in the Himalaya region: Sensitivity to Earth elastic structure, J. Geophys. Res. Solid Earth, v.119, pp: 5097–5113.

Chen, W., and Molnar, P., 1983. Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, J. Geophys. Res., v. 88, pp: 4183-4214.

Forsyth, D.W., 1985. Subsurface loading and estimate of flexural rigidity of continental lithosphere, J. Geophys. Res., v.90, pp: 12623– 12632.

Fu, Y., Freymueller, J.T., 2012. Seasonal and long-term vertical deformation in the Nepal Himalaya constrained by GPS and GRACE measurements, J. Geophys. Res., v.117, B03407, doi:10.1029/2011JB008925.

Gupta, S., Rai, S.S., Prakasam, K.S., Srinagesh, D., Chadha, R.K., Priestley, K., and Gaur, V.K., 2003. First evidence for anomalous thick crust beneath mid-Archean western Dharwar craton, Current Science, v.84, pp: 1219-1226.

Hammer, P., Berthet, T., Hetényi, G., Cattin, R., Drukpa, D., Chophel, J., Lechmann S., Le Moigne, N., Champollion, C., and Doerflinger, E., 2013. Flexure of the India plate underneath the Bhutan Himalaya, Geophys. Res. Lett., v.40 pp: 4225–4230, doi:10.1002/grl.50793.

Handy, M.R.,and Brun, J.-P., 2004. Seismicity, structure and strength of the continental lithosphere, Earth Planet. Sci. Lett., v.223., pp: 427– 441

Hetényi, G., Cattin, R., Vergne, J.,and Nábělek, J.L., 2006. The effective elastic thickness of the India Plate from receiver function imaging, gravity anomalies and thermomechanical modelling, Geophys. J. Int., v.167 pp: 1106–1118, doi:10.1111/j.1365-246X.2006.03198.x.

Jackson, J., 2002. Strength of the continental lithosphere: Time to abandon the jelly sandwich? GSA Today, v.12(9), pp: 4-10.

Jin, Y., McNutt, M.,and Zhu, Y., 1996. Mapping the descent of the Indian and Eurasian plates beneath the Tibetan plateau from gravity anomalies, J. Geophys. Res., v.101, pp: 11275-11290.

Jordan, T.H., 1988. Structure and formation of the continental tectosphere, J. Petrol., v.29, pp: 11–37.

Jordan, T.A., and Watts, A.B., 2005. Gravity anomalies, flexure and the elastic thickness structure of the India–Eurasia collisional system, Earth Planet. Sci. Lett., v.236, pp: 732–750.

Kaila, K.L., Roy Chowdhury, K., Reddy, P.R., Krishna, V.G., Hari Narain, Subbotin, S.I., Sollogub, V.B., Chekunov, A.V., Kharetchko, G.E., Lazarenko, M.A. and Ilchenko, T.V., 1979. Crustal structure along kavali-udipi profile in the indian peninsular shield from deep seismic sounding. Jour. Geol. Soc. India, v.20, pp:307-333.

Karner, G.D.,and Watts, A.B., 1983. gravity anomalies and flexure of the lithosphere at mountain ranges, j. geophys. res., v.88, pp: 10449 - 10477.

Kiselev, S., Vinnik, L., Oreshin, S., Gupta, S., Rai, S.S., Singh, A., Kumar, M.R.,and Mohan, G., 2008. Lithosphere of the Dharwar craton by joint inversion of P and S receiver functions, Geophys. J. Int. v.173, pp: 1106–1118.

Kumar, P., Ravi Kumar, M., Srijayanthi, G., Arora, K., Srinagesh, D., Chadha, R.K., and Sen, M.K., 2013. Imaging the lithosphere-asthenosphere boundary of the Indian plate using converted wave techniques, J. Geophys. Res., Solid Earth, v.118, pp: 5307–5319, doi:10.1002/jgrb.50366.

Lebedev, S.,and van der Hilst, R.D., 2008. Global upper-mantle tomography with the automated multi-mode surface and S waveforms, Geophys. J. Int., v.173, pp: 505–518.

Li, C., van der Hilst, R.D., Meltzer, A.S., and Engdahl, E.R., 2008. Subduction of the Indian lithosphere beneath the Tibetan Plateau and Burma, Earth Planet. Sci. Lett., v.274, pp: 157–168.

Lyon-Caen, H., and Molnar, P., 1983. Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexural model of the lithosphere, J. Geophys. Res., v.88, pp: 8171-8191.

Mahadevan, T.M., 2013. Evolution of the Indian Continental Lithosphere: Insights from episodes of crustal evolution and geophysical models, J. Ind. Geophys. Union, v.17(1), pp: 9-38.

Mandal, B., Sen, M.K., Vijaya Rao, V., and Mann, J., 2014. Deep seismic image enhancement with the common reflection surface(CRS) stack method: evidence from the Aravalli–Delhi fold belt of northwestern India, Geophys. J. Int., v. 196, pp: 902-917, doi: 10.1093/gji/ggt402

Mandal, P., Narsaiah, R., Sairam, B., Satyamurty, C.,and Raju, I.P., 2006. Relocation of early and late aftershocks of the.,2001. Bhuj earthquake using joint hypocentral determination (JHD) technique: implication toward the continued aftershock activity for more than four years, Pure Appl. Geophys., v.163, pp: 1561–1581.

Manglik, A., 2005. Rheological Modeling of the Indian Continental Lithosphere, J. Him. Geol., v.26(1), pp: 165-173.

Manglik, A., and Singh, R.N. 1991. Rheology of Indian continental crust and upper mantle, Proc. Ind. Acad. Sci. (EPS), v.100, pp: 389-398.

Manglik, A.,and Singh, R.N., 1992. Rheological thickness and strength of Indian continental lithosphere, Proc. Ind. Acad. Sci. (EPS), v.101, pp: 339-345.

Manglik, A., and Singh, R.N., 1995. Post-intrusive thermal evolution of continental crust: a moving boundary approach. J. Geophys. Res., v.100, pp: 18031-18043.

Manglik, A.,and Singh, R.N., 1999. Rheological stratification of the Indian continental lithosphere: Role of diffusion creep, Proc. Ind. Acad. Sci.(EPS), v.108, pp: 15-21.

Manglik, A., and Singh R.N., 2002. Thermomechanical structure of the central Indian shield: Constraints from 1997 Jabalpur earthquake. Current Science, v.82, pp: 1151-1157.

Manglik, A., Thiagarajan, S., Mikhailova, A.V.,and Rebetsky Yu., 2008. Finite element modelling of elastic intraplate stresses due to heterogeneities in crustal density and mechanical properties for the Jabalpur earthquake region, central India, J. Earth Sys. Sci., v.117, pp: 1-9.

Manglik, A., Arora, T., Thiagarajan, S.,and Mallick, A., 2009. Intraplate Stresses due to crustal heterogeneities along the Nagaur - Jhalawar transect, northwestern India. Current science, v.96, pp: 838-843.

McKenzie, D.P., and Fairhead, D., 1997. Estimates of the effective elastic thickness of the continental lithosphere from Bouguer and free air gravity anomaly. J. Geophys. Res., v.102, pp: 27523-27552.

Miller, J.S., Santosh, M., Pressley, R.A., Clements, A.S.,and Rogers, J.J.W., 1996. A Pan-African thermal event in southern India, J. Southeast Asian Earth Sci., v.14, pp: 127–136

Mukherjee, S.M., 1942. Seismological features of the Satpura earthquake of the 14 March 1938. Proc. Ind. Acad. Sci., v.XVI, pp: 167-175.

Murty, A.S.N., Tewari, H.C., and Reddy, P.R., 2004. 2-D Crustal velocity structure along Hirapur–Mandla profile in central India: An update, Pure Appl. Geophys., v.161, pp: 165–184.

Priestley, K., and McKenzie, D., 2006. The thermal structure of the lithosphere from shear wave velocities. Earth Planet. Sci. Lett., v.244, pp: 285–301.

Rajendra Prasad, B., Tewari, H.C., Vijaya Rao, V., Dixit, M.M., and Reddy, P.R., 1998. Structure and tectonics of the Proterozoic Aravalli–Delhi fold belt in NW India from deep seismic reflection studies, Tectonophysics, v.288, pp: 31–41.

Rajesh, R.S., and Mishra, D.C., 2004. Lithospheric thickness and mechanical strength of the Indian shield, Earth Planet. Sci. Lett., v.225, pp: 319-328.

Ranalli, G., 1995. Rheolgy of the earth. Springer (2nd Ed.), pp: 414.

Ratheesh-Kuma, R.T., Windley, B.F.,and Sajeev, K., 2014. Tectonic inheritance of the Indian Shield: New insights from its elastic thickness structure, Tectonophysics, v.615–616, pp: 40–52.

Reddy, P.R., Prasad, B., Vijaya Rao, V., Khare, P., Kesava Rao, G., Murty, A.S.N., Sarkar, D., Raju, S., Rao, G.S.P., and Sridher, V., 1994. Deep seismic reflection profiling along Nandsi-Kunjer section of Nagaur-Jhalawar transect: Preliminary results. In: Continental Crust of NW and Central India, edited by Sinha Roy S. & Gupta K.R., Geol. Surv. India, Memoir v.31, pp: 353–372.

Roy Chowdhury, K., and Hargraves, R.B., 1981. Deep seismic soundings in India and the origin of continental crust, Nature, v.291, pp: 648-650.

Singh, A.P., and Meissner, R., 1995. Crustal configuration of the Narmada-Tapti region (India) from gravity studies, J. Geodynamics, v.20 pp: 111-127.

Singh, R.N., 1981. State of stress in the northern part of the Indian shield. In: ZagrosHindukush, Himalaya geodynamic evolution (eds.) H.K. Gupta and F.M. Delany, Am. Geophys. Union, Washington D.C. and Geol. Soc. Am., Boulder, Colorado, v.3, pp: 307-312.

Srinagesh, D., and Rajagopala Sarma, P., 2005. High precision earthquake locations in Koyna-Warna seismic zone reveal depth variation in brittle-ductile transition zone. Geophys. Res. Lett., v.32, L08310, doi:10.1029/2004GL022073.

Stephen, J., Singh, S.B., and Yedekar, D.B., 2003. Elastic thickness and isostatic coherence anisotropy in the south Indian peninsular shield and its implications. Geophys. Res. Lett., v.30, pp:1853, doi:10.1029/2003GL017686.

Tewari, H.C., Dixit, M.M., Rao, N.M., Venkateswarlu, N., and Vijaya Rao, V., 1997. Crustal thickening under the Palaeo/Mesoproterozoic Delhi Fold Belt in NW India: evidence from deep reflection profiling, Geophys. J. Int., v.129, pp: 657–668.

Tiwari, V.M.,and Mishra, D.C., 1999. Estimation of effective elastic thickness from gravity and topography data under the Deccan Volcanic Province, India, Earth Planet. Sci. Lett., v.171, pp: 289-299.

Tiwari, V.M., Vyghreswara Rao, M.B.S., Mishra, D.C., and Singh, B., 2006. Crustal structure across Sikkim, NE Himalaya from new gravity and magnetic data. Earth Planet. Sci. Lett., v.247, pp: 61–69.

Trivedi, D., Singh, Y., Maji, T.K., Kandpal, S.Ch., and Nair, R.R., 2012. A new assessment of the elastic thickness (Te) structure of the Indianshield, and its implications, Ann. Geophys., v. 55, doi: 10.4401/ag-5172.

To, A., Bürgmann, R.,and Pollitz, F., 2004. Postseismic deformation and stress changes following the 1819 Rann of Kachchh, India earthquake: Was the ., 2001. Bhuj earthquake a triggered event?, Geophys. Res. Lett., v.31, L13609, doi:10.1029/2004GL020220.

Watts, A.B., 2001. Isostasy and flexure of the lithosphere, Cambridg Univ. Press, pp:458.

Watts, A.B., and Burov, E.B., 2003. Lithospheric strength and its relationship to the elastic and seismogenic layer thickness, Earth Planet. Sci. Lett., v.213, pp: 113–131.

Watts, A.B., and Cox, K.G., 1989. The Deccan Traps: an interpretation in terms of progressive lithospheric flexure in response to a migrating load, Earth Planet. Sci. Lett., v.93, pp: 85-97.

Dr. Ajay Manglik is a Senior Researcher at CSIR-National Geophysical Research Institute, Hyderabad, India, and a faculty of Academy of Scientific and Innovative Research (AcSIR). His research interests are in the fields of Geophysical Fluid Dynamics, Tectonophysics, Magnetotellurics, Groundwater flow modeling, and Geophysical Inversion.