Finite element modelling of elastic intraplate stresses due to heterogeneities in crustal density and mechanical properties for the Jabalpur earthquake region, central India

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Deep lower crustal intraplate earthquakes are infrequent and the mechanism of their occurrence is not well understood. The Narmada–Son-lineament region in central India has experienced two such events, the 1938 Satpura earthquake and the 1997 Jabalpur earthquake, having a focal depth of more than 35 km. We have estimated elastic stresses due to the crustal density and mechanical properties heterogeneities along the Hirapur–Mandla profile passing through the Jabalpur earthquake region to analyse conditions suitable for the concentration of shear stresses in the hypocentral region of this earthquake. Elastic stresses have been computed by a finite element method for a range of material parameters. The results indicate that the shear stresses generated by the density heterogeneities alone are not able to locally enhance the stress concentration in the hypocentral region. The role of mechanical properties of various crustal layers is important in achieving this localization of stresses. Among a range of material parameters analysed, the model with a mechanically strong lower crust overlying a relatively weak sub-Moho layer is 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.

1. Introduction

Rheological models of lithosphere integrating the effects of temperature, pressure, and fluids to mechanical deformation have been used extensively to understand tectonic processes and dynamics of lithospheric deformation (Meissner and Strehleau 1982; Chen and Molnar 1983; Kirby 1983; Ranalli 1995). These models are developed by assuming representative rheologies for different crustal layers (quartz and feldspar and other phases) and upper mantle (predominantly olivine) and extrapolating corresponding experimentally-derived steady-state flow laws to natural conditions (Kirby 1983; Ranalli 1995; Kohlstedt *et al* 1995). A typical model of continental lithosphere having about 35 km thick quartz and feldspar dominated crust and olivine dominated upper mantle, and a steady state geotherm representative of Archaean – early Proterozoic age yields a pine-tree-type rheological structure of the lithosphere with a ductile lower crust. More complicated rheological models can be developed depending on the controlling parameters such as temperature, thicknesses and composition of various crustal layers, strain rate, fluid pressure, etc. Despite large uncertainties involved in the estimation and extrapolation of the parameters of empirical flow laws, these models have been successful in deciphering the cut-off depth of intraplate seismicity, assuming that earthquakes occur in the brittle frictional regime and the brittle–ductile transition represents the cut-off

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depth of intraplate seismicity. The occurrence of earthquakes in the uppermost 20 km of the crust and then in the mantle lithosphere supported the ductile nature of the lower crust (Chen and Molnar 1983).

The above classical rheological model does not support the occurrence of earthquakes in the lower crust due to its ductile nature inhibiting sufficient stress accumulation leading to seismicity. However, earthquakes in the lower crust have been reported from Africa (Shudofsky *et al* 1987; Seno and Saito 1994; Foster and Jackson 1998), Baikal rift (Deverchere *et al* 1991, 2001), Rhine graben (Fuchs *et al* 1987), North-west America (Wong and Savage 1983; Wong and Chapman 1990), Andean foreland (Smalley and Isacks 1990), northern Switzerland (Diechman 1992), Norway (Bungum *et al* 1991) and India (Mukherjee 1942; Singh *et al* 1999). These lower crustal earthquakes have been explained mainly in terms of cold and compositionally strong lower crust depicting brittle instead of ductile behaviour and high strain rate (Shudofsky *et al* 1987; Wong and Chapman 1990; Doser and Yarwood 1994; Manglik and Singh 2002). In the context of the Indian shield, Manglik and Singh (1991, 1992, 1999) delineated a ductile layer between 32 km and the Moho for Kolar (low heat flow region) for a normal continental crust whereas the whole lower crust was ductile for high heat flow regions such as Jharia. High surface heat flow of 70–100 mW/m^2 has been reported for the NSL (Ravi Shankar 1988). Manglik and Singh (2002) critically analysed the thermal state of the NSL in view of the lower crustal seismicity and invoked two plausible scenarios to explain the occurrence of the 1997 Jabalpur earthquake at a depth of 36 ± 2 km in terms of rheological models. In one scenario, a very low conductive mantle heat flow was assumed while in another scenario, the presence of a compositionally strong (dry granulite type) layer just above the Moho and moderate mantle heat flow was invoked.

A thermally cold lower crust represented by surface heat flow much less than 55 mW/m^2, as used to explain lower crustal seismicity by brittle failure in the above studies, implicitly assumes that the underlying mantle is also cold and, thus, the brittle mantle layer constituted of olivine-dominated rheology is thick and mechanically strong (Manglik and Singh 2002). It is, however, difficult to better constrain the nature of the underlying mantle lithosphere from the above rheological modelling. Jackson (2002) inferred the presence of a rheologically weak mantle lithosphere underlying a rheologically strong crust based on relocation of some Himalayan earthquakes and flexure analysis. This is contrary to the mechanical behaviour of the mantle inferred on the basis of the above rheological models explaining lower crustal seismicity. Another approach to resolve the mechanical properties of the mantle lithosphere could be to model intraplate stresses and correlate the stress concentration with seismicity. This approach, along with the constraint that lower crustal earthquakes occur by brittle failure in a mechanically strong lower crust, can help in constraining the mechanical properties of both the lower crust and the mantle lithosphere.

In the present work, we follow the two-dimensional elastic stress modelling approach to infer the mechanical properties of the lower crust and the mantle lithosphere of the central Indian shield because this region has experienced two lower crustal earthquakes. A more realistic model of course would be the one that takes into consideration the brittle and the plastic behaviour of various layers and also includes temperature dependence of mechanical properties. However, the present work deals with only elastic stress modelling in which mechanically strong (brittle) and weak (ductile) layers have been simulated by varying the values of the elastic parameters, Young's modulus and Poisson's ratio. We analyse the conditions suitable for the concentration of shear stresses in the hypocentral region of the Jabalpur earthquake by computing intraplate stresses due to crustal density heterogeneities mapped by integrated deep crustal seismic and gravity studies along the Hirapur–Mandla profile passing through this region and variations in the mechanical properties of various layers. Earlier, Mandal *et al* (1997) carried out elastic stress modelling due to crustal density heterogeneities and topography to analyse the stress concentration in the focal region of the Killari earthquake and Mandal and Singh (1996) carried out stress analysis of the Deccan Volcanic Province. Both these studies were based on the perturbation theory which assumes very small variations in the crustal structure from the layered model.

2. Tectonic setup and seismicity

The Narmada-Son Lineament (NSL) in the central Indian shield is a conspicuous tectonic feature cutting across central India (figure 1) and extending more than 1600 km from the west coast of India. The region consists of horst and graben structures and is bounded by deep faults extending down to the Moho (Kaila *et al* 1989). Tectonically, this region is considered as a paleo-rift zone, originated during the middle- to late-Achaean period, presently undergoing a compressional stress regime as is evident from the thrust-type focal mechanisms of Broach and Jabalpur earthquakes from

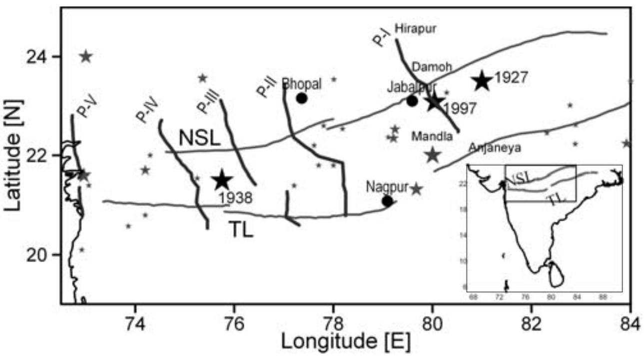

Figure 1. Figure showing distribution of seismicity in the Narmada–Son-Lineament (NSL) region. Epicentral data between 1920 and 2006 shown here have been compiled from ISC (http://www.isc.ac.uk/Bulletin/rectang.html) and NEIC (http://neic.usgs.gov/neis/epic/epic_rect.html) catalogs. The sizes of stars indicate the magnitude of events. Three events shown by large stars are earthquakes with magnitude greater than 6. Also shown are five deep seismic profiles (P-I to P-V) shot across NSL. Inset shows the location of NSL (modified after Manglik and Singh 2002).

this region. This region is also relatively seismically active (figure 1) compared to the rest of the peninsular shield, having experienced 6 earthquakes of magnitude ≥ 5 during the last 70 years. The Son Valley (1927, M 6.5), Satpura (1938, M 6.3), Balaghat (1957, M 5.5) and Broach (1970, M 5.4), and Jabalpur (1997, M 6.2) earthquakes are the large events associated with this structure. The available focal depths put Broach earthquake at 11 km depth (Chung 1993) whereas Satpura and Jabalpur events occurred at a depth of more than 35 km (Mukherjee 1942; Singh *et al* 1999). The 40 km focal depth of the Satpura event can be taken as only suggestive but the focal depth of 36 ± 2 km of the Jabalpur earthquake is well constrained (Singh *et al* 1999). A consistent average Moho depth of about 42 km in the region has been obtained by deep crustal seismic study (Kaila *et al* 1987; 1989). Thus, the Jabalpur event is a good example of the lower crustal event.

3. Crustal structure

Five deep crustal seismic sounding profiles (figure 1) were shot across the NSL to delineate the crustal structure of this tectonic belt (Kaila *et al* 1987, 1989). One of these profiles (Profile-I in figure 1) starts from Hirapur in the north of the NSL, passes through Damoh and Jabalpur, and ends at Mandla in the south, covering a total of 240-km distance. Initial interpretation of the travel time seismic data of this profile revealed a graben–horst type structure formed by dissection of the crust into four blocks by the deep faults penetrating up to the Moho (Kaila *et al* 1987, 1989). Average crustal model obtained by this study broadly consists of upper (depth range 8–18 km), middle (depth range 18–32 km), and lower (depth range 32–44 km) crustal layers of seismic velocity 6.5, 6.7, and 6.5 km/s, respectively. Mall *et al* (1991) refined these crustal velocity model results and introduced a high velocity layer (6.75 km/s) south of Jabalpur at the mid-crustal depth. More recent analyses of the wide-angle seismic data, employing both the travel time and amplitude data, supplemented by the gravity anomalies have delineated a complex upper crustal structure (Murty *et al* 2004). These results support broadly a four-layered crust with the seismic velocities of 5.8–5.9, 6.5–6.7, 6.35–6.40, and 6.8 km/s, respectively. Murty *et al* (2004) interpreted the second layer of 6.5–6.7 km/s velocity as an anomalous mafic intrusion within the normal upper crust of seismic velocity of 6.35–6.4 km/s. The upper crustal layer continues up to a depth of about 20–22 km where the lower crustal velocity of 6.8 km/s is encountered. The depth of the mafic intrusion is highly variable along the profile and it comes to 2 km depth between Katangi and Jabalpur in the central part of the profile.

The NSL appears as a prominent feature in the gravity map of India, dividing the Indian peninsular shield into two parts, the northern part characterized by relatively positive Bouguer anomaly as compared to the southern part (Verma and Banerjee 1992). The lineament itself appears as a linear elongated gravity anomaly zone extending east-west for almost 800–900 km from the west coast up to the southeast of Jabalpur in central India (Mishra 1992). Verma and Banerjee (1992) interpreted the Bouguer gravity high of the Jabalpur–Mandla section of the profile as a massive high-density intrusive body in the upper crust. They interpreted the presence of such intrusives for other profiles also. Singh and Meissner (1995) alternatively proposed the presence of an underplated layer at the Moho as a source of this gravity high for four profiles (P-II to P-V) west of the Hirapur–Mandla profile. The underplated layer is more than 20-km thick in the western part and thins towards east in their model.

Electrical structure of the crust of the Jabalpur earthquake region was delineated along a 190-km-long NW-SE trending Damoh–Jabalpur–Mandla–Anjaneya MT profile (figure 1) coinciding with the deep crustal seismic profile between Damoh and Mandla (Gokarn *et al* 2001). The results indicated the presence of a 5-km-thick layer of the Vindhyan sediments in the Damoh–Katangi region and a relatively low resistivity layer of about 200 Ωm below the sediments coinciding with the high seismic velocity layer of 6.5 km/s. Based on these results, Gokarn *et al* (2001) inferred this layer to be the lower crust, as earlier proposed by Kaila *et al* (1989), and conjectured that the upper crust might have been completely eroded by uplift and erosion processes before the deposition of the Vindhyan sediments. Murty *et al* (2004), however, considered this high velocity layer as a mafic intrusion instead of lower crust and treated the underlying 6.35–6.4 km/s layer as the upper crust, thereby assuming that the upper crust is in fact present beneath this mafic layer. Earlier, Arora *et al* (1995) reported a conductive body of 5 Ωm resistivity at a depth of 20–30 km and a lateral extent of about 100 km below Jabalpur and Mandla based on thin-sheet modelling of the geomagnetic depth sounding (GDS) data. This conductive body correlates with the high-velocity zone interpreted by Mall *et al* (1991) and the high-density body modelled by Verma and Banerjee (1992).

The delineated crustal structure along the Hirapur–Mandla profile by deep crustal seismic, gravity, and electrical resistivity investigations has been interpreted both in terms of complete erosion of the upper crust and the presence of the upper crust below the high-velocity layer. Since geophysical methods suffer from the problem of non-uniqueness, the use of integrated geophysical methods is expected to give better results. Therefore, we use the crustal structure obtained by Murty *et al* (2004) based on integrated interpretation of deep crustal seismic and Bouguer gravity anomaly data for the computation of elastic stresses. The ambiguity in the interpretation of the nature of the high velocity layer in the average depth range of 8–15 km is not expected to affect our analysis as we treat this layer as mechanically strong based on its high seismic velocity and density.

4. Finite element modelling

We take the crustal structure along the Hirapur–Mandla profile obtained by Murty *et al* (2004) based on integrated deep crustal seismic and gravity data (figure 2) to numerically model elastic stresses due to crustal density heterogeneities and mechanical property variations. As discussed in the introduction, we incorporate strong (brittle) and weak (ductile) layers in terms of Young's modulus and Poisson's ratio because it is not possible to incorporate the actual brittle and ductile behaviour in the elastostatic stress modelling carried out here. Nevertheless, the consideration of elastically strong and weak layers in the present modelling will help in capturing the patterns of stress concentration. The crustal model of Murthy *et al* (2004) provides the structure up to the Moho. We have included a

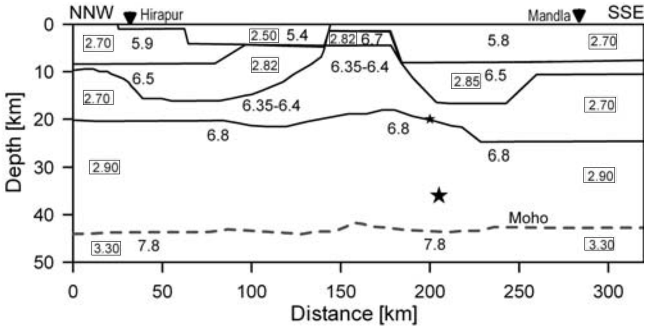

Figure 2. Simplified crustal structure along the Hirapur–Mandla profile (profile P-I in figure 1) obtained by integrated deep crustal seismic and gravity data (after Murty *et al* 2004). Values in large fonts are *P*-wave velocities in km/s and those enclosed in boxes are density in gm/cm^3.

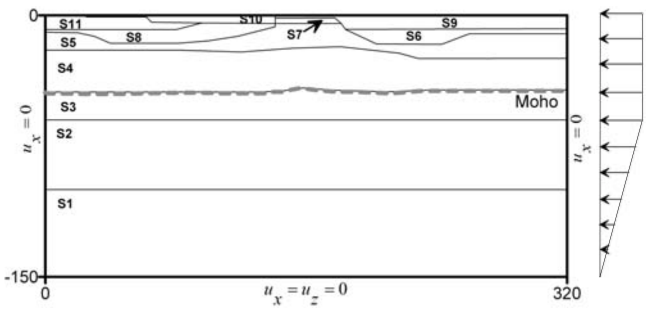

Figure 3. Geometry of the model used for finite element discretization along with boundary conditions at left, right, and bottom boundaries. Also shown is prescribed horizontal displacement boundary condition at the right boundary for the case discussed in section 5.2. The finite element model has been constructed from 11 patches marked as S1–S11. Material parameters of these patches are given in table 1.

sub-Moho layer up to 60 km depth and two additional artificial layers with weak elastic parameters (table 1) below 60 km down to the depth of 150 km to simulate the effect of lower lithosphere and asthenosphere. This also helps in avoiding any artefacts of the bottom boundary condition on the estimates of stresses at the Moho. The bases of these layers have been assumed to be horizontal in the absence of the lithospheric structure. The model thus generated for the finite element analysis is shown in figure 3.

The model has been sub-divided into 11 patches and discretized into 3099 plane strain 4-nodes quadrilateral elements and 3211 nodes. We have used plane strain approximation here because the profile is perpendicular to the NSL which is an approximately 1600 km long tectonic feature and the profile is across this tectonic feature. Elastic material properties for every patch were selected based on seismic velocity, density, and depth of various layers (table 1). Young's modulus lies in the range of 10^{10}–10^{12} Pa.s for crustal rocks (Zuber *et al* 1989; Pauselli and Federico 2003; Dyksterhuis and Mueller 2004). This can be estimated from seismic P-wave velocity and density values of various rocks using the following relationship (Pauselli and Federico 2003):

$$E = \rho V_P^2 \frac{(1+\nu)(1-2\nu)}{3\nu}, \tag{1}$$

where E, ν, ρ, V_P are Young's modulus, Poisson's ratio, density, and seismic P-wave velocity, respectively. For the density and seismic velocity values available for our model, we get Young's modulus values in the range of 5–20×10^{10} Pa.s assuming Poisson's ratio of 0.25. Since pressure and temperature both increase with the depth, the elastic parameters should be corrected for these effects. We indirectly incorporate the thermal effect in terms of reduction of Young's modulus of the mid-crustal layer by assuming that the temperature increase would result in a decrease in the value of Young's modulus. This correction is somewhat arbitrary. Nevertheless the 10^{10}–10^{12} order of the magnitude of the Young's modulus is maintained. For example, the upper crustal layer (S9, S11) has been considered as being stronger in comparison to the mid-crustal layer (S5) although both have the same density values and S5 has a higher velocity in comparison to S9 and S11. Murty *et al* (2004) considered the layer S5 as the upper crustal layer. From rheological considerations, an upper crustal layer with quartz-dominated rheology when buried at a depth of 15–20 km would be mechanically weaker than when it is placed within the top 10 km depth. Therefore, we have considered this layer as mechanically weak and assigned a lower value of Young's modulus. Similarly, the high velocity layer (S6, S7, S8) has been considered as a mechanically strong layer keeping in view its lower crustal affinity/mafic intrusion nature (Mall *et al* 1991; Murthy *et al* 2004) and its shallow depth. Computations have been carried out by using an FEM package UWay (Vlasov *et al* 2000, 2004). This package has options for numerical estimation of stress–strain state and mechanical behaviour of soil and consolidate rocks, homogeneous and heterogeneous media, and composite materials.

5. Numerical results

We analyse various cases to arrive at a model that is able to show the concentration of shear stress in the hypocentral region of the 1997 Jabalpur earthquake. Numerical results for different cases are discussed below.

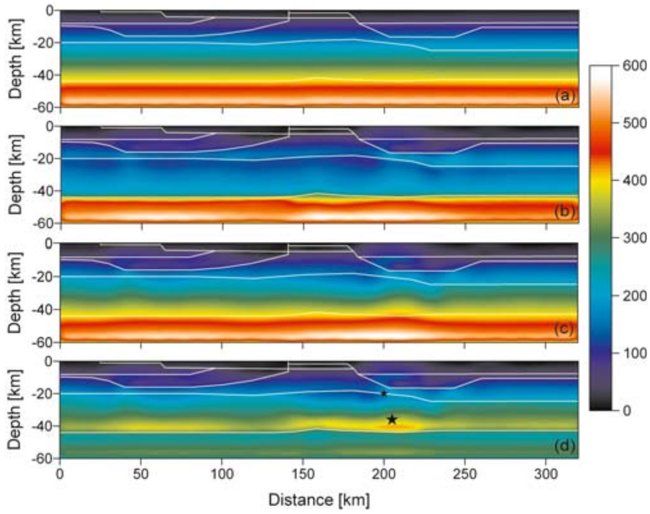

Figure 4. Computed maximum shear stresses in MPa for various model cases: **(a)** only density heterogeneities, **(b)** both density and mechanical property variations for elastically weak lower crust and strong upper mantle, **(c)** same as (b) but with elastically strong lower crust, and **(d)** strong lower crust and weak upper mantle. Large star represents the focal depth of the 1997 Jabalpur earthquake and small star corresponds to the 2001 Jabalpur earthquake.

5.1 *Stresses due to gravity load*

In the first model (M01), the effect of only density heterogeneities is analysed. Here, material parameters of all the layers, excluding the bottom two layers, have been fixed at $E = 1.0 \times 10^{10}$ Pa.s and $\nu = 0.25$. For this gravity loading case, no displacement condition ($u_x = u_z = 0$) has been applied at the bottom boundary of the model. This boundary is at a depth of 150 km and the layer just above this boundary (S1) is mechanically very weak to avoid the influence of this boundary on the stresses computed for the top 60 km of the model. The side boundaries impose the condition of no horizontal displacement ($u_x = 0$) and only vertical displacement (u_z) is allowed. The one-dimensional nature of the crustal structure at both sides of the model supports this boundary condition as the applied load is due to the gravity. The computed maximum shear stress (τ) is shown in figure 4(a). Crustal structure is also superimposed. The results indicate an increase in the value of τ with depth with the maximum value of about 550 MPa at a depth of 56–58 km. There is no remarkable lateral variation in τ due only to density variations.

In the next model (M02), material properties of lower crustal and upper mantle layers are so chosen that these represent a mechanically weak lower crust ($E = 1.0 \times 10^{11}$ Pa.s, $\nu = 0.38$) overlying a mechanically strong sub-Moho lithosphere ($E = 1.0 \times 10^{12}$ Pa.s, $\nu = 0.25$). Material properties of other layers are given in table 1. This model

Table 1. *Material properties assigned to various layers.*

Region	Patch no.	E ($\times 10^{10}$ Pa.s)	ν	Density [kg/m^3]	V_p [km/s]
Vindhyans	S10	2	0.25	2500	5.50
Upper crust	S9, S11	10	0.25	2700	5.90
High velocity layer	S6, S7, S8	50	0.25	2820	6.50
Middle crust	S5	2	0.25	2700	6.35
Lower crust*	S4	100	0.25	2900	6.80
Sub-Moho lithosphere*	S3	10	0.38	3300	7.80
Lower lithosphere	S2	0.8	0.45	2350	...
Asthenosphere	S1	0.1	0.499	3400	...

*Values of these two layers vary in various models analysed.

has been selected to represent a case similar to the rheological stratification of a typical continental lithosphere in which a weak, ductile lower crust rests on the top of a strong, brittle upper mantle. Here, elastically strong sub-Moho lithosphere and elastically weak lower crust can be correlated with the brittle upper mantle and ductile lower crust, respectively, of a rheological model. The results of τ for this case, shown in figure 4(b), indicate a decrease in τ in the depth range of 20–40 km and an enhancement in τ at the depth >50 km in comparison with the previous model. The maximum shear stress reaches to 575 MPa at the depth of 56–58 km and there are significant lateral variations in τ at different depth levels. Thus, variations in the mechanical property of various layers seem to have a profound effect on the shear stress distribution. Nevertheless this model is unable to produce the concentration of shear stress in the hypocentral region of the 1997 Jabalpur earthquake. Lateral variations in the shear stress are also seen in the upper and middle crust.

Further, we analyse a scenario (Model M03) in which both the lower crust and the upper mantle have strong mechanical properties ($E = 1.0 \times 10^{12}$ Pa.s, $\nu = 0.25$ for both the layers) keeping material properties of other layers the same as in M02. For this case shown in figure 4(c), the magnitude of τ in the lower crust increases by about 100 MPa in comparison to M02 but the maximum shear stress is once again confined to the sub-Moho lithosphere.

The last model (M04) consists of a strong lower crust ($E = 1.0 \times 10^{12}$ Pa.s, $\nu = 0.25$) resting on a weak upper mantle ($E = 1.0 \times 10^{11}$ Pa.s, $\nu = 0.38$). Material properties of other layers are the same as given in table 1. Computed τ for this case, shown in figure 4(d), reveals a zone of high stress concentration in the lower crust in the hypocentral region (large star) of the 1997 earthquake. The shear stress in this zone is about 60–80 MPa higher than the background shear stress of 330–350 MPa. Shear stress in the upper mantle layer is much smaller than that obtained for previous models. Another earthquake of 2000.10.16 at a depth of 20 km (small star) in the same region also falls in a zone where a perturbation in the computed shear stress is observed. This model shows a good correlation between the shear stress concentration/perturbation and the lower crustal seismicity.

5.2 *Stresses due to imposed horizontal displacement*

The above models incorporated only the effect of gravity loading due to density heterogeneities and mechanical properties variations. We have further computed the stresses induced in the crust as a result of horizontal plate tectonic forces. Two models, one having a weak lower crust resting on a strong upper mantle (M02), and the other having a strong lower crust resting on a weak upper mantle (M04) have been considered here. A horizontal plate tectonic force is applied in terms of specified displacement at the right boundary (figure 3). This displacement has a constant value of 30 m up to a depth of 60 km, below which it decreases linearly to zero at the bottom of the computation box. The value of 30 m has been arrived at by considering the probable magnitude of the plate tectonic forces. Coblentz *et al* (1998) used values of 2×10^{12} N/m and 4×10^{12} N/m for the ridge push and compressional force at the Himalayan collision boundary, respectively, in the modelling of the stress field of the Indian plate. This results in an average stress magnitude of 20–40 MPa. We use an average value of the above two to represent the plate tectonic force in the plate interior which yields on average 30 MPa stress. The 30 m displacement results in this stress level. Similar magnitude of regional maximum compressive stress was used by Mandal *et al* (1997) in the elastic stress modelling of the Killari earthquake region. The *in situ*

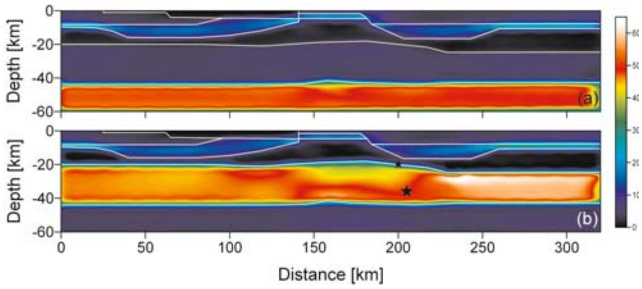

Figure 5. Computed maximum shear stresses in MPa for the case of prescribed horizontal displacement at the right boundary to simulate plate tectonic stresses. **(a)** elastically weak lower crust on strong upper mantle, and **(b)** strong lower crust and weak upper mantle.

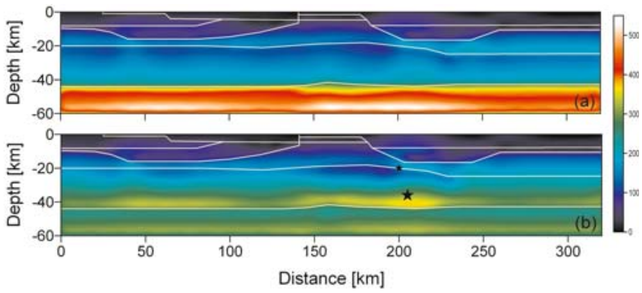

Figure 6. Maximum shear stresses in MPa after combining gravity stress shown in figure 4 and tectonic stress shown in figure 5 for the cases **(a)** weak lower crust, and **(b)** strong lower crust and weak upper mantle.

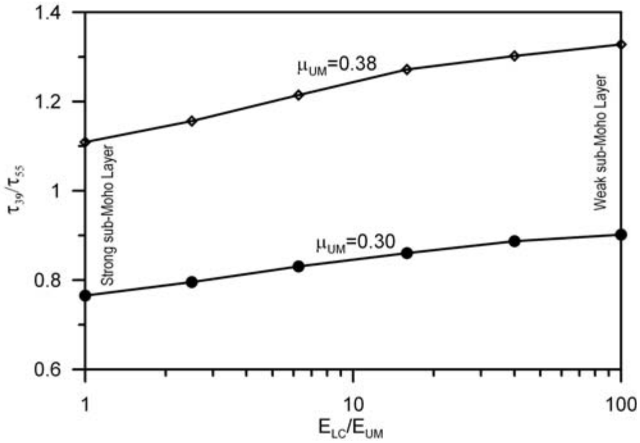

Figure 7. The effect of variations in the elastic parameters of the lower crust ($E_{\rm LC}, \nu_{\rm LC}$) and sub-Moho layer ($E_{\rm UM}, \nu_{\rm UM}$) on the concentration of maximum shear stress in the focal region of the lower crustal Jabalpur earthquake. Full details are described in the text.

stress measurements in the Indian shield and focal mechanisms of intraplate earthquakes suggest a mainly N–S direction of the maximum horizontal compression (Gowd *et al* 1992). Therefore, the horizontal displacement boundary condition applied in the present model is in good agreement with the direction of the maximum compressive stress in the Indian shield as the profile is almost NNW–SSE. We have considered a uniform displacement up to 60 km depth and then a linearly decreasing displacement keeping in view the mechanical properties of the lower lithosphere and the underlying asthenosphere. The boundary conditions at the left and bottom boundaries are the same as used for the previous case of gravity loading.

Computed distribution of τ for both the cases are shown in figure 5. Lateral variations in mechanical properties have a profound effect on the distribution of stresses. For the first case (figure 5a), concentration of large stresses is obtained within the upper lithosphere at the depth > 40 km. There is very little shear stress in the mid-crustal layer (S5) and lateral perturbations of about 10 MPa are observed within the high velocity layer (S6, S7, S8 in figure 3). The next model with a strong lower crust (figure 5b) shows a very different distribution of τ. In this model, τ is large within the lower crust. The hypocentral region (large star) falls in the region of large shear stress. Nevertheless the shear stresses produced by an imposed horizontal displacement of 30 m is much smaller than the shear stresses produced by gravity loading.

Combining shear stresses produced by horizontal displacement with the shear stresses due to the gravity loading does not change the distribution significantly for the lower crust (figure 6). However, there is very small change in the shear stress distribution in the hypocentral region of 2000.10.16 earthquake (small star in figure 6b).

6. Discussion and conclusion

The occurrence of intraplate seismicity in the lower crust can be used as an important constraint for mechanical models of continental lithosphere. Rheological models of continental lithosphere explain the lower crustal intraplate seismicity mainly in terms of cold and brittle lower crust under the assumption that earthquakes occur by frictional failure in the brittle regime. These models implicitly indicate a mechanically strong mantle lithosphere. Earlier work of Manglik and Singh (2002) on the lower crustal 1997 Jabalpur earthquake inferred low-to-moderate mantle heat flow in the NSL leading to a mechanically strong and brittle lower crust. We have analysed the mechanical properties of both the lower crust and the mantle lithosphere through elastic stress modelling. Our elastic stress modelling results indicate that the localized concentration of shear stresses at the lower crustal depths of more than 35 km can be attained only when the lower crust is mechanically strong in comparison to the underlying mantle lithosphere for elastic rheology. Thus, the present study provides a constraint on the mechanical properties of the mantle lithosphere by implying that it should be mechanically weak. This is further analyzed in figure 7.

In figure 7, we vary Young's Modulus (E) and Poisson's ratio ν for the lower crust (layer S4) and sub-Moho layer (layer S3) keeping all the other parameters the same as used for the model M04. Here $(E_{\mathrm{LC}}, \nu_{\mathrm{LC}})$ and $(E_{\mathrm{UM}}, \nu_{\mathrm{UM}})$ are Young's modulus and Poisson's ratio of S4 (lower crust (LC)) and S3 (mantle lithosphere (UM)), respectively. τ_{39}, τ_{55} are maximum shear stresses at a depth of 39 and 55 km, respectively, at the lateral profile distance of 210 km, which corresponds to the region of maximum stress concentration in our model. The depth 39 m is above the Moho whereas 55 km is below the Moho. The value of Young's modulus of the lower crust increases from left to right and two curves marked by solid circles and diamonds correspond to two values of Poisson's ratio ν_{UM} of the upper mantle, a higher value of which implies a weaker elastic rheology. ν_{LC} is taken as 0.25. The results indicate that a moderate increase in ν_{UM} to 0.30 from the standard value of 0.25 does not enhance the ratio τ_{39}/τ_{55} to make it larger than 1. It means that the maximum shear stress in the mantle lithosphere (S3) is still larger than the shear stress in the lower crustal layer (S4) even though Young's Modulus of the lower crust is increased by two orders of magnitude. The larger concentration of the shear stress in the lower crust in comparison to that in S3 is seen when ν_{UM} is further increased to 0.38, implying that the sub-Moho layer should be sufficiently weak for the stress concentration to take place in the lower crust. The results also indicate that variation in Young's modulus has only moderate effect on shear stress concentration whereas Poisson's ratio has a more profound effect.

To summarise, the shear stresses generated by density heterogeneities alone are not able to locally enhance the shear stress concentration in the hypocentral region of the lower crustal Jabalpur earthquake of 1997. The role of mechanical properties of various crustal layers is important in achieving this localization of shear stresses. Among a range of material parameters analysed in the present elastic stress modelling, the model with a mechanically strong lower crust overlying a relatively weak sub-Moho layer is 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. The mechanically strong lower crust is indicative of a dry granulite type rheology but even more interesting would be to understand what causes the mantle lithosphere of this region to behave as a relatively weak material in comparison to the lower crust. One possibility could be the presence of fluids in the sub-Moho layer which should reflect in P- and S-wave seismic velocities, attenuation factor, and electrical conductivity of the lower crust and upper mantle surrounding the hypocentral region. The P-wave seismic velocity of 7.8 km/s of the sub-Moho layer in this region (Murty *et al* 2004) is lower than the seismic velocity of 8.0–8.1 km/s representative of a normal continental mantle lithosphere. However, a detailed and high resolution integrated geophysical mapping of the hypocentral region is needed to more conclusively determine the nature of the upper mantle of this region.

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