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A note on the lithospheric thickness of the Kumaun - Garhwal Himalaya from change in viscosity at the lithosphere-asthenosphere boundary

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ABSTRACT The Himalaya with a strike length exceeding 2500 km is believed to have resulted from the collision of the Indian plate with the Eurasian plate during the Eocene to Miocene times. Based on the mean surface heat flow density and radioactive heat generation values of 68 mW / m^2 and 2.7 µW/ m^3 respectively, a part of the Kumaun-Garhwal Himalaya (Lat: 29°-31°N; Long: 79°- 81° E) is found to have a lithospheric thickness of about 123 km, as estimated by the depth, at which the high surface value of the viscosity dropped to about 10^{21} poise (10^{20} kg/m/sec) corresponding to the viscosity-depth curve. The intersection of the mantle melting (solidus) curve with the geotherm of the Kumaun-Garhwal Himalaya at a depth of about 123 km, also provided the lithospheric thickness in respect of the Kumaun-Garhwal Himalaya.

1. Introduction

The lofty Himalaya is an arcuate orogenic belt, convex towards south with a strike length in excess of 2500 km. It is believed to have been formed as a result of the Indian plate colliding with the Eurasian plate during Eocene to Miocene times. The oldest records mapped in the Himalaya are the metamorphosed sediments, phyllites and schists of Archaean age. The Precambrian metamorphics and the granites formed the foundation over which the thick sequence of sediments ranging from late Precambrian to Cretaceous deposited. Occasionally, a thrust separates the two rock types. This sedimentary sequence was deposited in the Tethyan basin. The vast sequence of high grade metamorphics and granites underlying the Tethys Himalaya has been thrust and pushed up as the great Himalayan range. Fig. 1 showed the regional geology of the Himalayas after Gansser (1964).

Compared to the vast size of the Himalayas, geophysical data, based on field surveys, are scarce and sparse. Qureshy *et al*. (1989) published Bouguer gravity data in regard of the northwest Indian Himalaya covering the Kumaun-Garhwal region. Das *et al.* (1979) undertook gravity and magnetic surveys along five transects stretching across northwest Indian Himalaya. Bellousov *et al*. (1983) and Kaila *et al*. (1984) carried out Deep Seismic Sounding (DSS) surveys along north - south profiles starting from the Kashmir Himalaya. Based on the DSS survey, Bellousov *et al*. (1983) estimated the lithospheric thickness from the Kashmir Himalaya to the Pamir of central Asia. A deep resistivity structure of the northwest Indian Himalaya was described by Arora *et al.* (2007) using magnetotelluric sounding data. Mahadevan (1994) provided spot lithospheric thickness values estimated by earthquake seismology data in respect of the central Indian Himalaya. A few surface heat flow measurements were reported pertaining

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to the northwest Indian Himalaya, Shankar (1988) published high surface heat flow values in the range of 100 to 180 mW/m^2 for the Kumaun-Garhwal Himalaya. The present work involved estimation of the lithospheric thickness of a part of the Kumaun-Garhwal Himalaya as shown in Fig. 1 from surface heat flow data.

2. Principles involved in the lithospheric thickness determination from change in viscosity at the lithosphere-asthenosphere boundary

The plate tectonic model of the Earth dynamics envisaged a rigid and, mechanically strong lithosphere overlying a weak and deformable asthenosphere. The base of the lithosphere has no rigorous definition, it is generally equated to the top of the upper mantle seismic, low velocity zone. The zone usually begins at depths of 50-150 km, depending on the tectonic set up of the region. Global geotherms usually intersect the mantle solidus at a depth coincident with the top of the seismic low velocity zone, giving the bottom of the lithosphere (Pollack and Chapman, 1977). We used the general relationship to calculate the one-dimensional temperature-depth profile (geotherm) (Duchkov and Sokolova, 1995) in respect of the Kumaun-Garhwal area.

The relationship is as follows:

$$T(Z) = T_0 + (q_0 - A_0\, Z/2) \cdot Z/K \tag{1}$$

where T_0 is the surface temperature in degree absolute, K is the thermal conductivity in W/m/^{0}C, A_0 is the radiogenic heat generation at the surface in μW/m^3, q_0 is the surface heat flow density in mW/m^2 and $T\,(Z)$ being the temperature in degrees absolute at a depth of Z km.

In order to calculate $T(Z)$ from Eq. (1) the following values are adopted. T_0 the mean surface temperature of this part of the Kumaun-Garhwal Himalaya is 10°C as obtained by taking the mean of the temperature ranges (downloaded from Website) in respect of six important places of the Kumaun-Garhwal Himalaya, the mean thermal conductivity of the crust is given by 2.5 W/m/°C, a standard value taken for similar calculations, A_0 is the radioactive heat generation value 2.7 μW/m^3 (Francheteau *et al.*, 1984) and a mean surface heat flow density of 68 mW/m^2 in respect of a part of the Kumaun-Garhwal Himalaya is given by Gupta (1995).

The mantle solidus curve provided by Pollack and Chapman (1977) is adopted for our work. According to Chapman and Pollack (1974), the lithosphere - asthenosphere boundary (LAB) may be formally defined as the depth at which the viscosity value of the Earth has diminished from its high surface value to about 10^{21} poise (10^{20} kg/m/s). This viscosity of the asthenosphere is suggested by postglacial rebounds and also by the velocity of the lithospheric plate movement over the deformable asthenosphere. The viscosity is computed as a function of temperature and thus of depth following the relationship deduced by Weertman (1970). Using the standard material constants, the relationship (Weertman, 1970) may be expressed as

$$\eta = 0.93 \times 10^{19} \times T/\overline{D}\ \sigma^2 \tag{2}$$

and $\overline{D}$ is given by

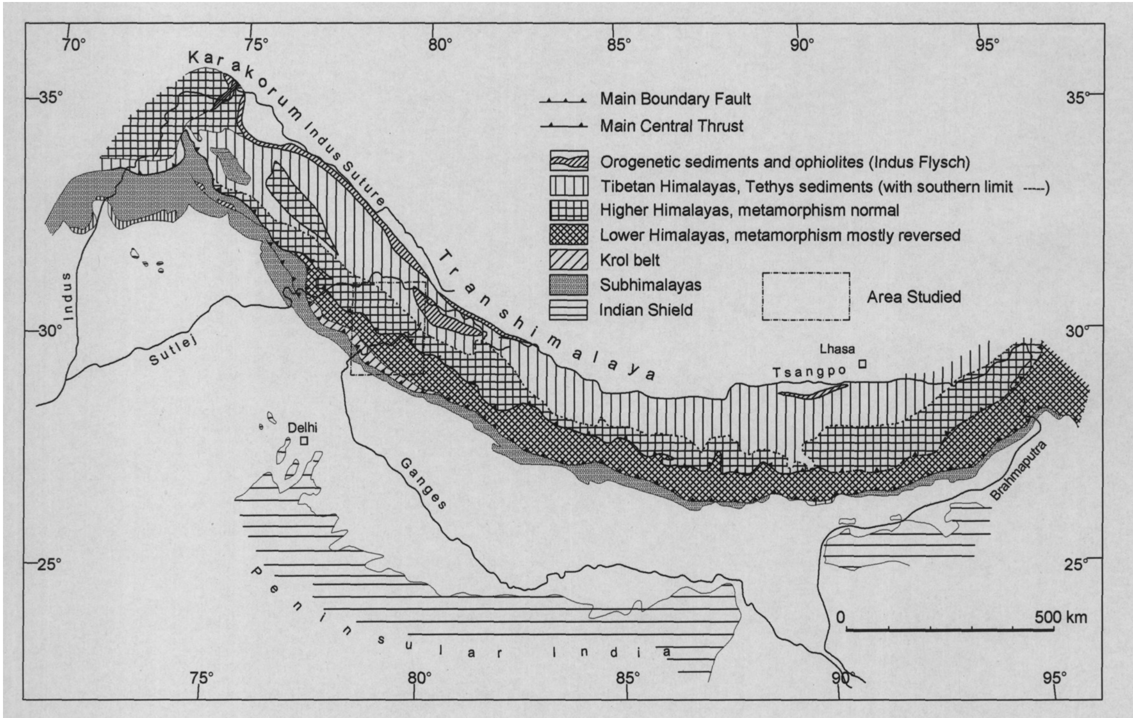

Fig. 1 - Map of regional geology of the Himalayas after Gansser (1964).

$$\bar{D} = D_0 \; exp \; (- \, g \, T_M \, / \, T) \qquad (3)$$

where T is the temperature of the geotherm at a given point measured in degrees absolute, g is a dimensionless constant approximately equal to 18 for most materials (Weertman, 1970), T_M is the temperature of the solidus curve corresponding to the temperature T at which viscosity is calculated, σ is the mean shear modulus of the area under consideration taken as 0.15 bar (Wang *et al*., 1982) and D_0 being 10^{-1} to 10^2 cm^2/s for most of the materials (Weertman, 1970).

3. Discussion of the results

The lithosphere geotherm of a part of the Kumaun-Garhwal Himalaya, Fig. 2a, as shown in gave the temperature variation of the lithosphere as a function of depth. The mantle solidus curve (Fig. 2b) is found to intersect the geotherm at a depth of about 123 km. Thus according to Gass *et al*. (1978), the lithospheric thickness of the area is about 123 km. The viscosity-depth profile (Fig. 2c) showed that the high surface value of viscosity got reduced to a value of 10^{21} poise (10^{20} kg/m/sec), as per the viscosity line (Fig. 2d), at a depth of about 123 km. Thus, the mean thickness of the lithosphere pertaining to the study area of Kumaun-Garhwal Himalaya is of the order of 123 km.

Radioactive heat generation value in respect of the Kumaun-Garhwal Himalaya is not available, therefore, we used the radioactive heat generation value of 2.7 $\mu W/m^3$ reported by Francheteau *et al*. (1984) in respect of the southern Tibet, which is close to the Kumaun-Garhwal Himalaya.

The differential of the mean surface heat flow density of 68 mW/m^2 (Gupta, 1995) and surface heat flow contribution of 45 mW/m^2 by the radioactive heat generation of 2.7 $\mu W/m^3$ (Francheteau *et al*., 1984) provided a mantle heat flow of 23 mW/m^2 for the Kumaun-Garhwal Himalaya area under study, which is of the same order of the mantle heat flow for shield area (Pollack and Chapman, 1977). Based on the seismic velocity variations, the Himalayas and the adjacent southern Tibet have been reported to have possessed a shield-like mantle structure (Lyon-Cean, 1986). Therefore, adoption of the radioactive heat generation of 2.7 $\mu W/m^3$ (Francheteau *et al*., 1984) in respect of the Kumaun-Garhwal Himalaya is generally correct.

Eq. (1) is widely used in calculating the temperature-depth profile (geotherm), given the required surface heat flow, radioactive heat generation and thermal conductivity of the crustal rocks. Wei and Deng (1989) used Eq. (1) in calculating the geotherm of a part of the Tibetan Himalaya.

Estimation of viscosity as a function of depth using Eqs. (2) and (3) provided a precise lithospheric thickness estimate. The high surface value of viscosity sharply comes down to a value of 10^{21} poise (10^{20} kg/m/s) at the LAB. On the other hand, seismic velocity change (based on earthquake seismology) at the LAB is generally transitional, leading to imprecise lithospheric thickness estimate (Chapman and Pollack, 1974). A uniform thermal conductivity of 2.5 W/m/°C was taken to be the average for the entire crustal thickness. According to Negi *et al*. (1987), the variation of thermal conductivity with depth would not have changed the calculated temperatures appreciably. In fact, Negi *et al*. (1987) showed that the calculation of geotherm taking a thermal conductivity value (K=3.0) would result in a variation of only 5 percent in respect of the estimated temperature. The mantle melting curve used in the present work is taken from Pollack and Chapman (1977). This melting curve corresponds to a slightly wet peridotite at shallow depths, then follows the general trend of both wet and dry peridotite melting curves up to a depth of 200 km. Starting from the surface, the melting curve maintains linearity for a considerable depth extent. The characteristics of the mantle melting curve, indeed are controlled by the regional variations of the lithosphere (Pollack and Chapman, 1977).

According to the bulletins of the International Seismological Centre (ISC), the focal depths of the earthquakes in respect of the Kumaun-Garhwal Himalaya range up to 70 km. Eastern and western extremeties of the Himalaya area were reported to have been affected by deeper focus earthquakes (e.g. Seeber and Armbruster, 1983; Khattri and Thyagi, 1983). The depth distribution of the earthquakes is also reported to be non-uniform along the Himalaya (Khattri *et al*., 1989). The focal depths of about twenty earthquakes of the northwest Himalaya with moderate magnitudes have been estimated using a waveform modelling method in addition to crustal reflection phases. The mentioned earthquakes are not uniformly distributed along the strike of the Himalayas. The ISC has reported events at depths of up to 130 km, indicating deformation within the upper mantle. According to Khattri (1987), there does not exist considerable variation in the structure of the Himalayan foredeep (Indo Gangetic Plain) or in the Himalayas along the strike.

A good percentage of the teleseismically located events of the Himalayas have focal depths confined to 33 km or so. Several earthquakes are located up to a focal depth of 80 km. It is

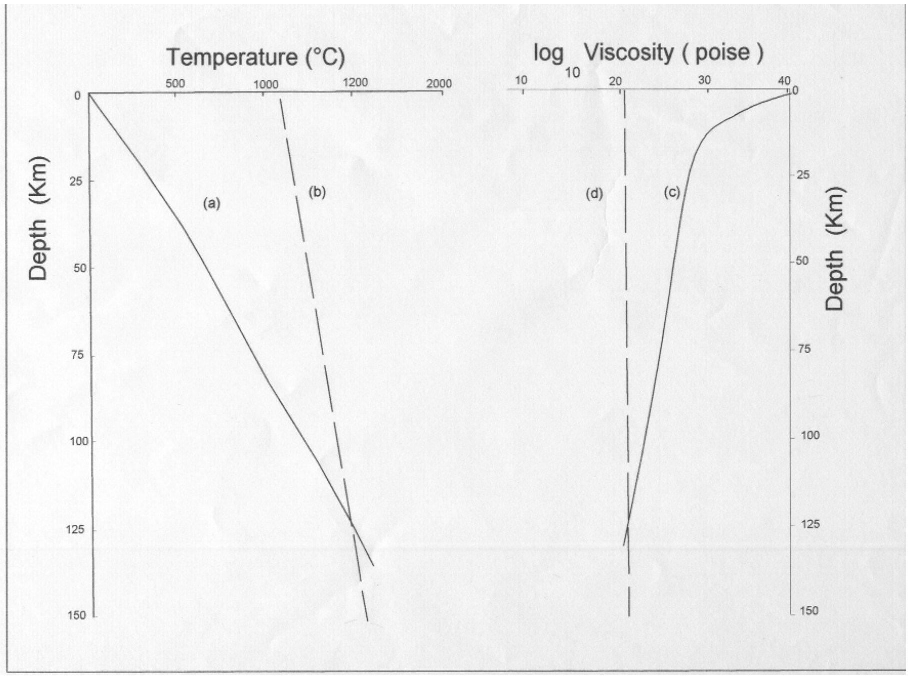

Fig. 2 - Lithosphere geotherm of the Kumaun-Garhwal Himalaya (a); mantle solidus curve (b); variation of viscosity with depth (c); viscosity line corresponding to 10^{21} poise (d).

interesting to note that earthquakes located by the local networks lie in the upper 23 km of the Kumaun-Garhwal Himalaya. In fact, the local seismic data conforms to the general picture of tectonics based on geological mapping. In other words, the seismicity zone occurs close to the Main Central Thrust (MCT).

The focal depths of the earthquakes provide a definite idea as to the prevailing rheology at these depths for the Kumaun-Garhwal Himalayas. The rocks must be in a state of britility to sustain earthquakes. Ni and Barazangi (1984) reported high shear wave velocities under the western Himalaya, suggesting normal temperature regime. Shankar (1988), reported high-surface, heat flow density, as pointed out earlier, in the range of 100-180 mW/m^2 in respect of the Kumaun-Garhwal area. The high heat flow density is suggestive of elevated temperatures at depths of 40 to 80 km, implying that rocks may not be in a position to generate earthquakes. Thus, high temperatures at depths of 40 to 80 km, and earthquakes having focal depths of the order of 40 to 80 km are apparently contradictory (Khattri, 1992).

4. Conclusions

Using direct measurements of surface heat flow density and radiogenic heat generation values, the lithospheric thickness of a part of the Kumaun-Garhwal area was estimated at about 123 km. The estimated lithospheric thickness was given by the depth of the viscosity-depth curve, where the high surface value of the viscosity dropped to about 10^{21} poise (10^{20} kg/m/s). The thickness of the lithosphere for the Kumaun-Garhwal Himalaya was, also estimated by the intersection of the geotherm with the mantle melting (solidus) curve, giving a thickness of about 123 km. Estimations of the lithospheric thickness based on the aforementioned concepts provided precise estimates as compared to the lithospheric thickness estimation by seismic velocity change at the LAB for the reasons already explained. The estimated lithospheric thickness is compatible with the surface heat flow density value (Negi *et al*., 1987). Gravity modelling of the lithospheric flexure of the central Himalaya-Indo Gangetic plain gave a lithospheric thickness in the range of 80 to 100 km (Karner and Watts, 1983). Bellousov *et al*. (1983) estimated lithospheric thickness from 150 to 180 km in respect of the western Himalaya-Kashmir-Pamir. The estimated thickness of the lithosphere of the order of 123 km pertaining to a part of the Kumaun-Garhwal Himalaya, lying between the central Himalaya-Indo Gangetic Plain and the western Himalaya-Kashmir-Pamir is, therefore, a reasonable estimation.

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