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Rheology of Indian continental crust and upper mantle

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

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Abstract. A rheological model of the Indian shield has been constructed using the thermal structure derived from available surface heat flow and heat generation data and the flow properties of characteristic minerals and rocks like quartz, diabase and olivine which respectively represent the upper crust, lower crust and upper mantle. Lateral variations in the thicknesses of the brittle and ductile crust and of the brittle upper mantle have thus been obtained for different tectonic environments. Implications of these results to interpretation of the seismic structure of the Indian shield have been pointed out.

Keywords. Rheology; brittle; ductile; crust; upper mantle.

1. Introduction

For understanding the complex architecture of the Indian crust and upper mantle as revealed by integrated geological, geophysical and geochemical studies, it is necessary to estimate its rheological state. A rheological model of the Indian lithosphere was constructed by Singh (1981) and Bhattacharji and Singh (1984) using available heat flow and heat generation data and the olivine flow laws. This study led to estimation of thickness of the upper brittle layer overlying the ductile layer. This thickness was found to vary laterally. However, such a simple model of elastic lithosphere, though useful in explaining some of the major features of tectonic stress distribution and earthquake occurrences, is not adequate to explain the finer scale phenomena, notably intraplate shallow seismicity, aseismic nature of the lower crust in the region of intraplate seismicity, rotation of stresses and existence of low angle normal faults (Brace and Kohlstedt 1980; Sibson 1983; Le Pichon and Barbier 1987; Yin 1989).

Intraplate seismicity within the continental and oceanic lithosphere depends on variations in plate boundary stresses (Cloetingh and Wortal 1986), stresses arising from local heterogeneities (Mareschal and Kuang 1986) and rheological properties of the crust and upper mantle rocks at ambient pressure and temperature (Chen and Molnar 1983; Sibson 1982, 1983). Results of experimental rock mechanical studies indicate that any rock, otherwise brittle can behave as a plastic substance when a combination of pressure and temperature conditions exceeds the threshold value which is different for different rock types (Kirby 1977; Goetze and Evans 1979; Kirby 1983). Therefore the geological constitution of upper crust, lower crust and upper mantle with known P-T regime can be of great importance in deciphering the depth, extent and thickness of the ductile layer. Although some other factors such as fluid pressure, presence of fluid in the quasi-plastic regime, quasi-plastic strain rate and mode of faulting influence the brittle/ductile (B/D) transformation (Sibson 1982), it is highly dependent on temperature distribution. A correlation between the B/D transformation and temperature of 350–450°C in the crust, and of 700–750°C in the upper mantle was reported by Meissner and Strehleau (1982).

In this paper we discuss a rheological model for the Indian shield region using quartz, diabase and olivine rheologies to represent the upper crust, lower crust and upper mantle respectively with a view to developing a framework for unfolding the possible tectonic processes that have successively operated on the Indian shield.

2. Rheology of the earth's crust and upper mantle

The distribution of brittle and ductile zones within the earth depends on the assumed composition of the earth's crust and upper mantle. As an attempt towards a more realistic modelling of tectonic processes in the crust and upper mantle, a complex, rheologically stratified model was earlier proposed (Kirby 1977; Brace and Kohlstedt 1980; Meissner and Strehlau 1982; Ranalli and Murphy 1987). In a simple model a quartzite crust over an olivine upper mantle was assumed (Kirby 1983). Ranalli and Murphy (1987) considered a quartz/granite upper crust and intermediate/basic lower crust over olivine upper mantle for precambrian shield. In another model of the shield they assumed quartz/granite crust of 40 km thickness over olivine upper mantle.

The flow law for quasi-plastic deformation has the form

$$\dot{\varepsilon} = A(\sigma_1 - \sigma_3)^n \exp[-Q/RT], \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, σ_1 and σ_3 the principal stresses, R the gas constant, T the absolute temperature and Q, A and n the material parameters. The shear strength is obtained from this equation as

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

The strength of the material for thrust, strike slip and normal faulting cases is given as

$$\begin{aligned}(\sigma_1 - \sigma_3) &= (R' - 1)\rho g z(1 - \lambda)\\ &= [(R' - 1)/(R' + 1)]2\rho g z(1 - \lambda)\\ &= [(R' - 1)/(R')]\rho g z(1 - \lambda),\end{aligned} \tag{3}$$

where ρ is the density, g the gravitational acceleration, λ the pore fluid factor and R' the minimum value of the ratio of maximum to minimum principal stresses required to initiate sliding (Sibson 1974).

3. Thermal structure

The quasi-plastic creep mechanism for the deformation of deep crustal material depends on the temperature distribution within the region of interest. Sufficient increase in the temperature stimulates the B/D transformation and thus the flow of material. The computation of temperature-depth distribution profile mainly involves the extrapolation of surface heat flow and heat generation values by solving steady-state diffusion equation (Lachenbruch and Sass 1977)

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(K\frac{\mathrm{d}T}{\mathrm{d}z}\right) = -A(z), \tag{4}$$

where K is the thermal conductivity, T the temperature, z the depth co-ordinate positive downward and $A(z)$ the radiogenic heat source distribution in the crust. Different models of heat source distribution have been discussed by Lachenbruch (1968) and Singh and Negi (1982). However we consider the one proposed by Lachenbruch (1970):

$$A(z) = A_0 \exp[-z/D], \tag{5}$$

where A_0 is the surface value of the radiogenic heat source and D the characteristic depth.

In the earlier models of temperature distribution in Indian shield the effects of lattice effect on thermal conductivity were considered (Singh and Negi 1982). We incorporate both the lattice and radiative heat component in the temperature-dependent thermal conductivity model as considered in England (1978) and Singh (1985) for realistic thermal properties of crust and upper mantle. This model is given as

$$K(T) = \frac{K_0}{1 + C_1 T} + C_2(T - T^*)H(T - T^*), \tag{6}$$

K_0, C_1 and C_2 are constants and T^*, the characteristic temperature above which radiative heating is effective. To solve (4), the following conditions are needed:

$$T = T_s \quad \text{at } z = 0,$$

$$K\frac{\mathrm{d}T}{\mathrm{d}z} = Q_s \quad \text{at } z = 0. \tag{7}$$

Here T_s is the surface temperature and Q_s the surface heat flow.

The temperature distribution is obtained from the solution of (4) as

$$\ln\left[\frac{1 + C_1 T}{1 + C_1 T_s}\right] = \frac{C_1 Q_s}{K_0} z + \frac{A_0^2 C_1 D}{K_0}(1 - z/D - \exp[-z/D]) \quad \text{for } 0 \leqslant z < z^* \tag{8a}$$

and

$$\ln\left[\frac{1 + C_1 T}{1 + C_1 T^*}\right] + \frac{C_1 C_2}{2K_0}(T - T^*)^2 = \frac{Q_1^* C}{K_0}(z - z^*) + \frac{C_1 A_0 D^2}{K_0}\left[[\exp(-z/D) - \exp(-z^*/D)] - \frac{(z - z^*)}{D}\exp(-z^*/D)\right] \quad \text{for } z \geqslant z^*, \tag{8b}$$

where

$$Q^* = Q_s + A_0 D(\exp[-z^*/D] - 1). \tag{8c}$$

z^* is the depth at which the effect of radiative heating is included and Q^*, the flux at that depth. Equation (8b) is nonlinear in temperature and is solved using Newton-Raphson method.

4. Crustal structure of Indian shield

We next need a model of the crustal structure beneath the Indian shield. This has been obtained from the analysis of shallow earthquake body and surface wave travel time data, and from the DSS surveys. Body wave data from the December 10, 1967 Koyna earthquake was analysed in terms of a two-layer crustal model by Tandon and Choudhary (cf. Bhattacharya 1971). The thicknesses of upper granitic layer and lower basaltic layer were obtained as 22·5 km and 18·5 km respectively. The gravity data over Cuddapah basin, analysed by Qureshy *et al* (1968), gave the estimates of thicknesses for upper crust as 20 km and the lower crust as 10 km. DSS survey along Kavali-Udipi section (Kaila *et al* 1979) revealed crustal thickness of 36–38 km in its western part increasing to 42–45 km in the eastern section of Cuddapah. DSS profile across northern part of cuddapah basin (Kaila *et al* 1985) along Alampur-Koniki-Ganopeshwaram shows a variation in crustal thickness from 35–38 km in Kurnool sub-basin to 42–45 km in the eastern sector. The surface wave studies along Kodaikanal-Delhi section suggested thicknesses of 12·5 km and 28·5 km for upper and lower crust respectively. Since we do not have finer details of crustal structure at the sites of available heat flow-heat generation data we consider this averaged model of continental crust for modelling purpose (Bhattacharya 1971).

5. Results and discussion

The rheological parameters given in table 1 were used in the computation of depth to the brittle/ductile transition and thickness of ductile crust in different regions of known heat flow and heat generation (table 2, figure 1). The coefficients K_0, C_1 and

Table 1. Rheological model parameters (cf. Smith and Bruhn 1984; Chen and Molnar 1983).

Rock type	A (M Pa^{-n}s^{-1})	Q (KJ mol^{-1})	n (power)
Quartz	$5·0 \times 10^{-6}$	190	3
Diabase	$5·2 \times 10^{2}$	356	3
Olivine	$3·4 \times 10^{4}$	520 ± 60	3·5

Table 2. Heat flow, heat generation data for different regions (cf. Rao *et al* 1976).

Region	Heat flow Q_s(mW/m^2)	Heat generation A_0(μW/m^3)	Charact. depth D(km)
Khetri	74	2·19	14·8
Singhbhum	54	1·15	14·8
Kolar	44	1·50	7·5
Karadikuttam	55	2·93	7·5
Jharia	79	2·80	14·8
Agnigundala	75	2·61	14·8

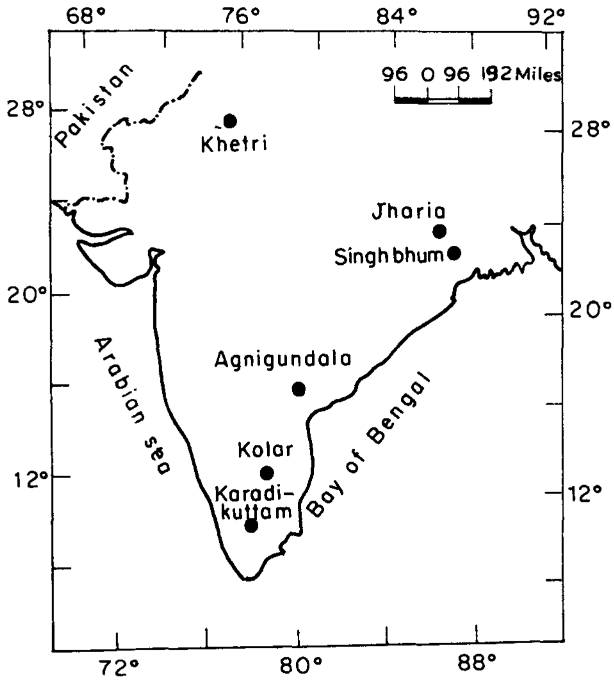

Figure 1. A map of Indian shield showing the locations of heat flow and heat generation data used in the computation of rheological model (after Rao *et al* 1976).

C_2, which describe thermal conductivity, are assigned values of 3·441 W/m K, 6·406 × 10^{-4} K^{-1} and 1·674 × 10^{-3} W/m K^2 respectively (England 1978).

The contribution of radiative heat component in the conductivity model is included above a temperature T^* of 550°C. For strain rate we take a value of $10^{-14} s^{-1}$ as suggested by Ranalli and Murphy (1987) for shield regions. We have calculated the temperature and the strength distribution at six locations in the Indian shield (figures 2–7) as at these sites both the heat flow and the heat generation values have been comprehensively estimated. These results are compiled in table 3.

A significant lateral variation in the thickness of upper brittle layer is seen in the models obtained for different regions. A northward thinning trend of brittle layer is clearly evident. The thickness of this layer under Kolar is 32 km but it decreases to 19 km under Jharia for thrust-faulting case. This estimate of thickness increases by a small amount for the other two types of tectonic environments. The B/D transition coincides with the temperature isotherm of 450°C for thrust-faulting, 475°C for strike-slip and 490°C for normal faulting for the given set of parameters used in the analysis. These results would constrain the possible depth of shallow seismicity.

The thickness of ductile crust below the southern part of Indian shield is approximately 10 km whereas the thickness attains a value of 21 km under the northern shield (table 3). The thickness of ductile layer for normal faulting case is lesser than that in the case of thrust-faulting. The crustal structure obtained from DSS profile along Kavali-Udipi (Kaila *et al* 1979) is marked by numerous reflectors. These reflectors are distributed over the entire crust in the eastern section but a large reflectivity is seen mainly at the lower crustal depth in the western side. The eastern part of the profile is traversed by shallow thrust faults. In general the lower 20 km

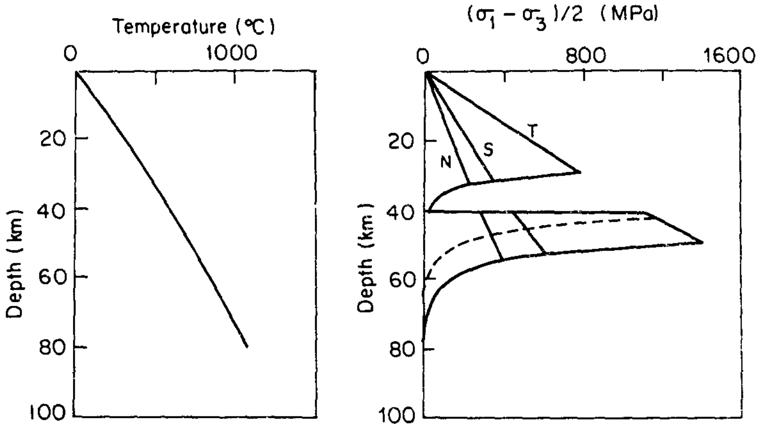

Figure 2. a. Temperature and b. mechanical strength profiles for Karadikuttam. *T*, *S* and *N* denote mechanical strength for thrust, strike slip and normal faulting cases respectively. Dashed curve is the creep strength profile for activation energy of 520 KJ mol^{-1}.

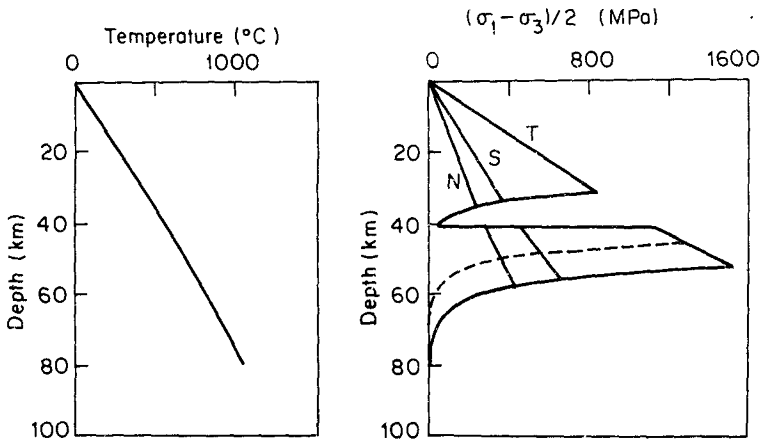

Figure 3. a. Temperature and b. mechanical strength profiles for Kolar. Other notations are the same as described in figure 2.

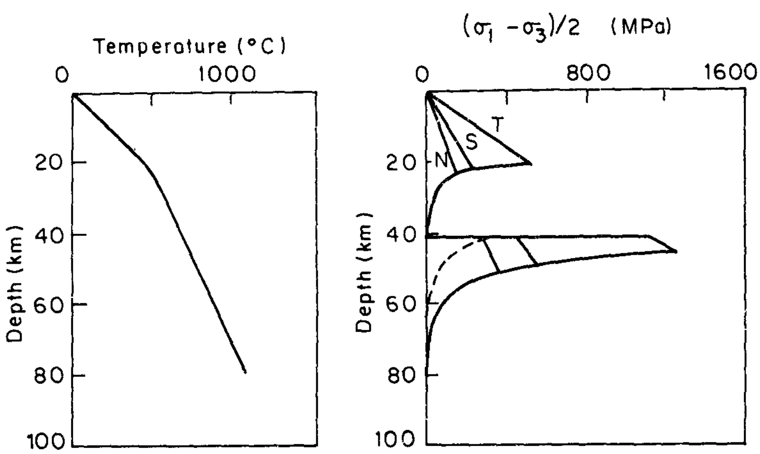

Figure 4. a. Temperature and b. mechanical strength profiles for Agnigundala. Other notations are the same as described in figure 2.

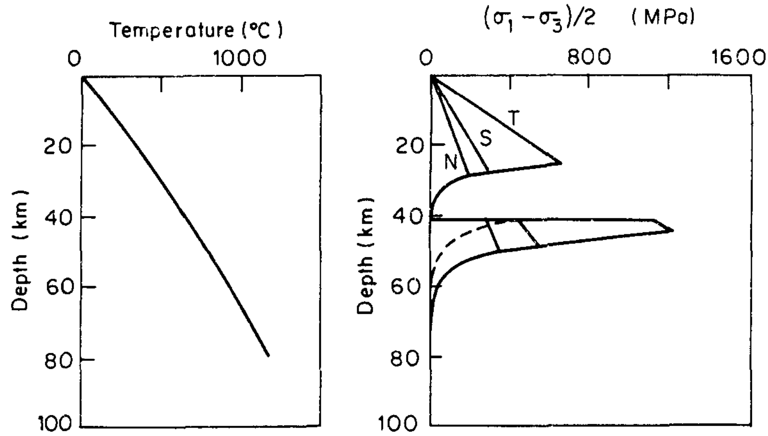

Figure 5. **a.** Temperature and **b.** mechanical strength profiles for Singhbhum. Other notations are the same as described in figure 2.

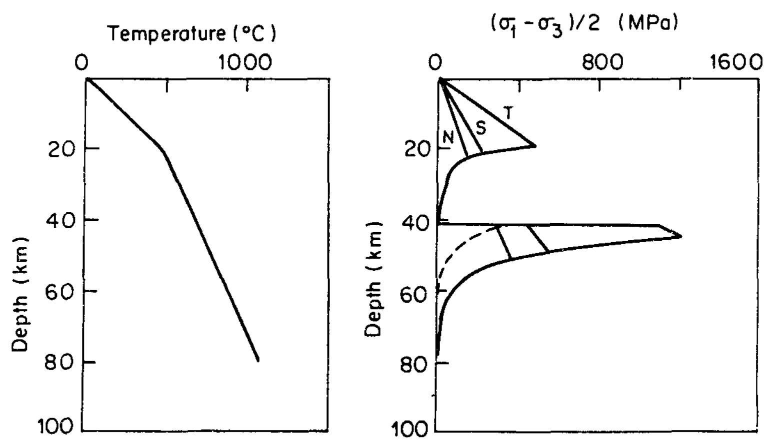

Figure 6. **a.** Temperature and **b.** mechanical strength profiles for Jharia. Other notations are the same as described in figure 2.

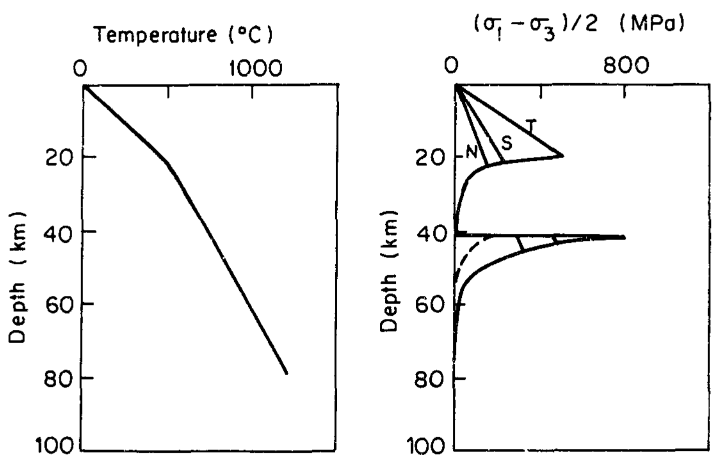

Figure 7. **a.** Temperature and **b.** mechanical strength profiles for Khetri. Other notations are the same as described in figure 2.

Table 3. Thicknesses of brittle and ductile crust, and brittle upper mantle for different regions in Indian shield. *T, S, N* denote thicknesses for thrust, strike slip and normal faulting cases respectively.

	Thickness of brittle crust (km)			Thickness of ductile crust (km)			Thickness of brittle mantle (km)		
Region	*T*	*S*	*N*	*T*	*S*	*N*	*T*	*S*	*N*
Khetri	19·5	21·0	22·0	21·5	20·0	19·0	0·5	2·5	4·5
Jharia	19·0	21·0	21·5	22·0	20·0	19·5	4·0	7·5	9·5
Agnigundala	20·5	22·0	23·0	20·5	19·0	18·0	5·0	8·5	10·5
Singbhum	26·5	27·0	28·0	14·5	14·0	13·0	4·0	7·0	9·0
Karadikuttam	29·5	31·5	33·0	11·5	9·5	8·0	9·0	12·0	14·0
Kolar	32·0	33·0	35·5	9·0	8·0	5·5	11·5	15·0	16·5

of the crust in this region is highly reflective and reflectors become horizontal to sub-horizontal near moho (Roy Chowdhury and Hargraves 1981). These observations support the concept of ductile lower crust.

The interesting feature in Indian shield is the presence of comparatively thin brittle uppermost mantle layer even for the maximum suggested value of activation energy of olivine (Chen and Molnar 1983; Smith and Bruhn 1984; Sibson 1984). The uncertainty in the shear strength of olivine, at a constant depth and temperature, for the given uncertainty limit in the activation energy is considerably large in comparison to the uncertainty bars for quartz and diabase rheology (Chen and Molnar 1983). Therefore, we considered the upper bound of activation energy for olivine only in the computation of thickness of lower brittle layer. The transition temperature in the uppermost mantle is 730°C, 760°C and 785°C for the three cases of faulting respectively.

The thinness of the uppermost mantle brittle layer can be viewed as a consequence of high temperature of the Indian shield. The faulted moho reflector in the crustal structure, in the above mentioned crustal section, indicates the possibility of existence of brittle layer at moho depth. Thus the existence of brittle layer and experimental studies on rheological behaviour of rocks impose a constraint on the upper limit of temperature at moho.

The rheological model can further be constrained using the nature of seismicity. Indian shield has experienced many earthquakes in the recent past (Chandra 1977; Indra Mohan *et al* 1981; Rao and Rao 1984). However, the data base of these earthquakes has been mainly used to discuss the spatial distribution of the seismicity in the Indian shield. The focal mechanism solutions for a few moderate intraplate earthquakes e.g. Midnapore, Ongole, Bhadrachalam, Koyna and Broach have been analysed by Chandra (1977). In the absence of depth distribution of seismicity and well-constrained focal mechanism solution we will not be able to explore and correlate between the vertical distribution of seismicity and the rheological model.

6. Conclusions

A complex model of the Indian shield is discussed based on the quartz, diabase and olivine rheology for upper crust, lower crust and upper mantle respectively.

The mechanical strength profiles obtained for different regions indicate the presence of a lower ductile crust and a brittle layer in the upper mantle in addition to the top brittle crustal layer. The thickness of ductile crustal layer increases northward whereas the thickness of brittle crustal layer decreases northward and the brittle upper mantle layer is rather thin under the Indian shield. The large reflectivity and horizontal to sub-horizontal nature of reflectors just above moho, observed in the crustal section obtained from DSS along Kavali-Udipi profile, support a possibility of ductile flow. Moho faulting in this region indicates the presence of a brittle layer.

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