Rheological stratification of the Indian continental lithosphere: Role of diffusion creep

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Dynamic recrystallization and reduction in grain-size at large strains, e.g. in shear zones, leads to rheological weakening of the lithosphere and facilitates intense ductile deformation. In the present work, we include this effect into the rheological models of the Indian continental lithosphere to analyse its role in modifying the rheological structure and strength of the Indian lithosphere. The results computed by using quartz and felspar rheologies for the upper and lower crust, respectively, and grain-size dependent olivine rheology for the upper mantle, indicate an increase in the ductility of the mantle lithosphere.

1. Introduction

Rheological models of the lithosphere integrate the effects of temperature and fluids to mechanical deformation as rocks undergo different modes of deformation under varying pressure and temperature conditions (Kirby 1977; Goetze and Evans 1979; Brace and Kohlstedt 1980; Meissner and Strehleau 1982). Despite large uncertainties involved in establishing the empirical flow laws (Rutter and Brodie 1991), these models have been successfully used to explain many enigmatic features unraveled by sophisticated deep crustal probing techniques (Sibson 1983; Chen and Molnar 1983; Le Pichon and Barbier 1987; Yin 1989). Recently, rheological models have been used to explain the dynamics of continental rifting and sedimentary basin formation (Zuber and Parmentier 1986; Kusznir *et al* 1987; Harry and Sawyer 1992; Peper and Cloetingh 1992; van der Beek and Cloetingh 1992). In most of these studies a power law type nonlinear stress-strain rate relationship has been used to demarcate the brittle/ductile (B/D) transition. In this relationship, stress is sensitive to the temperature and strain rate for a given composition. This gives a dislocation creep and ignores the effect of grain-size on the ductility of a mineral/rock. This relation gives an inverse dependence of the depth on the B/D transition and temperature. However, there are some regions which have low surface heat flow and yet require very small shear stress for slip. One such example is the San Andreas fault. This enigmatic behaviour, contrary to the rheological modeling results based on dislocation creep, has been explained by Furlong (1993) and Hopper and Buck (1993) invoking the diffusion creep mechanism in olivine. In diffusion creep the stress-strain rate relationship becomes a function of grain-size also and supports ductile deformation in the regions of low heat flow. Karato *et al* (1986) have discussed an empirical relationship for olivine based on experimental studies on grain-size effect.

In the Indian continental region, rheological models of lithosphere were initially developed by Singh (1981) and Bhattacharji and Singh (1984) using olivine rheology and the available surface heat flow and heat production data. These models were later modified by Manglik and Singh (1991) to include more realistic quartz and felspar rheologies for the continental upper and lower crust respectively. Manglik and Singh (1992) estimated the rheological thickness and strength of the lithosphere in different regions of the Indian shield. Cermak *et al* (1991) have developed a rheological model for Arakan-Yoma region using Westerly granite, Maryland diabase and Aheim dunite rheologies for the upper and lower crust, and upper

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mantle respectively. These models, however, are based on dislocation creep mechanism for olivine rheology and use a power law empirical relationship. In the present paper, we include the effect of grain-size variation and study its effect on the rheological structure of the Indian shield.

2. Rheological modeling for diffusion creep

In a ductile regime, the steady state flow with diffusion creep is given by (Karato *et al* 1986; Hopper and Buck 1993):

$$\sigma_1 - \sigma_3 = \left(\frac{\dot{\epsilon}}{A}\right)^{1/n} d^{m/n} \exp[-Q/RT] \qquad (1)$$

where $\dot{\epsilon}$ is the strain rate, σ_1, σ_3 the principal stresses, d the mineral grain-size, T the absolute temperature, Q the activation energy, A and n the material parameters, m the grain-size exponent and R is the gas constant. This relationship is different from the power law creep in terms of grain-size and the numerical values of material parameters A, Q, n and m. The power law relationship is given as:

$$\sigma_1 - \sigma_3 = \left(\frac{\dot{\epsilon}}{A'}\right)^{1/n'} \exp[-Q'/RT]. \qquad (2)$$

In a brittle regime, the shear strength is computed by combining the Navier-Coulomb criterion and the stress condition of the Anderson theory of faulting (Sibson 1974). This relationship for the cases of thrust, strike-slip and normal faulting is given as:

$$\sigma_1 - \sigma_3 = \begin{cases} [R'-1]\rho g z(1-\lambda) & \text{Thrust case} \\ [(R'-1)/(1-\delta+\delta R')] & \\ \qquad \times \rho g z(1-\lambda) & \text{Strike slip case} \\ [(R'-1)/R']\rho g z(1-\lambda) & \text{Normal case} \end{cases} \qquad (3)$$

where R' is the ratio of maximum to minimum principal stress required for the rock to fail by faulting and is expressed in terms of the coefficient of static friction μ_s as:

$$R' = [\sqrt{1+\mu_s^2} + \mu_s]/[\sqrt{1+\mu_s^2} - \mu_s].$$

For $\mu_s = 0.75$, R' becomes equal to 4. The parameters ρ, g, λ and z are density, gravity acceleration, pore fluid factor, and depth coordinate respectively. δ is a constant which gives the maximum and minimum limits of the shear strength required for strike slip faulting. This takes a value between 0 and 1.

Computation of shear strength according to the diffusion creep law (equation 1) requires a knowledge of the thermal structure of the lithosphere. We have computed the thermal structure at different locations in the Indian shield by extrapolating the surface heat flow and heat generation data. This is achieved by solving the 1-D heat conduction equation with an exponential radiogenic heat distribution model. Details of mathematical analysis are given in the paper by Manglik and Singh (1991). The surface heat flow and heat generation (Rao *et al* 1976) values used are shown in figure 1.

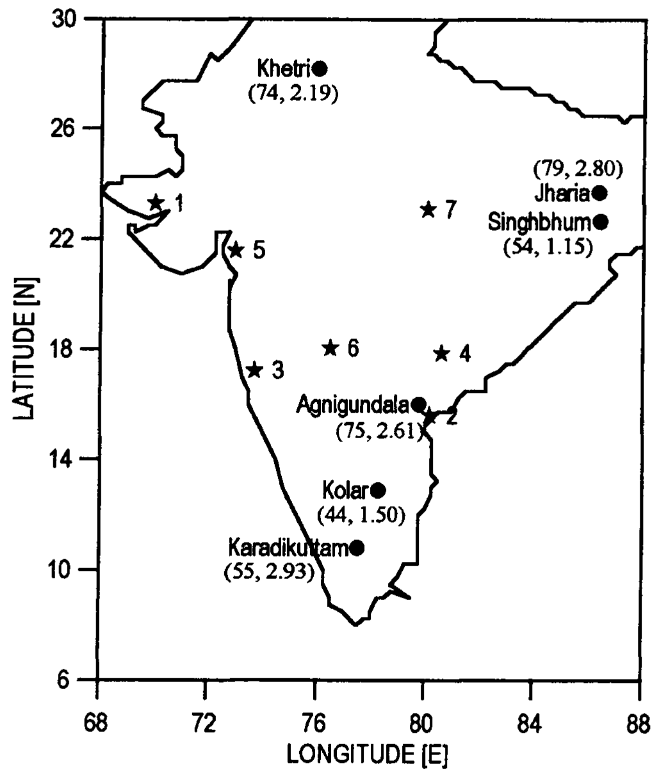

Figure 1. Map showing locations of heat flow-heat generation pairs (solid circle) and epicenters of some of intraplate earthquakes (solid star). The values of surface heat flow (Q in mW/m^2) and radiogenic heat generation (A in μW/m^3) are also given as (Q, A) pairs. The epicenters numbered 1 to 7 correspond to Anjar [1956], Ongole [1959], Koyna [1967], Bhadrachalam [1969], Broach [1970], Killari [1993], and Jabalpur [1997], respectively.

The subsurface structure is another important parameter, required for rheological modeling. We have considered a three-layered model of the Indian shield with quartz, diabase and olivine rheologies for the upper crust, lower crust, and mantle lithosphere respectively. Manglik and Singh (1991, 1992) have used the crustal structure given by Bhattacharya (1971) in the rheological modeling with dislocation creep. This model gives upper and lower crustal thicknesses of 12.5 and 28.5 km respectively. However, Hwang and Mitchall (1987) have estimated the upper and lower crustal thicknesses of 20.4 and 18.3 km respectively based on surface wave studies. Deep seismic sounding results of the southern Indian shield give crustal thickness variations between 36 and 45 km (Kaila and Krishna 1992). Rai *et al* (1992) have estimated a crustal thickness of 36–38 km in the

Dharwar craton and granulite terrain based on travel time residual analysis. Based on these studies, we assume for our rheological modeling, a 38 km thick crust with an upper crustal thickness of 20 km. This is, however, a general model and more specific models would require a detailed knowledge of the crustal structure.

3. Results

3.1 *Rheological stratification*

Rheological parameters given in table 1 are used to compute the thicknesses of the brittle and ductile layers in the lithosphere at different locations in the Indian shield. We have assumed the grain-size of 1 mm for olivine which is suggested as the critical value at which results of dislocation and diffusion creep roughly match (Hopper and Buck 1993). Stratification is computed for a range of strain rate values between 10^{-11} and $10^{-16}\,s^{-1}$ and these results are shown in figure 2. The results for strain rate of $10^{-14}\,s^{-1}$ are given in table 2. Figure 2 shows the shear strength profiles in normal and thrust environments for different strain rate values at different locations. The shear strength for normal faulting is shown on the negative side of the stress axis. The temperature is shown by the thick line.

A significant lateral variation in the thickness of brittle and ductile layers is seen in the models obtained for different regions (table 2). These results show the presence of a ductile layer in the upper crust which is different from the results of Manglik and Singh (1991). This effect is obtained because of the presence of a thick upper crustal layer having quartz-rich rheology. In the case of a thin upper crust this layer vanishes and results for the crustal part are the same as those obtained by Manglik and Singh (1991).

The upper crustal B/D transition is at a depth of 12.5 km under Jharia but the whole upper crust becomes brittle under Kolar for a thrust faulting case. These two locations represent regions of minimum and maximum brittle layer thicknesses. At other locations, values fall between these two extremes. Similarly, the lower crustal B/D transition is at a depth of 32 km at Kolar for thrust regime but the lower crust is ductile under Jharia. The mantle B/D transition is at 45.5 km depth for Kolar in thrust regime. Under Jharia the mantle lithosphere is ductile. These results indicate mostly the ductile nature of the lithosphere under Jharia which is not the case with the Kolar region. Variations in strain rate affect these estimates. The increase in strain rate increases the thickness of brittle layers. For example, in Kolar the mantle B/D transition is at 65.5 km depth for a strain rate of $10^{-11}\,s^{-1}$ and normal faulting regime. This transition moves upward to 40 km for a strain rate of $10^{-16}\,s^{-1}$ (figure 2).

The results of diffusion creep for 1 mm grain-size are compared with those obtained by the dislocation creep (Manglik and Singh 1991). These results are computed for $10^{-14}\,s^{-1}$ strain rate and are given in table 3. The results indicate shallowing of the mantle B/D transition. The dislocation creep results yield a thin brittle mantle layer under Khetri, Jharia and Agnigundala. For diffusion creep, this layer disappears and the mantle lithosphere becomes ductile. For Kolar the B/D transition moves upward from 56.5 to 48 km for normal faulting and from 51.5 to 45.5 km for thrust faulting regimes when the deformation mechanism is changed from dislocation to diffusion with 1 mm grain-size.

Table 1. *Values of rheological parameters used in the computations of rheological profiles (c.f. Smith and Bruhn 1984; Hopper and Buck 1993).*

Rheology	A $MPa^{-n}\,s^{-1}$	Q $kJ\,mol^{-1}$	n	m
Quartz	5.0×10^{-6}	1.90×10^{5}	3.0	...
Diabase	5.2×10^{2}	3.56×10^{5}	3.0	...
Olivine	1.5×10^{-3}	2.50×10^{5}	1.0	3.0

3.2 *Thickness of rheological lithosphere*

The rheological thickness of the lithosphere is obtained from the depth at which shear strength drops below 10 MPa (Fadaie and Ranalli 1990). The results for diffusion creep are compiled in table 4. These results indicate that the rheological thickness of lithosphere decreases significantly when the diffusion creep mechanism is included. For example, the rheological thickness of lithosphere for Kolar at $10^{-14}\,s^{-1}$ strain rate becomes 57 km for olivine grain-size of 1 mm as against the 79 km thickness obtained by dislocation creep (Manglik and Singh 1992). This reduction in thickness leads to weakening of the lithosphere and, hence, a modification in its flexural response.

3.3 *Lithospheric strength*

The total strength of the lithosphere is obtained by integrating the shear strength profile over the thickness of the rheological lithosphere (Fadaie and Ranalli 1990) i.e.

$$F = \int_0^L (\sigma_1 - \sigma_3)(z)dz \tag{4}$$

where σ_1, σ_3 are principal stresses, L the rheological thickness of lithosphere and F the total strength. The difference between principal stresses $(\sigma_1 - \sigma_3)$ obtained in the earlier section for brittle and ductile regimes is integrated numerically to obtain the total strength of the lithosphere. These results obtained for six locations in the Indian shield are shown in figure 3 for

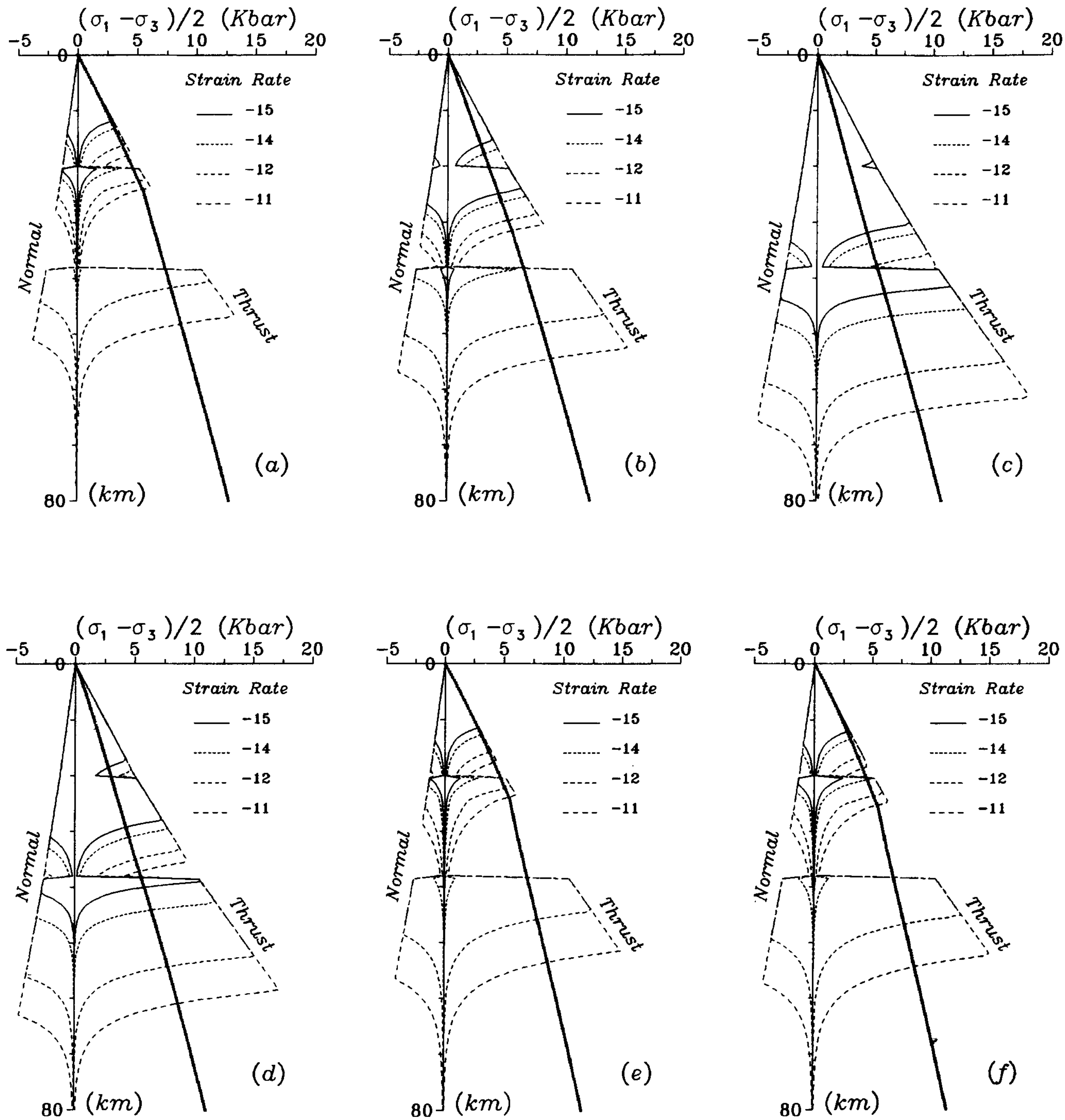

Figure 2. Rheological stratification at different locations in the Indian shield for quartz, diabase and olivine rheologies and different strain rates. Diffusion creep is assumed as dominant mechanism for olivine having grain-size of 1 mm. Positive axis shows the strength profile for thrust faulting regime and negative axis corresponds to the normal faulting regime. For strike-slip faulting strength ranges between these two extremes. Temperature profile is shown by thick line. Different locations are: (**a**) Khetri, (**b**) Singhbhum, (**c**) Kolar, (**d**) Karadikuttam, (**e**) Jharia, and (**f**) Agnigundala.

strain rate ranging between 10^{-11} and $10^{-16}\,s^{-1}$. The maximum and minimum strengths are obtained for Kolar and Khetri respectively. At Kolar it increases from 2.69×10^{13} to $11.68 \times 10^{13}\,Nm^{-1}$ for strain rate increasing from 10^{-16} to $10^{-11}\,s^{-1}$ for thrust regime. For the same strain rate values, it varies from 0.42×10^{13} to $4.73 \times 10^{13}\,Nm^{-1}$ at Khetri. The total strength in normal faulting case varies from 0.95×10^{13} to $3.4 \times 10^{13}\,Nm^{-1}$ for Kolar and from 0.18×10^{13} to $1.73 \times 10^{13}\,Nm^{-1}$ for Khetri for the same strain rate variation.

3.4 *Effect of grain-size reduction*

We have computed the effect of olivine grain size reduction on the nature of rheological stratification

Table 2. *Depths to the B/D transitions in the upper crust, lower crust and upper mantle for normal and thrust faulting cases respectively. The shear strength values for strike-slip case range between these two limits.*

Station	Depth of Upp. crustal B/D Transition		Depth of Low. crustal B/D Transition		Depth of mantle B/D Transition	
	N	T	N	T	N	T
Khetri	15.5	13.0	22.0	D	D	D
Singhbhum	B	17.0	28.5	25.5	40.0	D
Kolar	B	B	35.0	32.0	48.0	45.5
Karadikuttam	B	19.0	33.0	29.5	45.0	42.5
Jharia	15.0	12.5	21.5	D	D	D
Agnigundala	16.0	13.0	23.0	D	D	D

Table 3. *A comparison of the B/D transition depth in the mantle lithosphere obtained for diffusion creep at 1 mm grain-size with that obtained for dislocation creep at different locations. Strain rate of* 10^{-14} s^{-1} *is used.*

Station	Dislocation creep N	Dislocation creep T	Diffusion creep N	Diffusion creep T
Khetri	44.5	40.5	D	D
Jharia	49.5	44.0	D	D
Agnigundala	50.5	45.0	D	D
Singhbhum	49.0	44.0	40.0	D
Karadikuttam	54.0	49.0	45.0	42.5
Kolar	56.5	51.5	48.0	45.5

Table 4. *Thickness of rheological lithosphere for grain-size of 1 mm at different values of strain rate.*

Station	Strain rate (s^{-1}) 10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-16}
Khetri	66	56	48	41	28	25
Jharia	75	63	54	46	29	25
Agnigundala	76	64	54	46	29	26
Singhbhum	73	63	55	48	35	33
Karadikuttam	80	69	61	54	48	43
Kolar	83	72	64	57	51	46

using data from the Kolar region. For this purpose we have considered two values of olivine grain-size, 0.1 mm and 1 mm. These results are obtained for strain rates varying between 10^{-16} and $10^{-11}\,s^{-1}$ and are shown in figure 4(a). Variation in the B/D transition is given in table 5. The total strength is also shown in figure 4(b). The rheological behaviour of the crust remains the same because the grain-size effect is included only for olivine. For the grain-size of 0.1 mm the mantle B/D transition moves upward to 48 km which is significantly different from the depth to B/D transition of 65.5 km obtained for normal faulting regime with a strain rate of $10^{-11}\,s^{-1}$. In this case the mantle brittle layer disappears (figure 4(a)) for the strain rate of $10^{-14}\,s^{-1}$. These results indicate a prominent role of grain-size in controlling the nature of deformation. The total strength for the thrust faulting case also reduces from $5.27 \times 10^{13}\,Nm^{-1}$ to $3.07 \times 10^{13}\,Nm^{-1}$ for a strain rate of $10^{-14}\,s^{-1}$ (figure 4(b)).

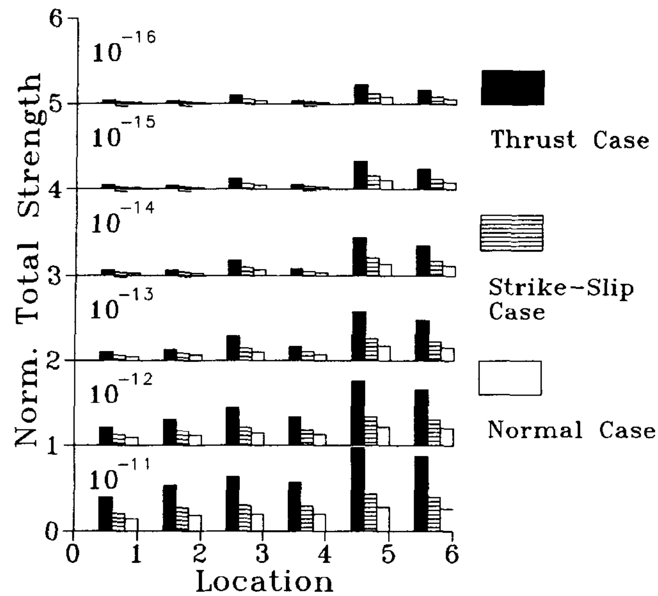

Figure 3. Normalized total strength of the Indian continental lithosphere at different locations: (**1**) Khetri, (**2**) Jharia, (**3**) Singhbhum, (**4**) Agnigundala, (**5**) Kolar, and (**6**) Karadikuttam for strain rate ranging between 10^{-11} and $10^{-16}\,s^{-1}$. These strength values are computed for diffusion creep in olivine. the normalization is done w.r.t. $12.0 \times 10^{13}\,Nm^{-1}$. The three bars at any location correspond to thrust, strike-slip and normal faulting cases respectively.

4. Discussion and conclusion

The effect of grain-size on the rheological structure is important in the regions of large strains where dynamic recrystallization facilitates grain-boundary diffusion and ductile flow which focusses itself into the shear zone. This results in the generation of rheological heterogeneities of reduced strength in the lithosphere. Tommasi and Vauchez (1997) showed through numerical modeling of rheologically heterogeneous medium that the pre-existing rheological heterogeneities favour the development of a heterogeneous strain field with strain localization in weak zones and stress concentration at the tips of stiff inclusions. Vauchez *et al* (1997) invoked the rheological heterogeneity model of continental lithosphere, where old cratonic nuclei form cold, stiff zones and surrounding mobile belts form rheologically weak zones, to explain the

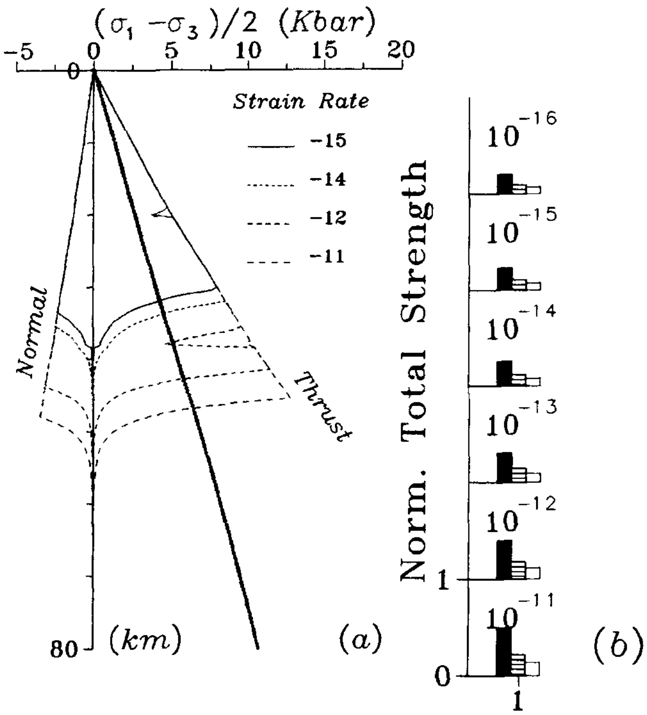

Figure 4. (a) Rheological stratification at Kolar for olivine diffusion creep with grain-size of 0.1 mm, and (b) the total strength of lithosphere for the three faulting cases corresponding to the above rheological stratifications. These values are computed for strain rate values ranging from 10^{-16} to 10^{-11} s^{-1}.

Table 5. *Effect of grain-size reduction on the shallowing of the mantle B/D transition at Kolar. These results are computed for strain rate of* 10^{-14} s^{-1}.

Grain-size (mm)		Strain rate (s^{-1}) 10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-16}
0.1	N	48.0	43.5	40.5	D	D	D
	T	45.5	41.5	38.5	D	D	D
1.0	N	65.5	58.5	53.0	48.0	43.5	40.0
	T	61.0	55.0	49.5	45.5	41.5	D

localization of extensional deformation at the boundaries of cratonic nuclei. In these zones large deformation can facilitate grain-size reduction. The Indian shield also is an assemblage of cratonic nuclei and surrounding mobile belts. The rheological models mentioned above can, therefore, be used to understand the strain localization in the Indian shield. The rheological structure, thickness, and strength of the Indian continental lithosphere obtained above by including the grain-size effect show a significant increase in the ductility of the mantle lithosphere in comparison to those obtained for dislocation creep mechanism (Manglik and Singh 1991, 1992). Of the six heat flow locations used in the study, three viz., Kolar, Karadikuttam, and Singhbhum correspond to the cratonic regions and have the much lower surface heat flow values in comparison to the other three sites viz., Khetri, Jharia, and Agnigundala. Correspondingly, the results indicate a rheologically weak lithosphere for Khetri, Jharia, and Agnigundala where ductile deformation is dominant.

A lateral variation in the rheological structure and strength of the lithosphere can also be manifested in the flexural response of lithospheric plate. A reduction in the mechanical thickness and strength of the lithosphere implies a decrease in its flexural rigidity. A rheologically laterally heterogeneous lithosphere, therefore, would give rise to a plate of laterally variable flexural rigidity which would flex differently in response to the applied load and would show up in topography and Bouguer gravity anomaly. Jin *et al* (1996) modeled the gravity and topography over the Himalaya and Tibet and showed that the strength of the Indian plate reduces as it thrusts under the High Himalaya. The grain-size induced diffusion creep might be an important mechanism in reducing the lithospheric strength.

A detailed understanding of the lateral distribution of rheological heterogeneities requires a detailed knowledge of the thermal structure besides the crustal structure. However, only about a dozen values of the heat flow-heat generation pairs are available for the Indian shield. There are other indirect methods to infer the rheological state of the crust and uppermost mantle e.g. large reflectivity of the lower continental crust and depth distribution of intraplate seismicity. The Indian shield has experienced moderate intraplate seismicity in the recent past. Some of these events for which focal depths are available are shown in figure 1. These events are: Anjar [1956], Ongole [1967], Koyna [1967], Bhadrachalam [1969], Broach [1970], Killari [1993], and Jabalpur [1997]. The estimated focal depths of these events are less than 15 km (Chung and Gao 1995; Chandra 1977; Gupta *et al* 1969; Chung 1993; Gupta 1994) except for the Jabalpur event for which a focal depth of more than 35 km (Bhattacharya *et al* 1997) has been estimated. This information can be used to infer a 15 km thickness for the upper crustal brittle layer. Although all other events are away from the heat flow sites the Ongole event is close to the heat flow site at Agnigundala (figure 1) for which we have obtained an upper brittle layer of 16 and 13 km thickness for normal and thrust faulting cases, respectively (table 2). This is in good agreement with the focal depth of Ongole events.

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References

Bhattacharya S N 1971 Seismic surface wave dispersion and crust mantle structure of India peninsula; *Indian J. Met. Geophys.* **22** 179–186

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; *Curr. Sci.* **73** 855–863

Bhattacharji S and Singh R N 1984 Thermo-mechanical structure of the southern part of the Indian shield and its relevance to Precambrian basin evolution; *Tectonophys.* **105** 103–120

Brace W F and Kohlstedt D L 1980 Limits on lithospheric stress imposed by laboratory experiments; *J. Geophys. Res.* **85** 6248–6257

Cermak V, Bodri L and Saikia M M 1991 Geothermal and rheological implications of the crustal earthquakes within and west of the Arakan-Yoma fold belt (Northeastern India); *J. Geol. Soc. India* **38** 282–292

Chandra U 1977 Earthquakes in Peninsular India: A seismotectonic study; *Bull. Seismol. Soc. Am.* **67** 1387–1413

Chen W P 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.* **88** 4183–4214

Chung W-Y 1993 Source parameters of two rift-associated intraplate earthquakes in peninsular India: the Bhadrachalam earthquake of April 13, 1969 and the Broach earthquake of March 23, 1970; *Tectonophys.* **225** 219–230

Chung W-Y and Gao H 1995 Source parameters of the Anjar earthquake of July 21, 1956, India, and its seismotectonic implications for the Kutch rift basin; *Tectonophys.* **242** 281–292

Fadaie K and Ranalli G 1990 Rheology of the lithosphere in the East African rift systems; *Geophys. J. Int.* **102** 445–453

Furlong K P 1993 Thermal-rheologic evolution of the upper mantle and the development of the San Andreas fault system; *Tectonophys.* **223** 149–164

Goetze C and Evans B 1979 Stress and temperature in a bending lithosphere as constrained by experimental rock mechanics; *Geophys. J. R. Astron. Soc.* **59** 469–478

Gupta H K 1994 Latur earthquake; *Geol. Soc. India Mem.* **35** 149pp

Gupta H K, Hari Narain, Rastogi B K and Indra Mohan 1969 A study of the Koyna earthquake of December 10, 1967; *Bull. Seismol. Soc. Am.* **59** 1149–1162

Harry D L and Sawyer D S 1992 A dynamic model of extension in the Baltimore Canyon Trough region; *Tectonics* **11** 420–436

Hopper J R and Buck W R 1993 The initiation of rifting at constant tectonic force: role of diffusion creep; *J. Geophys. Res.* **98** 16213–16221

Hwang H G and Mitchall B J 1987 Shear velocities Q_β, and the frequency dependence of Q_β in stable and tectonically active regions from surface wave observations; *Geophys. J. R. Astron. Soc.* **90** 575–613

Jin Y, McNutt M K, and Zhu Y S 1996 Mapping the descent of Indian and Eurasian plates beneath the Tibetan plateau from gravity anomalies; *J. Geophys. Res.* **101** 11275–11290

Kaila K L and Krishna V G 1992 Deep seismic sounding studies in India and major discoveries; *Curr. Sci.* **62** 117–154

Karato S, Paterson M S and Fitzgerald J D 1986 Rheology of synthetic olivine aggregates: influence of grain-size and water; *J. Geophys. Res.* **91** 8151–8176

Kirby S H 1977 State of stress in the lithosphere: Inference from the flow laws of olivine; *Pure Appl. Geophys.* **115** 245–258

Kusznir N J, Karner G D and Egans K 1987 Geometric, thermal and isostatic consequences of detachments in continental lithosphere extension and basin formation; In: Sedimentary basins and basin forming mechanisms. (eds) C Beaumont and A J Tankard, *Cand. Soc. Petrol. Geolo. Mem.* **12** 185–203

Le Pichon X and Barbier F 1987 Passive margin formation by low angle faulting within the upper crust: The northern Bay of Biskay margin; *Tectonics* **6** 133–150

Manglik A and Singh R N 1991 Rheology of Indian continental crust and upper mantle; *Proc. Indian Acad. Sci (Earth Planet. Sci.)* **100** 389–398

Manglik A and Singh R N 1992 Rheological thickness and strength of the Indian continental lithosphere; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **101** 339–345

Meissner R and Strehleau J 1982 Limits of stresses in continental crust and their relation to the depth-frequency distribution of shallow earthquakes; *Tectonics* **1** 73–89

Peper T and Cloetingh S 1992 Lithospheric dynamics and tectono-stratigraphic evolution of the Mesozoic Betic rifted margin (Southeastern Spain); *Tectonophys.* **203** 345–361

Rai S S, Ramesh D S, Srinagesh D, Suryaprakasam K, Mohan G, Rajagopala P V S S, Satyanarayana Y and Gaur V K 1992 Seismic tomography of the south Indian shield; *Curr. Sci.* **92** 213–226

Rao R U M, Rao G V and Hari Narain 1976 Radioactive heat generation and heat flow in the Indian shield; *Earth Planet. Sci. Lett.* **30** 57–64

Rutter E H and Brodie K H 1991 Lithospheric rheology – a note of caution; *J. Struct. Geol.* **13** 363–367

Sibson R H 1974 Frictional constraints on thrust, wrench and normal faults; *Nature* **249** 542–544

Sibson R H 1983 Continental fault structure and the shallow earthquake source; *J. Geol. Soc. London* **140** 747–767

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

Smith R B and Bruhn R B 1984 Intraplate extensional tectonics of the eastern Basin-Range: Inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation; *J. Geophys. Res.* **89** 5733–5762

Tommasi A and Vauchez A 1997 Continental-scale rheological heterogeneities and complex intraplate tectono-metamorphic patterns: insights from a case-study and numerical models *Tectonophys.* **279** 327–350

van der Beek P A and Cloetingh S 1992 Lithospheric flexure and the tectonic evolution of the Betic Cordilleras (SE Spain); *Tectonophys.* **203** 325–344

Vauchez A, Barruol G, and Tommasi A 1997 Why do continents break-up parallel to ancient orogenic belts?; *Terra Nova* **9** 62–67

Yin A 1989 Origin of regional rooted low angle normal faults: A mechanical model and its tectonic implications; *Tectonics* **8** 469–482

Zuber M T and Parmentier E M 1986 Extension of continental lithosphere: a model for two scales of Basin and Range deformation; *J. Geophys. Res.* **91** 4826–4836

MS received 29 November 1996; revised 25 January 1999