Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 101, No. 4, December 1992, pp. 339–345.
© Printed in India.

Rheological thickness and strength of the Indian continental lithosphere

A MANGLIK and R N SINGH
National Geophysical Research Institute, Hyderabad 500 007, India

MS received 30 April 1992; revised 12 October 1992

Abstract. The estimates of rheological thickness and total lithospheric strength for the Indian continental lithosphere have been obtained based on the representative rheological properties of upper crust, lower crust and upper mantle, and some of the available heat flow and heat generation data. The rheological thickness, computed at different locations in the Indian shield, shows lateral variation ranging from 79 km in the southern part to 65 km in the northern part for a strain rate of $10^{-14}s^{-1}$. The total strength of the continental lithosphere is of the order of $10^{13}Nm^{-1}$ for the same value of strain rate and decreases northward. The computations carried out for a range of strain rates show an increase in the rheological thickness and strength of the lithosphere with increasing strain rate. These results would be important in understanding the flexural response of the Indian continental lithosphere to surface and subsurface loading, and response to tectonic forces acting on it.

Keywords. Strength; rheology; continental lithosphere; brittle; ductile.

1. Introduction

Rheological models of the crust and upper mantle are finding applications in understanding structure, seismicity and tectonic phenomena occurring in continental and oceanic regions (Kirby 1977, 1983; Goetze and Evans 1979; Brace and Kohlstedt 1980; Sibson 1982). Rheological models are constructed using the thermal structure as determined from the heat flow and heat generation studies, and the rheological laws as determined from the experimental studies of the mechanical behaviour of rocks. Rheological model for the Indian region, following this approach, has been constructed by Singh (1981) and Bhattacharji and Singh (1984) using olivine flow laws to represent the lithosphere. Manglik and Singh (1991) have recently constructed a stratified model using the flow laws of quartz, diabase and olivine as representative of upper and lower crust, and upper mantle respectively. Implications of these results in the seismicity in terms of presence of brittle layers in the crust and upper mantle have been discussed.

Two other results of geophysical relevance *viz* rheological thickness and strength of the lithosphere can also be determined from the computed rheological profiles. Rheological thickness is determined as the depth below which the shear stress reduces to a value generally observed in the upper mantle such as 1–10 MPa. This depth is useful in the analysis of flexural response of the crust and upper mantle. The strength of the lithosphere is defined as force per unit length required to maintain deformation at a given strain rate (England 1983). England computed the strength of continental lithosphere undergoing extension by considering only the ductile flow law of olivine as representative rheology of the lithosphere. Sawyer (1985) gave a modified estimate of strength by including the effect of upper brittle layer. These models of lithospheric strength have been discussed mainly to study the failure mechanism in different rift systems, and to estimate the strength of continental lithosphere in shield areas. The strength estimates are needed to understand the response of the lithosphere shield areas. The strength estimates are needed to understand the response of the lithosphere to compressional forces such as in Himalayan collision and tensional forces such as in Indian continental margins and rifts.

In this paper we present the estimates of the rheological thickness and total strength of the Indian continental lithosphere based on the rheological models discussed by Manglik and Singh (1991).

2. Rheological modelling

In the modelling of complex rheological stratification of the continental lithosphere the mechanical properties of rocks under differing conditions of pressure and temperature regime play a vital role. The rocks which otherwise are brittle behave as a ductile substance under the conditions of increasing temperature. Therefore the flow laws of rock types representative of upper and lower crust, and upper mantle are used to model the thicknesses and depth extent of different brittle/ductile layers in the lithosphere. In brittle regime the shear strengths for thrust, strike-slip and normal faulting cases are given by

$$(\sigma_1 - \sigma_3) = (R' - 1)\rho g z(1 - \lambda)$$
$$2[(R' - 1)/(R' + 1)]\rho g z(1 - \lambda)[(R' - 1)/R']\rho g z(1 - \lambda) \quad (1)$$

where ρ is the density, g the gravity acceleration, λ the pore fluid factor, σ_1 and σ_3 the principal stresses and R' the value of the ratio of maximum to minimum principal stresses required to initiate sliding (Sibson 1974). Sibson (1974) obtained the above expressions for principal stresses difference for cohesionless medium combining Navier–Coulomb condition of failure and Anderson theory of faulting. In Anderson theory of faulting, the effective overburden pressure at any depth is considered as the least principal stress for thrust, the maximum principal stress for normal and the intermediate principal stress for strike-slip faulting cases. Sibson derived principal stresses difference in a medium, with coefficient of internal friction μ, for failure on a plane which is most favourably inclined to the principal stresses (i.e. $\tan 2\theta = 1/\mu$; θ is the angle of fault plane with σ_1). We have taken μ as 0·75. It is thus seen that the shear stress required for brittle failure is more in thrust faulting case than in the case of normal faulting. Recently Ranalli and Yin (1990) have extended Sibson's work for finite cohesive medium. They also analysed the failure criterion in the presence of strength anisotropies in the medium. Yin and Ranalli (1992) have further extended this analysis for cases where none of the principal stresses is vertical. However, in the present computations we consider the above expressions given by Sibson (1974) for the computation of principal stresses difference.

In ductile regime the shear strength is given by power law as:

$$(\sigma_1 - \sigma_3) = (\dot{\varepsilon}/\mathrm{A})^{1/n}\exp[Q/nRT] \quad (2)$$

where $\dot{\varepsilon}$ is the strain rate, R the gas constant, T the absolute temperature and Q, A and n the material parameters.

One of the most important parameters, the thermal structure of the lithosphere, is obtained by solving the 1-D steady-state heat conduction equation for a depth dependent thermal conductivity structure and exponential radioactive source distribution. The solution is discussed in detail by Manglik and Singh (1991). Manglik and Singh computed shear strength profile for a strain rate of $10^{-14}s^{-1}$, a value suggested by Ranalli and Murphy (1987) for shield regions. The average crustal structure given by Bhattacharya (1971) was taken to represent the Indian continental crust. We have obtained shear strength profile for strain rate $\dot{\varepsilon}$ ranging between $10^{-11}-10^{-16}s^{-1}$ (Kirby 1977) to analyse the effect of variation in strain rate on the rheological thickness and strength of the lithosphere.

3. Rheological thickness of the lithosphere

The depth at which the shear strength drops below 10 MPa is taken as rheological thickness. We estimate the rheological thickness of the lithosphere at different locations shown in figure 1, for different values of strain rate, taking into account the upper limit of activation energy of olivine given by Chen and Molnar (1983). The estimates of rheological thickness (table 1) show a southward increasing trend. The rheological thicknesses of 65 and 79 km are obtained for Khetri and Kolar respectively for a strain rate of $10^{-14}s^{-1}$. The thickness varies between these two limits for other locations. The rheological thickness of the lithosphere increases with increasing strain rate. A maximum thickness of 96 km is obtained for Kolar for strain rate of

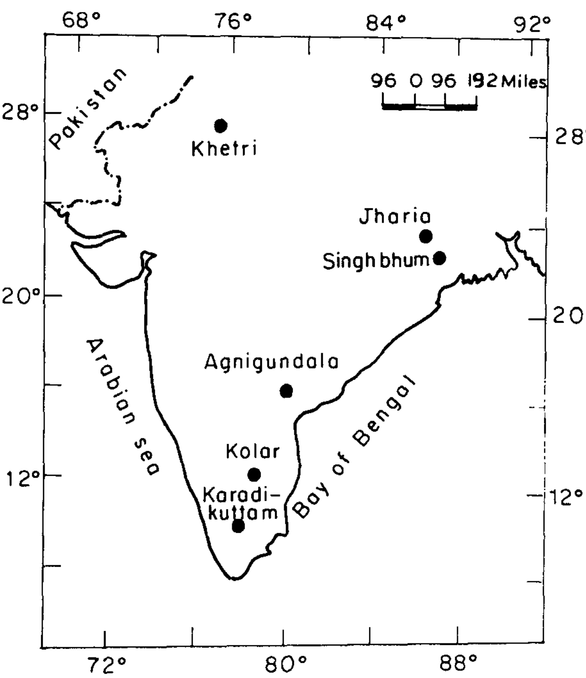

Figure 1. A map of the Indian shield showing the locations of heat flow and heat generation data used in the computation of rheological thickness and strength of the lithosphere (after Rao *et al* 1976).

Table 1. The estimates of rheological thickness of the Indian continental lithosphere at different locations for different values of strain rate. The thickness is in km.

	Strain Rate (s^{-1})					
Location	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-16}
Khetri	81	75	70	65	60	56
Jharia	95	88	81	75	70	65
Singhbhum	86	80	74	69	65	61
Agnigundala	95	88	81	75	70	65
Kolar	96	89	84	79	74	70
Karadikuttam	93	87	81	76	71	67

$10^{-11}s^{-1}$. The results indicate that Jharia and Agnigundala have lesser rheological thickness than Kolar for values of strain rate less $10^{-13}s^{-1}$. The increase in the strain rate, however, reduces the difference and the thickness estimate for these locations becomes comparable to that for Kolar. Khetri and Singhbhum have lesser rheological thickness than the other locations for all values of strain rate considered in the computations.

A problem wherein the estimates of rheological thickness would find applications is connected with the flexure of the lithosphere due to surface and subsurface loads. The flexure of the northern part of the Indian lithosphere due to the load of Himalaya has been modelled by Karner and Watts (1983) by the analysis of gravity data. They estimate the plate thickness as 82·5–104 km. The maximum rheological thickness obtained for Khetri region is 81 km which compares favourably with the above estimates. Recently Watts and Cox (1989) analysed the deformation of the southern part of the Indian lithosphere due to the load of Deccan Traps which was triggered by the passage of the Reunion hotspot. The elastic plate thickness used to simulate the layering of the Deccan Traps is 100 km. We have obtained a maximum thickness of above 95 km. This also compares favourably with the above estimates.

4. Strength of the continental lithosphere

Fadaie and Ranalli (1990) defined the strength as:

$$\sigma_L = \frac{1}{L}\int_0^L (\sigma_1 - \sigma_3)(z)\mathrm{d}z \tag{3}$$

where $(\sigma_1 - \sigma_3)(z)$ expresses the dependence of strength on depth and L is the rheological thickness. The difference between the principal stresses σ_1 and σ_3 required for the computation of total strength of the lithosphere is obtained from the brittle failure and power creep laws as discussed in the earlier section. The equation (3) includes the strength profile in brittle and ductile regimes of both the crust and mantle

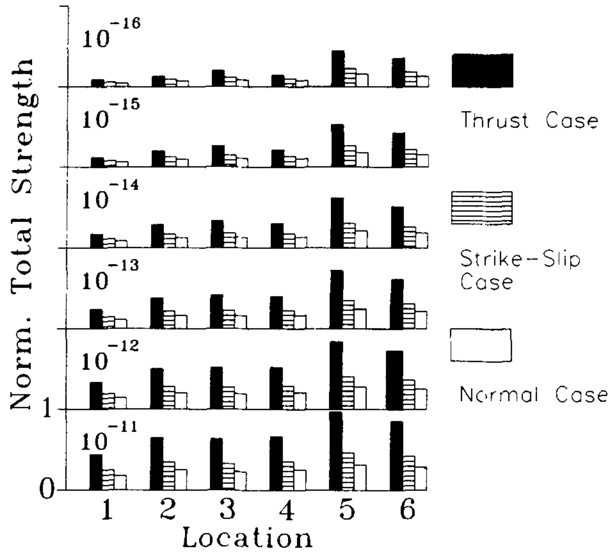

Figure 2. Normalized total strength of the Indian continental lithosphere at different locations; **1** Khetri, **2** Jharia, **3** Singhbhum, **4** Agnigundala, **5** Kolar and **6** Karadikuttam; for strain rate ranging between $10^{-11} - 10^{-16}s^{-1}$. The normalization is done w.r.t. a coefficient which is equal to $12{\cdot}0 \times 10^{13}\mathrm{Nm}^{-1}$. Three different bars at any of these locations correspond to thrust, strike-slip and normal faulting cases.

lithosphere. The total strength F in this case is given as:

$$F = \sigma L \tag{4}$$

In a simple stratified model of the lithosphere, the integration given by equation (3) can be performed analytically to obtain the rheological strength. However, the complex form of equation defining the temperature distribution (Manglik and Singh 1991) restricts the use of a simple analytical expression for strength. Therefore, a numerical integration scheme has been adopted to obtain the estimates of the rheological strength from equations (3) and (4).

The values of total strength of lithosphere at different locations in the Indian continent are shown in figure 2. The strength is computed for all the three types of faulting and for strain rate varying between $10^{-11} - 10^{-16}s^{-1}$. The maximum and minimum strengths are estimated for Kolar and Khetri respectively. At Kolar, in thrust faulting case, it increases from $5{\cdot}29 \times 10^{13}\mathrm{Nm}^{-1}$ to $11{\cdot}54 \times 10^{13}\mathrm{Nm}^{-1}$ for strain rate increasing from $10^{-16}s^{-1}$ to $10^{-11}s^{-1}$. At Khetri for the same strain rate variation it ranges from $1{\cdot}09 \times 10^{13}\mathrm{Nm}^{-1}$ to $5{\cdot}23 \times 10^{13}\mathrm{Nm}^{-1}$. For strike-slip faulting the variation is from $2{\cdot}66 \times 10^{13}$ to $5{\cdot}9 \times 10^{13}\mathrm{Nm}^{-1}$ for Kolar and from $0{\cdot}65 \times 10^{13}$ to $2{\cdot}89 \times 10^{13}\mathrm{Nm}^{-1}$ for Khetri. For normal faulting it is between $1{\cdot}85 \times 10^{13} - 3{\cdot}71 \times 10^{13}\mathrm{Nm}^{-1}$ for Kolar and $0{\cdot}51 \times 10^{13} - 2{\cdot}11 \times 10^{13}\mathrm{Nm}^{-1}$ for Khetri. For other locations the strength assumes some intermediate values.

Lynch and Morgan (1987) obtained the lithospheric strength of $(1{\cdot}5\text{–}6{\cdot}0) \times 10^{13}\mathrm{Nm}^{-1}$ for continental shield. Fadaie and Ranalli (1990) estimated this to be $3{\cdot}0 \times 10^{13}\mathrm{Nm}^{-1}$ for a strain rate of $10^{-15}s^{-1}$. The order of magnitude of strength obtained for the Indian continental lithosphere is in good agreement with these results.

5. Conclusions

The rheological thickness and total strength of the Indian continental lithosphere have been estimated from the rheological profiles based on the variation in surface heat flow and heat generation data, and different rheological parameters for upper crust, lower crust and upper mantle respectively. The computation is done for values of strain rate ranging between $10^{-11} - 10^{-16} s^{-1}$. The rheological thickness is more for the southern part of the Indian shield than for the northern part of the Indian shield, although at Jharia it is nearly equal to that obtained for the southern part of the Indian shield for high strain rates. The total strength obtained is also more for southern part than for northern part of the Indian shield. The strength increases with increasing strain rate. The order of the magnitude of total strength agrees well with that obtained by Lynch and Morgan (1987) and Fadaie and Ranalli (1990).

The thickness of rheological lithosphere can be obtained by other methods also, for example from the flexural response of the plate to surface and subsurface loads. The available elastic plate thickness estimates to explain flexure related geophysical data compare favourably with these estimates. The rheological thickness obtained by the elastic flexure studies, and the method discussed here can help constraining the thermal and mechanical structure of the lithosphere (McNutt 1984; Solomon and Head 1990).

Acknowledgements

The authors are thankful to the Director, National Geophysical Research Institute, Hyderabad for his kind permission to publish this work.

References

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

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; *Tectonophysics* **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

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

England P 1983 Constraints on extension of continental lithosphere; *J. Geophys. Res.* **88** 1145–1152

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

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

Karner G D and Watts A B 1983 Gravity anomalies and flexure of the lithosphere at mountain ranges; *J. Geophys. Res.* **88** 10449–10477

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

Kirby S H 1983 Rheology of the lithosphere; *Rev. Geophys. Space Phys.* **21** 1458–1487

Lynch H D and Morgan P 1987 The tensile strength of the lithosphere and the localization of extension; In: Continental Extensional Tectonics (eds) M P Coward, J F Dewey and P L Hencock *Geol. Soc. London Sp. Pub.* **28** pp. 53–65

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

McNutt M 1984 Lithospheric flexure and thermal anomalies; *J. Geophys. Res.* **89** 11180–11194

Ranalli G and Murphy D C 1987 Rheological stratification of the lithosphere; *Tectonophysics* **132** 281–295

Ranalli G and Yin Z M 1990 Critical stress difference and orientation of faults in rocks with strength anisotropies: the two-dimensional cases; *J. Struct. Geol.* **12** 1067–1071

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

Sawyer D S 1985 Brittle failure in the upper mantle during extension of continental lithosphere; *J. Geophys. Res.* **90** 3021–3025

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

Sibson R H 1982 Fault zone models, heatflow, and the depth distribution of earthquakes in the continental crust of the United States; *Bull. Seismol. Soc. Am.* **72** 151–163

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 Vol. 3, pp. 307–312

Solomon S C and Head J W 1990 Lithospheric flexure beneath the Freyja Montes foredeep, Venus: Constraints on lithospheric thermal gradients and heatflow; *Geophys. Res. Lett.* **17** 1393–1396

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.* **93** 85–97

Yin Z M and Ranalli G 1992 Critical stress difference, fault orientation and slip direction in anisotropic rocks under non-Andersonion stress systems; *J. Struct. Geol.* **14** 237–244