

robust effect of climate change on plant–herbivore interaction would change the feeding behaviour of *S. litura*.

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Thermomechanical structure of the central Indian shield: Constraints from deep crustal seismicity

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Intraplate seismicity in the Indian shield is confined to the upper 10–15 km except for the Jabalpur and Satpura events which occurred at a depth of 35–40 km in the region bounded by the Narmada–Son and Tapti lineaments, two major palaeo-rift-related tectonic features in the central Indian shield. Interestingly, high surface heat flow of 70–100 mW/m² has been suggested for the above region. Rheological models of continental crust in such a high heat flow regime do not support occurrence of deep crustal seismicity. In the present work we computed a range of rheological models for the region for different values of thermal parameters and analysed these in light of deep crustal seismicity. The study suggests that mantle-derived heat flow should be significantly low for the occurrence of deep crustal events in the above region and the excess surface heat flow could be a manifestation of fluid advection in the uppermost part of the crust, as is evident from the presence of many hot springs.

THE Indian shield has experienced many intraplate earthquakes of magnitude > 5.0 during the last fifty years. These include Anjar (1956), Broach (1970), Bhadrachalam (1969), Killari (1993), Jabalpur (1997), Koyna (1967), and Satpura (1938) events^{1–6}. The focal depths of these events are confined to the upper 10–15 km, except for the Jabalpur and Satpura events which occurred at a depth of more than 35 km in the region (hereafter called

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NSTL) bounded between the Narmada–Son lineament (NSL) and Tapi lineament (TL) (Figure 1), major palaeo-rift-related features, in the central Indian shield. Occurrence of deep-focus earthquakes in the central segment of the NSTL, makes this an interesting region for the understanding of the tectonics responsible for the occurrence of deep crustal intraplate seismicity.

The focal depth of the 1997 Jabalpur earthquake has been estimated by many workers^{5,7,8} by using the digital broadband data from 10 permanent seismic observatories of the India Meteorological Department (IMD), and Hyderabad Geoscope station. All these studies suggest a focal depth of 35–37 km for the Jabalpur event. The *pP* and *sP* waveform modelling gives a focal depth of 36 ± 4 km (refs 5, 7, 9). Bhattacharya *et al.*⁵ used depth phases *Pn* and *sPn* instead of direct arrivals and crustal model of the Indian shield¹⁰ for better accuracy, as nearest stations Nagpur and Bilaspur were located at a distance of 231 and 237 km from the epicentre, respectively. They obtained a focal depth of 35.6 km. Singh *et al.*⁸ have obtained a crustal model for this region by using the Rayleigh and Love waves dispersion data and then used their model to arrive at a focal mechanism through waveform modelling. They inferred a twin event with the nucleation of the main event at a depth of 36 km. These studies suggest a well-constrained focal depth for the Jabalpur earthquake. This depth, when compared with the Moho depth of 39–42 km obtained by deep crustal studies¹¹, suggests a hypocenter in the lower continental crust very close to the Moho. The focal depth of the 1938 Satpura earthquake was also reported at 40 km (ref. 6). However, the focal depth of the Broach earthquake on the

western extremity of the NSTL has been estimated as 11 ± 3 km based on the body waveform modelling¹. Focal mechanism of the Jabalpur event (strike = 61° , dip = 64° , rake = 74°) suggests a reverse faulting mechanism with a small strike-slip component⁸. Similar reverse faulting mechanism (strike = 273° , dip = 58° , rake = 130°) has also been obtained for the Broach earthquake¹. The reverse faulting mechanism of these earthquakes indicates that the NSTL is at present under compressive state of stress.

NSTL is also interesting in terms of its thermal structure. Available heat flow map of India¹² suggests a high heat flow regime (> 100 mW/m² in the central part of NSTL, decreasing to 70 mW/m² on both the sides, as shown by iso-heat flow contours (Figure 1)). The heat flow map was prepared by incorporating (i) sixty earlier published heat flow values and 90 geothermal gradient values, (ii) geothermal gradient data from nearly 200 (100–700 m) boreholes drilled for geothermal, mineral, coal, and groundwater exploration, and (iii) heat flow estimates based on silica content (ref. 12 and papers therein). Some of the drill-hole locations in the NSTL, used in the preparation of the heat flow map, are shown in Figure 1 by open triangles along with the locations of thermal springs (circle with plus sign) in this region. In another study, Rao *et al.*¹³ reported two heat flow measurements from NSTL (150 km SW of Jabalpur), one at Damua (22.14°N , 78.26°E) and other at Mohapani (22.45°N , 78.49°E) (filled triangles, Figure 1). Measurements at Damua were made in a 506 m deep borehole and at Mohapani, the depth of the borehole was 380 m. The surface heat flow values reported for these two locations are 62 and 49 mW/m², respectively, which are significantly low in comparison to those indicated by the heat flow map. There are two more surface heat flow values available south of NSTL, one at Bodal (20.511°N , 80.766°E) 100 km SW of Raipur and other at Malanjhand (22.026°N , 80.719°E) 120 km NW of Raipur (filled triangles, Figure 1)¹⁴. The heat flow values at these two locations are 64 ± 2.3 mW/m² and 52 ± 2.1 mW/m², respectively. Interestingly, these values of surface heat flow also are at a variance with the heat flow contours. Nevertheless, these are higher than the heat flow values of 40–45 mW/m² expected for shield regions. In this scenario, where the region has been experiencing deep crustal seismicity and the heat flow seems to be high, rheological models can provide useful constraints on the thermal structure of the region.

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 (see refs 15, 16, 17, 18). 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

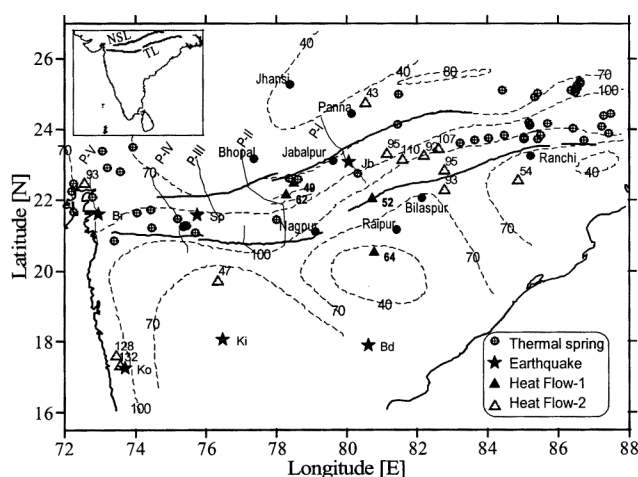


Figure 1. Map showing surface heat flow contours (dashed lines) and location of drill-hole sites (open triangles) taken from the heat flow map of India¹² and measured surface heat flow values (solid triangles) reported by Rao *et al.*¹³ and Gupta *et al.*¹⁴. Values of surface heat flow are also mentioned. Also shown are location of hot springs³⁵ and epicentres of earthquakes of magnitude > 5.0 in the region (stars). These are: Sp – Satpura, 1938; Jb – Jabalpur, 1997; Ko – Koyna, 1967; Ki – Killari, 1993; and Bd – Bhadrachalam, 1969. The solid lines P-I to P-V are the five deep seismic sounding profiles shot across the region. Modified after Ravi Shankar³⁵.

laws to natural conditions. 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 and can be used as an indirect indicator for thermal state of the lithosphere. For example, experimental results have shown that quartz and feldspar become ductile at 300–450°C for natural strain rates, whereas the brittle–ductile (B/D) transition in olivine takes place at 700–750°C (refs 15 and 16). This B/D transition when compared with the maximum depth of seismicity gives a probable estimate of prevailing temperature at that depth. However, in an alternative mechanistic interpretation, the maximum depth of seismicity may represent the transition from unstable stick-slip sliding on faults to stable aseismic sliding^{19,20}. In this case stability of frictional sliding depends on temperature as well, and on sliding velocity, effective normal stress, and characteristics of the sliding surface and gouge along the fault²¹. It is unclear at present whether the brittle–ductile transition or the transition from stick-slip sliding to stable frictional sliding controls the maximum depth of seismicity.

In the present work we assume that maximum depth of seismicity represents the transition from brittle failure to ductile flow, and thus constrains thermal structure, and computes rheological structure of the central Indian shield for a range of heat flow and radiogenic heat production values by using available crustal structure model of the region. The depths to the lower crustal and upper mantle brittle/ductile transitions in these rheological models are then compared with the focal depth of the Jabalpur earthquake, to arrive at a plausible thermo-rheological model of the region.

Construction of rheological models of continental crust requires knowledge of the thermal and crustal structure. In order to obtain the temperature distribution at a given location, one needs the values of the surface heat flow Q_s and surface heat generation A_0 , also known as the surface heat flow–heat generation pair, at that location. The value of the characteristic depth d for a region is obtained through the regression analysis of many such heat flow–heat generation pairs. However, no such heat flow–heat generation pair is available for the NSTL. Gupta *et al.*¹⁴ provided heat generation values for the rock types from the Bastar craton (south of NSTL) which show radiogenic heat source concentrations of 2.98 $\mu\text{W}/\text{m}^3$ for rhyolite at Bodal (20.511°N, 80.766°E) and 2.1 $\mu\text{W}/\text{m}^3$ for granodiorite at Malanjhand (22.026°N, 80.719°E). The average surface heat flow for these two locations is $64 \pm 2.3 \text{ mW}/\text{m}^2$ and $52 \pm 2.1 \text{ mW}/\text{m}^2$, respectively. The available heat flow–heat generation pairs at other locations in the Indian shield show that radiogenic heat production ranges between 1.15 and 2.93 $\mu\text{W}/\text{m}^3$ (ref. 22). In the absence of radiogenic heat source data from the NSTL we assumed two values 1.0 and 2.0 $\mu\text{W}/\text{m}^3$ of surface

radiogenic heat generation, corresponding to low to moderate surface radiogenic heat contribution.

A model crustal structure of the NSTL region is available from deep crustal seismic and gravity studies. Kaila *et al.*¹¹ obtained a crustal thickness of 39–42 km along four (P-I to P-IV, Figure 1) of the five DSS profiles shot across the NSTL. The fifth profile (P-V, Figure 1) in the western part of the NSTL indicates a crustal thickness of about 25 km. They inferred the presence of magmatic underplating in the western segment of the NSTL, but showed normal lower crust in the eastern part around Jabalpur. Singh and Meissner²³ interpreted Bouguer gravity data along four profiles (P-II to P-V, Figure 1) and suggested magmatic underplating of 15–20 km thickness beneath profile P-V, decreasing to less than 3 km beneath profile P-II at the base of the crust. However, they have not interpreted the fifth profile (P-I, Figure 1) passing through the Jabalpur region. Recently Bhattacharya *et al.*⁵ used a two-layered model for crustal structure of the Indian peninsula constrained by body wave (upper crust 20.0 km, lower crust 18.7 km)²⁴ and surface wave (upper crust 20.4 km, lower crust 18.3 km)¹⁰ analysis to compute source parameters of the Jabalpur earthquake. Based on these two models we have selected upper and lower crustal thicknesses of 20 and 18 km, respectively, which is also similar to normal continental crust. We assumed quartz-rich and diabase rheologies for the upper and lower crust, respectively, and assigned olivine (dry dunite) rheology to the mantle part of the lithosphere. These rheological parameters are given in Table 1. Rheological models were constructed by computing shear strength profiles for brittle and ductile regimes.

In view of the lack of requisite surface heat flow and heat generation data from the Jabalpur region and a prevailing understanding that the NSTL has a high heat flow regime, we analysed a series of models for a range of thermal parameters to arrive at a plausible rheological model which is consistent with the occurrence of Jabalpur-type deep crustal seismicity. We first considered a normal continental crust of 38 km thickness and generated a large number of one-dimensional thermal models using the following heat conduction equation

$$K \frac{\partial^2 T}{\partial z^2} + A_0 \exp(-z/d) = 0, \quad (1)$$

Table 1. Rheological parameters used in the computation of B/D transitions

Rheology	A ($\text{MPa}^{-n} \text{ s}^{-1}$)	n	E (kJ mol^{-1})	Reference
Quartzite	6.30E – 06	2.4	156	36
Diabase	2.00E – 04	3.4	260	37
Dry dunite	4.85E + 04	3.5	535	38
Microgabbro	5.00E + 09	3.4	497	28
Pikwitonei granulite	1.40E + 04	4.2	445	28

for surface heat-flow values ranging between 45 and 90 mW/m², surface radiogenic heat source concentration A_0 of 1.0 and 2.0 $\mu\text{W}/\text{m}^3$, characteristic depth d of 11.5 km, and thermal conductivity values of 2.5 and 3.0 W/m.K. In this equation an exponential model of radiogenic heat production is considered. These thermal structures were used to obtain rheological stratification of the lithosphere. In these rheological models the B/D transition was considered as a depth at which the mode of deformation changed from entirely brittle to that by crystalline plasticity. This was obtained by computing shear strength profiles using pressure sensitive Navier–Coulomb criterion for the brittle regime and temperature-sensitive power creep law for the ductile regime^{25,26}.

The depths to the B/D transitions in the upper and lower crust, and in the upper mantle are shown in Figure 2 as a function of surface heat-flow Q_s . Values of other parameters are given in Figure 2. The results indicate a variation in the thickness of upper crustal brittle layer from 20 km at $Q_s = 45 \text{ mW}/\text{m}^2$ to less than 10 km at $Q_s = 90 \text{ mW}/\text{m}^2$. Varying other parameters does not influence much the brittle upper crustal layer thickness at high heat flow. However, the lower crust becomes ductile between 30 and 38 km depth at $Q_s = 45 \text{ mW}/\text{m}^2$ when $A_0 = 2.0 \mu\text{W}/\text{m}^3$, $K = 2.5 \text{ W}/\text{m.K}$ and $\dot{\epsilon} = 10^{-14} \text{ s}^{-1}$ (Figure 2 a). The strain rate of 10^{-14} s^{-1} is slightly higher than the strain rate values of 10^{-15} s^{-1} – 10^{-16} s^{-1} suggested for shield regions. However, a higher value of strain rate is used to get an upper limit of the depth of B/D transitions. This layer thickens with the increase in heat flow and the

lower crust becomes totally ductile at $Q_s > 65 \text{ mW}/\text{m}^2$. Similarly, rheologically hard (dry dunite) mantle material also becomes ductile at $Q_s > 60 \text{ mW}/\text{m}^2$, whereas at $Q_s = 45 \text{ mW}/\text{m}^2$ a brittle mantle layer of $\approx 20 \text{ km}$ is present. Increasing the thermal conductivity to 3.0 W/m.K enhances the brittleness of all the layers due to the reduction in temperature at these depths (Figure 2 b). The thicknesses of brittle lower crustal and mantle layers are 17 and 32 km, respectively at $Q_s = 45 \text{ mW}/\text{m}^2$. These layers vanish when $Q_s > 70 \text{ mW}/\text{m}^2$.

We next studied the effect of reducing crustal radiogenic heat sources on the rheological structure. In this case, for a given surface heat flow, the contribution of subcrustal (reduced) heat flow increases in comparison to previous cases, thereby increasing the temperature of the crust. This results in the decrease in the extent of brittle response of both the lower crustal and upper mantle layers to shear stresses (Figure 2 c); with brittle behaviour in layers about half the dimensions of comparable brittle layers in the previous case (Figure 2 b). These layers become ductile at $Q_s > 65 \text{ mW}/\text{m}^2$. Since the strain rate is considered to be between 10^{-15} and 10^{-16} s^{-1} for many continental shield regions, we analysed the effect of decrease in strain rate to 10^{-15} s^{-1} on the rheological stratification of the crust. In this case (Figure 2 d) the lower crustal and upper mantle layers become ductile at $Q_s > 65 \text{ mW}/\text{m}^2$, which is about 5 mW/m² less than the case of 10^{-14} s^{-1} strain rate (Figure 2 b). All these results suggest an upper limit of approximately 65 mW/m² on surface heat flow for the lower crust and upper mantle to

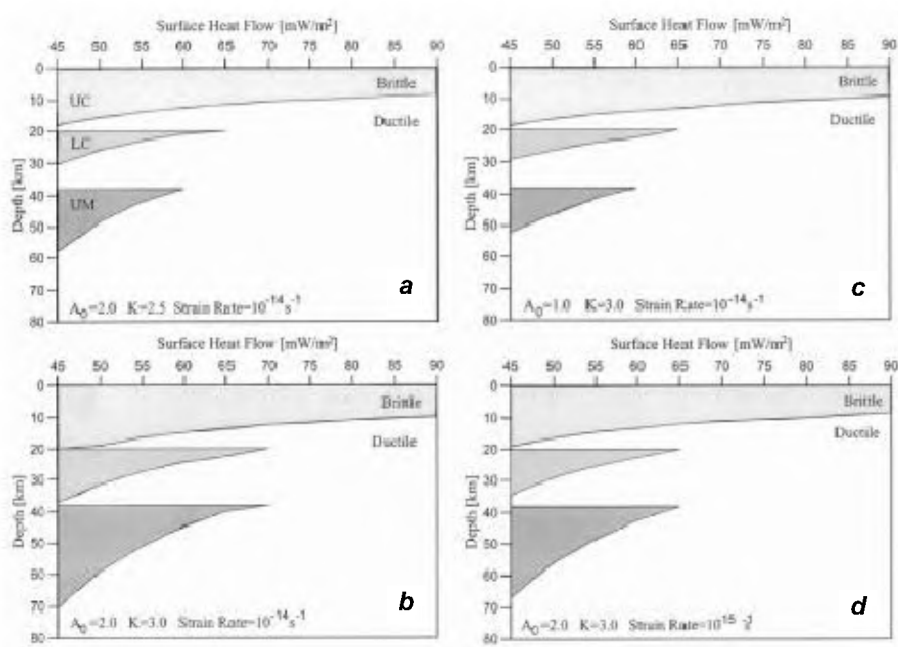


Figure 2. Variation in depth to brittle/ductile transitions in the upper crust (UC), lower crust (LC), and upper mantle (UM) with surface heat-flow. Other controlling parameters are thermal conductivity K in $\text{W}/\text{m.K}$, surface radiogenic heat-source distribution A_0 in $\mu\text{W}/\text{m}^3$, and strain rate in s^{-1} . Exponential model of radiogenic heat distribution is used in the computation of thermal structure. a–d correspond to cases for different combinations of controlling parameters.

become totally ductile. Among all the models considered above, the one shown in Figure 2 *b* gives the largest thickness of brittle layers. In this case also, the lower crust becomes ductile in the depth range of 30–38 km when surface heat-flow increases beyond 52 mW/m². The occurrence of a deep crustal event at 35–37 km depth would, therefore, require the surface heat-flow to remain lower than 48 mW/m² in a simple two-layered crustal model. This is inconsistent with the high heat-flow regime of the NSTL as indicated by the heat flow map of the region¹².

We, next developed rheological models by incorporating magmatic underplating at the Moho. Addition of magma at the base of the crust has two important effects; (i) it supplies additional heat to the crust, and (ii) it emplaces high-density material at the base of the crust. The thermal effect vanishes with time, but the compositional effect remains. At large times after the emplacement, these layers are characterized by a density of 3.02–3.07 g/cm³ and seismic velocity of 7.2–7.7 km/s (ref. 27). Presence of such a layer has been inferred from the deep crustal seismics and gravity results for the western part of the NSTL^{11,23} and has been correlated with the Deccan volcanism at 65 Ma. Since no estimates of the thickness of the underplated layer beneath the Jabalpur region are available, we assumed a thickness of 6 km between 32 and 38 km above the Moho. This assumption was made in view of the focal depth of 35–37 km of the Jabalpur event. Choice of an appropriate rheology for underplated material is difficult. These layers form as a result of accumulation of partial melt, generated in an upwelling plume, at the crust–mantle boundary, and are considered as having gabbro (mafic) composition. Wilks and Carter²⁸ obtained parameters of the power-law creep for microgabbro and Pikwitonei granulite (mafic) samples (Table 1) to represent an appropriate rheology for continental lower-crustal rocks. Of these two, Pikwitonei granulite rheology gives a higher strength estimate for temperatures greater than 450°C in comparison to microgabbro rheology. Therefore, we take the parameters of Pikwitonei granulite to represent the rheology of underplated material in order to get an upper limit on the strength estimates of the underplated material. Similarly, microgabbro rheology can also be used to represent underplating of mafic magma.

The results computed for strain rate of 10^{−14} s^{−1}, surface heat generation of 2.0 μW/m³, and thermal conductivity of 3.0 W/m.K are shown in Figure 3 for surface heat flow values ranging between 60 and 70 mW/m². The innermost light-shaded curve represents rheological stratification for surface heat flow of 70 mW/m². A decrease in the surface heat flow to 60 mW/m² results in lowering of the brittle/ductile transitions of all the layers (dark shaded curves). We compare the models without underplating (Figure 3 *a*) with those having underplated layer (Figure 3 *b*). In the absence of underplated layer the

lower crust shows ductile behaviour below 25 km depth for the surface heat flow value of 60 mW/m². When an underplated layer is introduced in the depth range of 32–38 km, there is an enhancement in the shear strength of crust at this depth, although only the ductile behaviour is obtained for this layer for the considered heat flow values. A further decrease in the heat flow value to less than 55 mW/m² results in appearance of a brittle layer within the underplated layer. These results support a brittle behaviour in the lowermost crust in a moderately hot lithosphere, if presence of a high strength underplated layer is invoked. It is, therefore, plausible to consider an underplated layer above the Moho to explain a deep lower crustal Jabalpur earthquake. However, these models also put a constraint on the upper limit of the surface heat flow.

The above results of rheological modelling bring out two plausible scenarios for the occurrence of deep seismicity in the central segment of NSTL of the central Indian region. In the first model a sufficiently low heat flow from the mantle, similar to that of a cratonic-type, is warranted to sustain a brittle regime at 30–38 km depth in the lower crust of typical feldspar-rich composition. In the second model, the brittleness at the lower crustal depth (> 35 km) in a moderately hot crust can be explained by incorporating a rheologically high-strength magma underplating (mafic) at the Moho. In this case the heat contribution from the mantle could be moderately large. In either case, the heat flow should be below 55 mW/m², as revealed by the present analysis. Since the upper limit on heat flow is dependent on whether an underplated layer exists below the Jabalpur region, an understanding of the crustal structure of the region is necessary to discriminate between the models without and with magmatic underplating. The region south of Jabalpur has a high Bouguer gravity anomaly of about

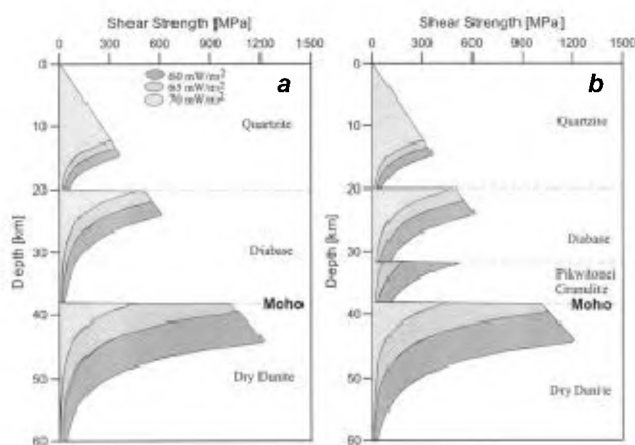


Figure 3. Rheological stratification in the crust and upper mantle (*a*) without and (*b*) with magmatic underplating for strain rate of 10^{−14} s^{−1}. Different shades represent shear strength profiles for three different values of surface heat flow ranging between 60 and 70 mW/m².

40 mgal (ref. 29), similar in magnitude to that shown by Singh and Meissner²³ for the western part of the NSTL for which they inferred the presence of magmatic underplating. Verma and Banerjee²⁹ interpreted the gravity high as due to mid-crustal high-density intrusives. It would be interesting to re-analyse this gravity anomaly to isolate any signatures of magmatic underplating in this region. The deep seismic sounding results along the profile passing through this anomaly (Profile P-I, Figure 1), however, indicate presence of a normal crust with the Moho at a depth of 39–42 km¹¹. If we assume a normal crust, as deciphered by the deep crustal seismic studies, and ignore the presence of high gravity anomaly then the conductive heat flow in this region should be very low. However, if the gravity anomaly were a signature of magmatic underplating, then we can expect a moderate heat flow regime for the region.

These discussions are mainly based on the assumption that the Jabalpur event occurred at a focal depth of 36 km in the lower crust. However, close proximity of the Moho (39–42 km), as revealed by the deep seismic studies, and the focal depth of the event may be used to visualize an alternative situation where the event may be considered as a mantle event instead of a lower crustal one. In this case, the upper limit of the heat flow is controlled by the dunite rheology used to represent mantle in our calculations. The results discussed in the previous section provide an upper limit of 65–70 mW/m² for the surface heat flow even in this case. Although no surface heat flow and radiogenic heat generation measurements are available from the Jabalpur region, the surface heat flow of 70–100 mW/m² in the central Indian region shown in the heat flow map of India¹² is high compared to the above values and would favour a ductile deformation of the crust and upper mantle, if used in a pure heat conduction model. The heat flow values obtained by Rao *et al.*¹³ and Gupta *et al.*¹⁴, however, are below this limit. Therefore, a relatively low heat flow regime is required, at least for the lower crust and mantle, to explain deep crustal seismicity.

Fluid advection in the uppermost crust can provide a mechanism to explain excess surface heat flow and yet a thermally cool lower crust and upper mantle. Bickle and McKenzie³⁰ showed, through a simple one-dimensional thermal model, that the temperature in the crust can be increased if upward advection of fluid in the crust is incorporated in the model. In this model fluids enter the base of the crust from the mantle, raising the temperature of the whole crust. If this model is applied to incorporate advection in the shallow crust, it would imply an increase in temperature of the shallow crust. The above model is applicable for pervasive flow. Hoisch³¹ modified this model and suggested a channel flow model for heat transport by fluids. In this model fluids advect upward along fractures, thereby locally raising the temperature around the fracture zones. In such a model one can

expect locally high surface flow, but a cool rock mass. As a limiting case, this channel flow model becomes a pervasive flow model when the spacing between the channels reduces to zero. If we consider a similar situation for the NSTL, we can expect locally high surface heat flow along the faults, but still a cool lower crust and upper mantle. A number of hot springs, present all along the NSTL (Figure 1), support an advective regime. Additionally, a fluid-filled low-velocity and high-electrical conductivity layer at 6–10 km depth has been inferred by deep seismic³² and magnetotelluric³³ studies carried out in the Indian shield, south of the NSTL.

There are some other sources of uncertainty. For example, laboratory experiments on different rocks indicate that thermal diffusivity decreases linearly with the increase in temperature³⁴. A similar relationship can be expected for the thermal conductivity and temperature also. If such a temperature-dependent thermal conductivity is incorporated in the model, this would result in a hotter and thus more ductile crust, indicating that the mantle-derived heat flow should be further lower. Therefore, our estimate of surface heat flow provides an upper limit of the depth to B/D transition. The value of strain rate is also somewhat high to get an upper limit. In many continental shield regions, a strain rate of 10⁻¹⁵ s⁻¹–10⁻¹⁶ s⁻¹ has been suggested. As shown in Figure 2, such a strain rate would indicate a shallow depth for the B/D transition in comparison to the depth of B/D transition obtained for the strain rate of 10⁻¹⁴ s⁻¹. Once again our estimates give an upper limit for the plausible heat flow values. Occurrence of the Jabalpur earthquake very close to the crust–mantle boundary, thus, provides a constraint on the thermo-mechanical structure of the central Indian shield, by favouring a low mantle heat flow.

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Cryptic metasomatism in the upper mantle beneath Kutch: Evidence from spinel lherzolite xenoliths

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Spinel lherzolite xenoliths entrained in the alkaline rocks from central Kutch vary from fertile (10–12% modal clinopyroxene) to depleted (2–3% modal clinopyroxene) types. Low equilibrium temperatures (884–972°C) indicate entrainment of lherzolite xenoliths from shallow depths within the lithosphere. Variations of major oxides and incompatible elemental concentrations in clinopyroxene indicate a primary control by partial melting. In most of the depleted xenoliths however, the light rare earth elements (LREE), thorium (Th) and niobium (Nb) are strongly enriched and cannot be attributed totally to the process of partial melting. The absence of typical ‘metasomatic’ minerals, low equilibration temperatures and enriched LREE patterns indicate that the upper mantle below Kutch underwent an event of cryptic metasomatic enrichment prior to partial melting. The distinctive chemical features, viz. LREE enrichment, strong Ti depletion relative to Eu, and slight Nb enrichment, fractionation of Zr and Hf and therefore high Zr/Hf ratio, high La/Yb, Nb/La and low Ti/Eu are all results of interaction of refractory peridotite residues with carbonatite melts.

METASOMATISM is a process in which the chemical composition of the rock is changed by the addition or removal of elements. In the recent years, mantle metasomatism

has been invoked to account for the geochemical and isotopic inhomogeneities within the upper mantle documented in peridotite xenoliths entrained in kimberlite and alkali basalts. Although metasomatism in the xenoliths is partly attributed to the transporting magma, most metasomatism takes place before entrainment and is of interest, particularly if its effect can be correlated with coeval and/or later magmatism and tectonic events such as plateau uplift and rifting. Detailed chronological data are, however, needed in this regard.

The appreciation of the fact that metasomatic processes may be important in the upper mantle has led to the terms cryptic and patent metasomatism¹ or modal metasomatism² being applied to mantle xenoliths. Patent or modal metasomatism is ‘petrographically recognizable due to replacement textures and development of hydrous mineral phases (additional to those commonly seen in peridotites) rich in incompatible elements, replacing anhydrous phases and sometimes associated with the injection of fluids in channel-ways. The more subtle cryptic metasomatism has been proposed for when trace element enrichment occurs in xenoliths, apparently unaccompanied by mineralogical changes.

The alkaline rocks in central Kutch occur as plug, sheet or cone-like intrusions and entrain peridotite xenoliths of mantle origin^{3,4}. Prominent plugs occur at Dhrubia, Sayala Devi, Vethon and Dinodhar, whereas sheet-like bodies occur at Bhujia and Lodlai. These rocks are seen intruding the flat-lying or gently-dipping Jurassic sandstones in central Kutch. At Dhrubia, Vethon and Bhujia contact between sandstones and alkaline rocks is concealed by overlying Tertiary limestones or aeolian deposits. While in the other localities where the contact is exposed, the Jurassic strata are upturned and exhibit steep dips, or have become silicified near the contact. The mantle xenoliths from Bhujia and Lodlai occur in the central portion

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