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Correlation of Heat Flow and Crustal Topography in the Indian Region

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Summary

Possible correlations of geothermal data, over the Indian sub-continent, with respect to topography, crustal thickness, geological age and Bouguer gravity anomaly, have been examined. Heat flow and geothermal gradient in general decrease with the increase in topography, crustal thickness and geological age. A significant correlation between the Bouguer gravity anomaly and the geothermal parameters is also noted. From the analysis of results, in terms of factors contributing to the geothermal field, one may surmise that in the high heat flow areas, contributions from the isotherms, due possibly to a partial melting zone, might also be considerable. A brief discussion of the geothermal field distribution, as conceived from the study, is also given in view of the protocontinental type of crustal growth.

1. Introduction

The study of the geothermal field is of vital significance for understanding the evolution of the crust and thermal processes in the Earth's interior. The consistent correlation between high and low heat flows with unstable and younger, and stable and older regions respectively, on the global scale, has already been investigated by Lee (1970) and Negi & Pandey (1974). Recently global heat flow data have been correlated with the parameters affecting the first-order steady state dynamic-processes of the Earth, namely geothermal characteristics of the crust (Horai & Nur 1970; Negi, Panda & Pandey 1974, 1976; Negi & Pandey 1976a), regional geotectonics (Lee & Uyeda 1965), areas of rejuvenation (Lee & Uyeda 1965), thermal history (MacDonald 1965), ages of the continental and oceanic regions (Hamza & Verma 1969; Sclater & Francheteau 1970; Verma, Hamza & Panda 1970), basement and topographic relief (Lee & Uyeda 1965; Gupta *et al.* 1970), radioactive heat generation (Lachenbruch 1968; Roy, Blackwell & Birch 1968; Swanberg *et al.* 1974), low velocity channel (Panda 1974), transient geomagnetic fluctuations (Warren *et al.* 1969), gravity field (Lee & MacDonald 1963; Wang 1965; Girdler 1967) and elastic parameters of the Earth (Horai & Simmons 1968; Horai 1969). Though, to a large extent, these studies have helped in the understanding of problems related to the thermal regime

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of the Earth, they have also led to some inconsistent results as pointed out by Negi *et al.* (1974, 1976). The latter may, perhaps, be due to the fact that our knowledge of the dependence of heat flow on its possible sources, their magnitudes and distribution pattern, is far from complete despite the insight gained by studies due to Von Herzen (1967), Lubimova (1966, 1969), Tikhonov, Lubimova & Vlasov (1969, 1970), Beloussov (1972) and Negi *et al.* (1974).

The present study proposes to examine the possible correlation between the geothermal characteristics of the continental Indian region with other geophysical parameters, namely topography, crustal undulation, geological age and gravity anomaly. We express the heat flow values in units of μ cal cm^{-2} s^{-1} and geothermal gradients in unit of deg C km^{-1}.

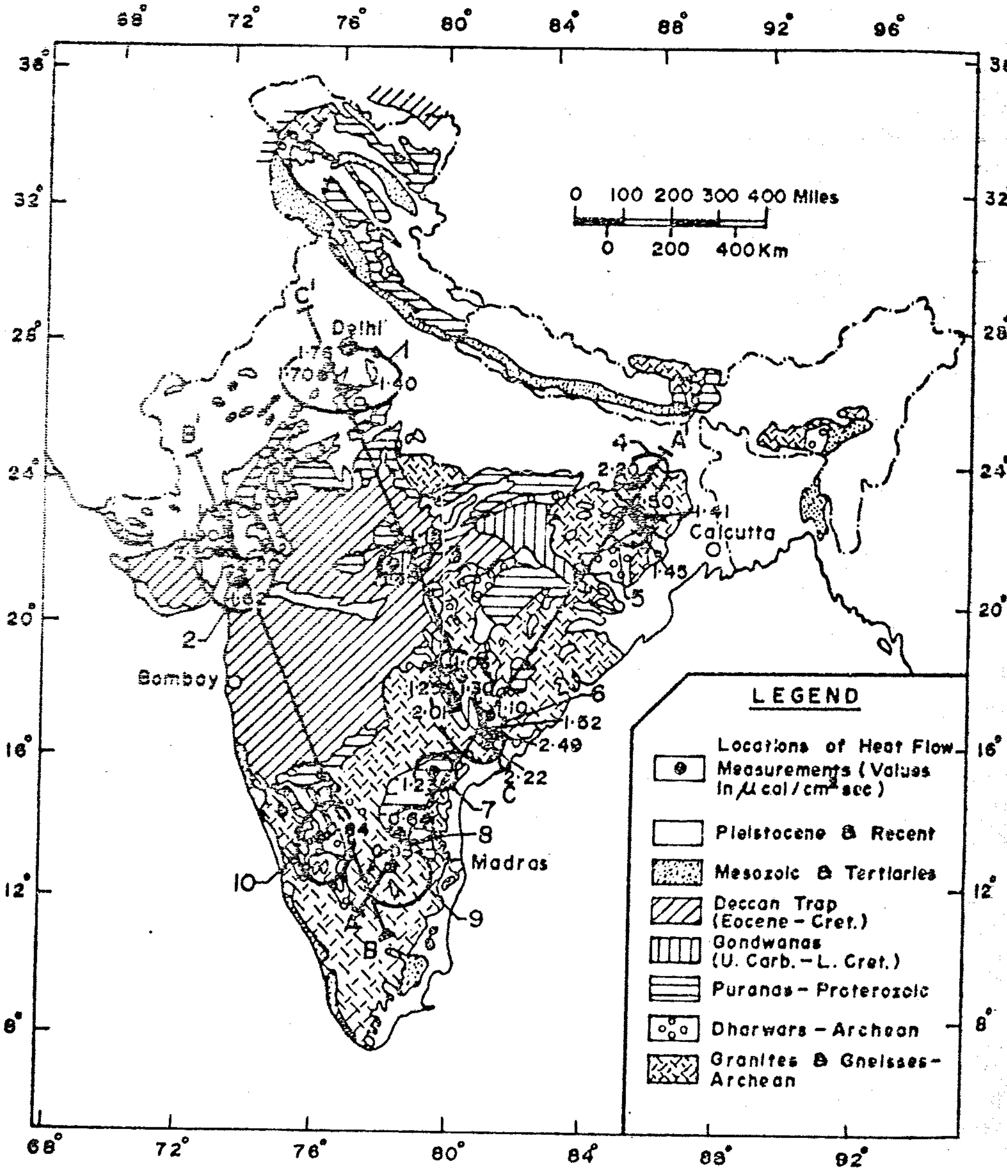
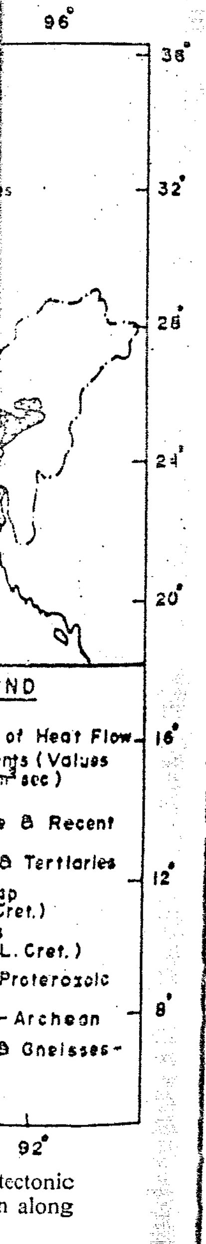


FIG. 1. Heat flow measurement sites with respect to major geological and tectonic units. The numbers give heat flow values. Heat flow profiles are taken along AA', BB' and CC'.



2. Heat flow and other geotectonic patterns of India

The heat flow measurements were initiated by the National Geophysical Research Institute (Hyderabad) in 1962 at the Kolar, which is the deepest known mine in shield areas (Verma & Rao 1965). Since then such studies have been extended to other areas like the Aravalli belt, the Singhbhum thrust zone and the basins of Cuddapah, Gondwana, Satpura and Cambay, which have different histories of evolution. In these investigations, more than 50 measurements of geothermal gradient and 25 measurements of heat flow were made over representative formations with exceptions over the Deccan Traps and Foothills of the Himalaya. The locations of the sites whence the heat flow values were obtained are shown in Fig. 1, along with the major geological and tectonic units. From the heat flow data, it is noted that the observed heat flow varies from 0·64 to 2·49 (with a mean of 1·56), while the geothermal gradients range from 10·35 to 74·9. Further, in the entire Indian region, the high and low heat flow values are well correlated with the high and low geothermal gradient values respectively (Negi *et al.* 1974).

Geologically, the Indian continental areas are quite intricate owing to different types of geological formations, associated with complex structural features of large dimensions. These formations may be characterized by the ages, and represent the complete geological time scale (from Archean in the south to Tertiary and younger ones towards the north). Geotectonically, the peninsular region is broadly classified as (Wadia 1957):

1. Archean non-orogenic areas (Dharwars),
2. Precambrian orogenic belt related to mountain building activity,
3. Precambrian sedimentary basins (Cuddapah and Vindhyans),
4. Gondwana basins,
5. Deccan Traps (Cret.–Eocene), covering an area of 510 000 sq. km and volume of 700 000 km^3 with a thickness of roughly 1·8 km,
6. Tertiary basins of Cambay and Cauvery.

Further the repeated metamorphism and complexity of geotectonic patterns also seem to have greatly influenced the thermal characteristics of this continent.

3. Analysis of geothermal data

The correlation analysis is carried out between the geothermic data of a given area (Verma & Narain 1968; Annual report 1968–69, 1969–70, 1971–72; Verma *et al.* 1969; Gupta & Rao 1970; Gupta *et al.* 1970; Rao *et al.* 1970) and corresponding geophysical parameters, the correlation coefficients (r) are calculated using the formula

$$r = \frac{\sum xy}{\sqrt{((\sum x^2)(\sum y^2))}}, \tag{1}$$

where $x = X - \bar{X}$ and $y = Y - \bar{Y}$ are the deviations from the respective means and $\bar{X}$ and $\bar{Y}$ are the means of parameter series (X) and (Y) respectively such that

$$\bar{X} = \frac{\sum X}{N}, \tag{2}$$

$$\bar{Y} = \frac{\sum Y}{N}; \tag{3}$$

N is the number of terms in series (X) and (Y).

The standard error is derived from

$$\text{S.E.} = \frac{1-r^2}{\sqrt{N}} \tag{4}$$

Using Fisher's Z transformation (Waugh 1952), 95 per cent confidence limit for the computed correlation coefficients (r) have been obtained.

Wherever possible different percentile lines (namely, 75, 50 and 25 per cent) are also drawn, such that the 25-percentile line separates the data into two groups, 75 per cent of the data points above it and 25 per cent of the data points below it. In drawing the percentile lines, horizontal lines of different percentages (75, 50 and 25) of data points are drawn for small intervals on the horizontal axis and then sets of same percentile lines are connected smoothly.

The results obtained from this analysis are discussed below with respect to different parameters.

(a) *Topography and crustal thickness*

The topographic values used here have been taken from the survey of India toposheets (one inch = one mile) and the studies cited above. In the absence of deep seismic sounding data which are not yet available, the crustal thickness values are those as derived from the gravity studies of Qureshy (1971).

Correlation coefficients with estimates of uncertainties are calculated for heat flow and geothermal gradient with (i) elevation, and (ii) crustal thickness. The results are presented in Table 1.

Negative correlation coefficients of significant magnitude are obtained (Table 1), suggesting that heat flow and geothermal gradient generally decrease with the increase in the elevation and crustal thickness. This observation is also shown up in Figs 2–5, where the percentile lines of different amplitudes (namely, 75, 50 and 25 per cent) and the least square fit (Table 1) are drawn for the entire set of the data.

On the geological map of India (Fig. 1), three profiles (AA′, BB′ and CC′) were considered that cover most of the heat flow sites of different geological ages, and using

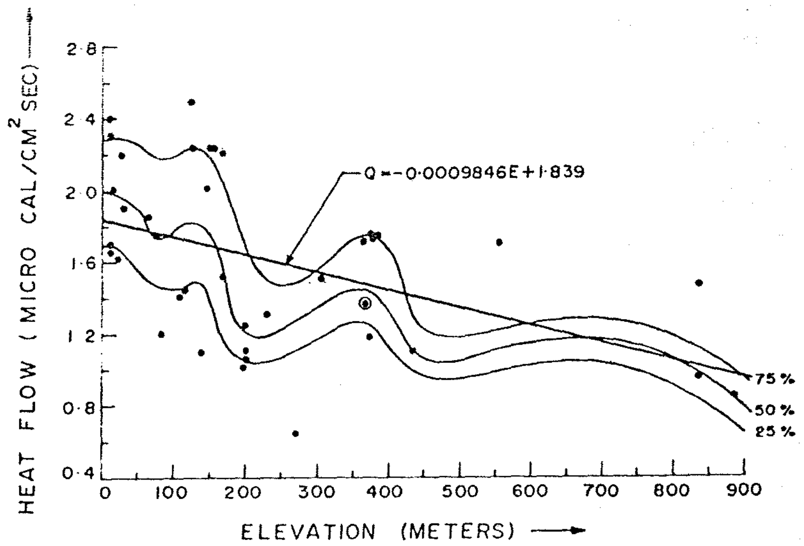


FIG. 2. Heat flow versus elevation.

Table 1

Results of the statistical analysis for a possible dependence of geothermal parameters on topographic and crustal thickness data

Parameters	Size of data	Correlation coefficient	Standard error	Confidence limits (95%)	Linear equation	Fig.
Heat flow and elevation	40	−0·47554	0·1224	−0·1877 to 0·6858	$Q = -0{\cdot}0009846E + 1{\cdot}839$	2
Geothermal gradient and elevation	53	−0·55944	0·0943	−0·3452 to −0·7211	$G = -0{\cdot}03725E + 38{\cdot}749$	3
Heat flow and crustal thickness	40	−0·47584	0·1224	−0·1877 to −0·6858	$Q = -0{\cdot}16688C + 7{\cdot}6798$	4
Geothermal gradient and crustal thickness	53	−0·55978	0·0943	−0·3452 to −0·7211	$G = -6{\cdot}316C + 259{\cdot}82$	5

Note: Q, G, E and C stands for heat flow, geothermal gradient, elevation and crustal thickness, respectively.

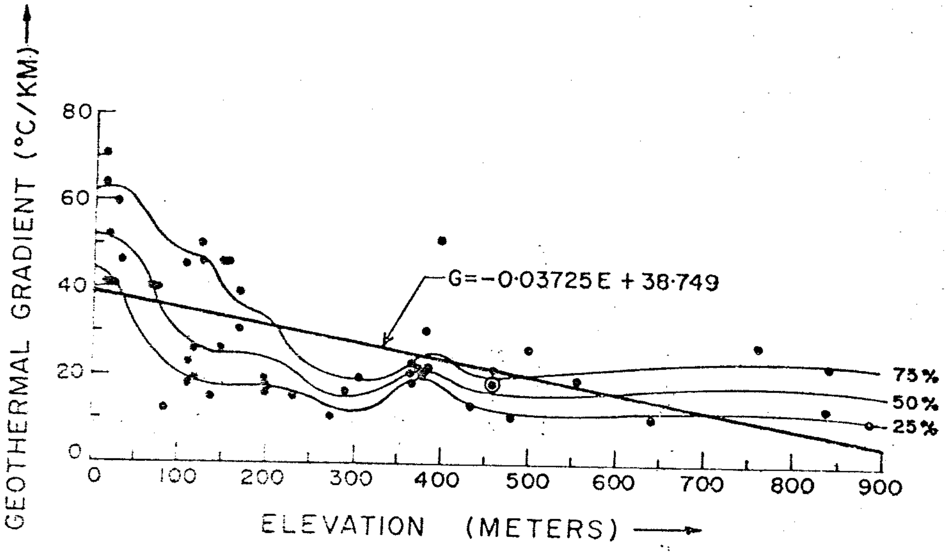


FIG. 3. Variation of the geothermal gradient with the elevation.

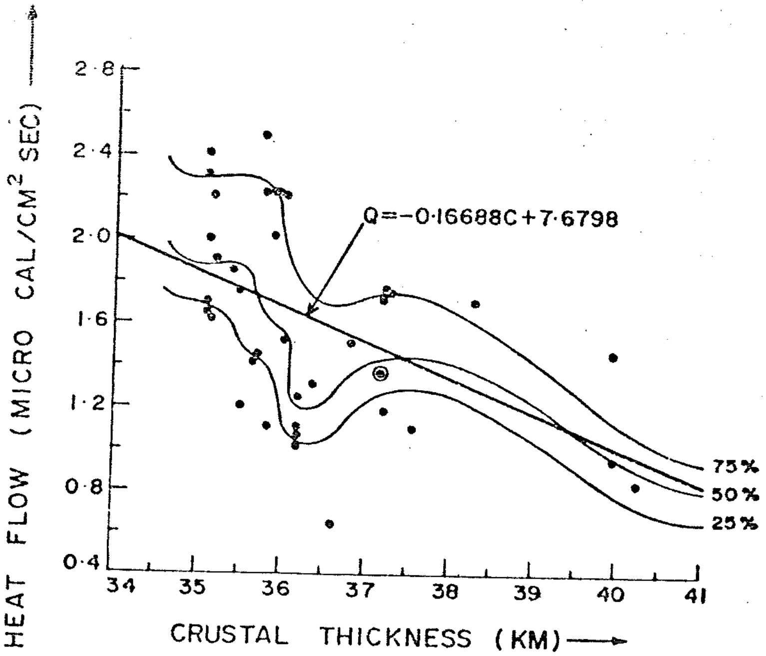
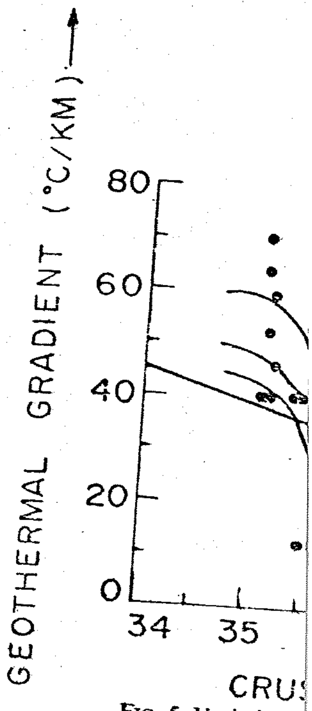


FIG. 4. Heat flow versus crustal thickness.



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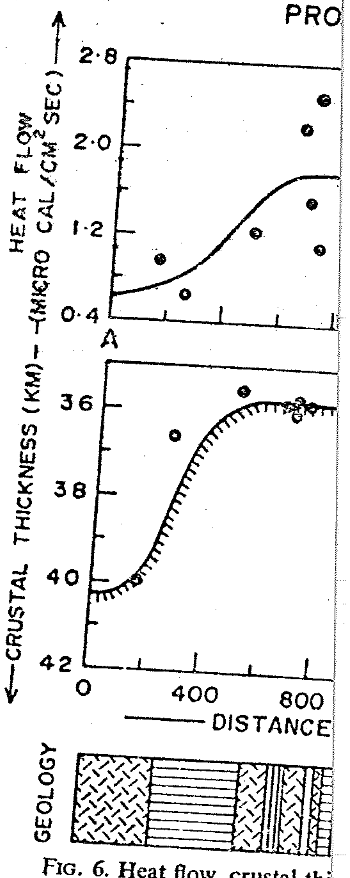

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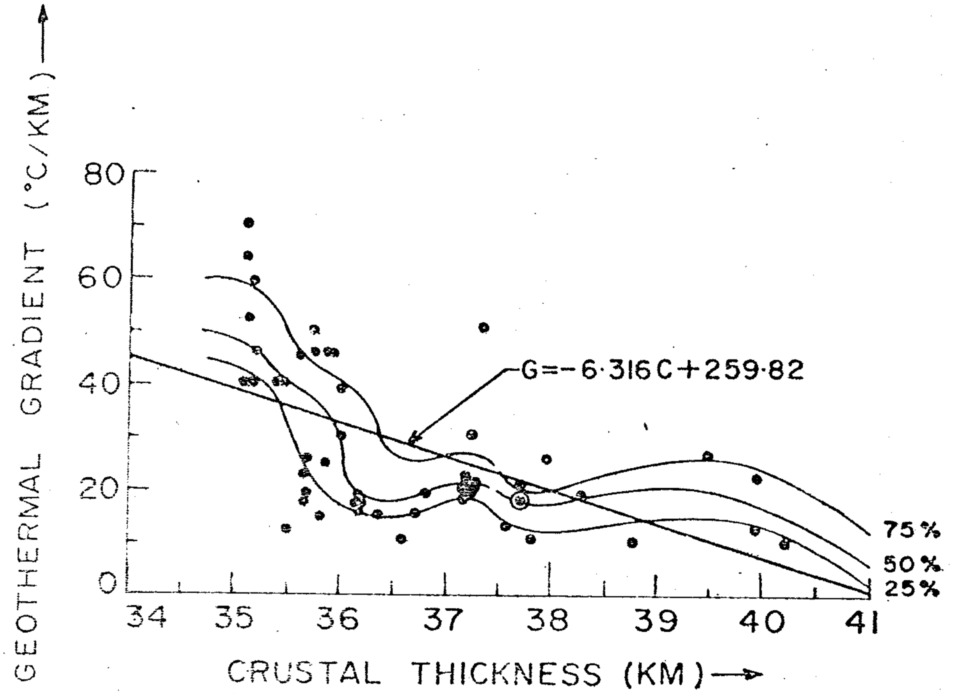


FIG. 5. Variation of the geothermal gradient with the crustal thickness.

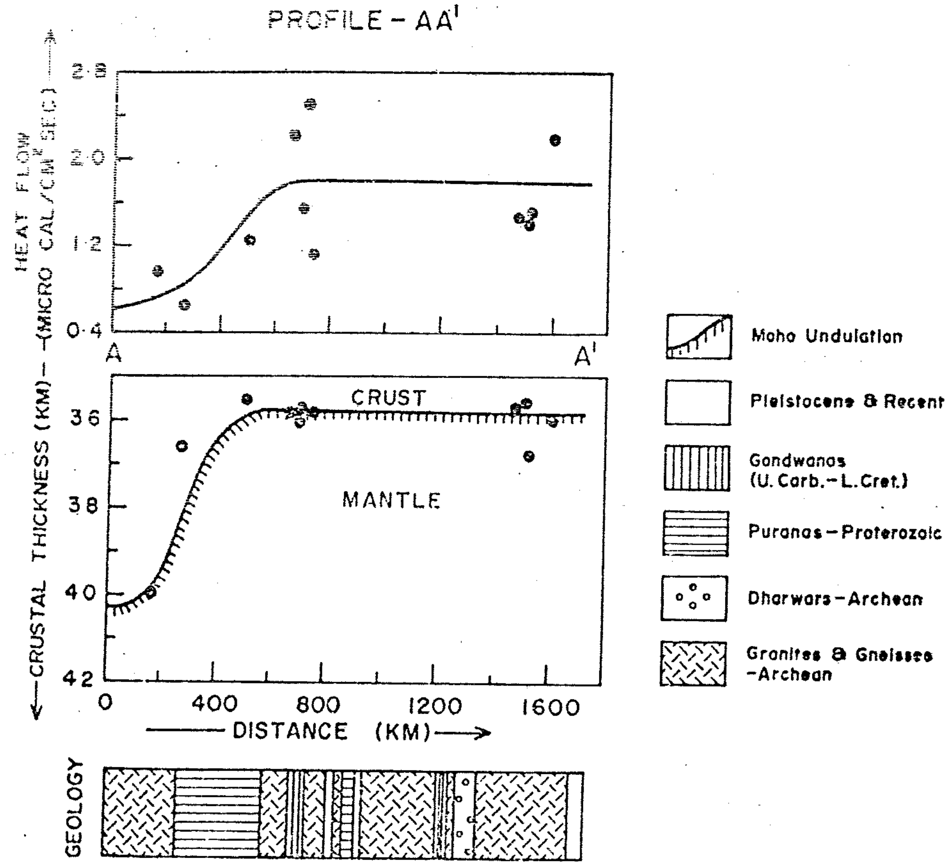


FIG. 6. Heat flow, crustal thickness and geological cross-section along the profile AA′ (Fig. 1).

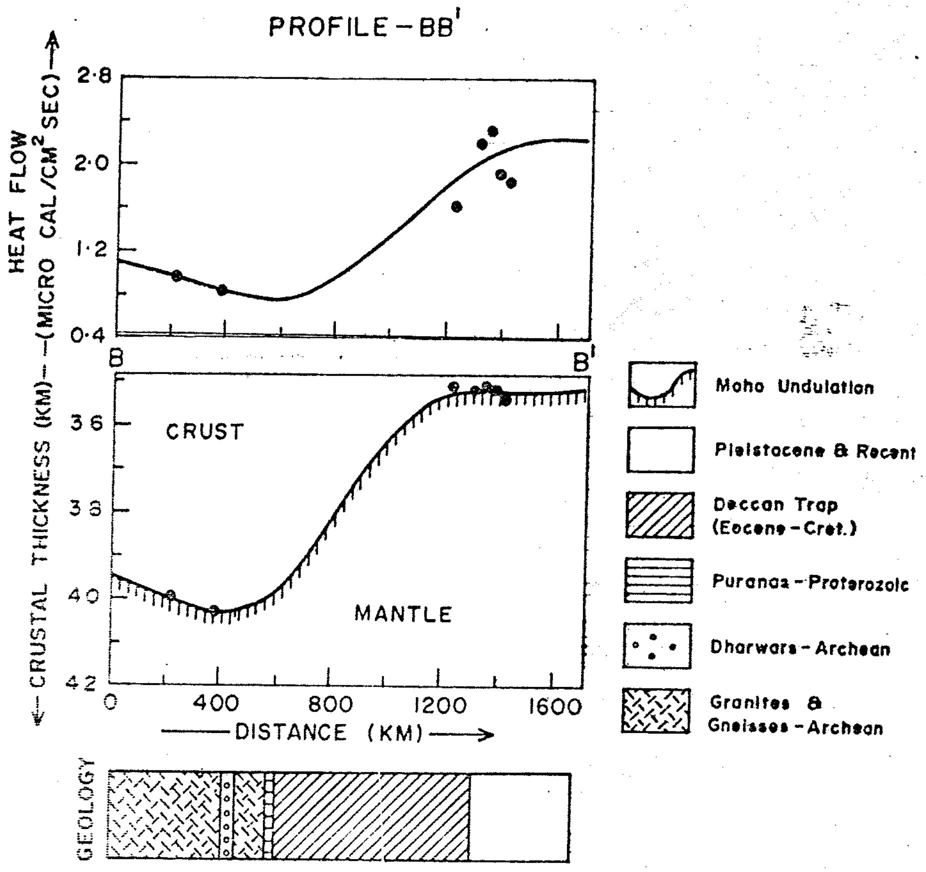


Fig. 7. Heat flow, crustal thickness and geological cross-section along the profile BB′ (Fig. 1).

the crustal thickness and heat flow data, their possible crustal sections have been estimated as shown in Figs 6–8. These figures reflect the correlation of heat flow with the crustal thickness.

It may be noted that similar results exist for other areas also, e.g. Europe (Scheffer 1964), Fossa Bradanica, Southern Italy (Mongelli & Ricchetti 1970), regions of Ukraine (Kutas 1972). In USA also, a similar effect is prominently demonstrated (Roy, Blackwell & Decker 1972) through a profile (Fig. 9) which passes through Arizona, New Mexico and Texas.

(b) *Geological age*

Correlation of heat flow with the geological ages of the rock formations, on the regional and global scale studied by various authors (Lee & Uyeda 1965; Lubimova 1967; Hamza & Verma 1969; Verma, Hamza & Panda 1970) is extended for the data on Indian continent. Here, we choose 10 areas, representative of geological formations of different ages as represented by closed solid lines on the geological map of India (Fig. 1). The geological ages have been taken from Aswathanarayan (1964a, b), Sarkar *et al.* (1964), Venkatasubhramanian & Gopalan (1967) and Saxena & Miller (1972). Plots of the heat flow and geothermal gradient versus geological age are given in Figs 10 and 11. It is found that both parameters in general decrease exponentially with the increase of geological age in conformity with corresponding

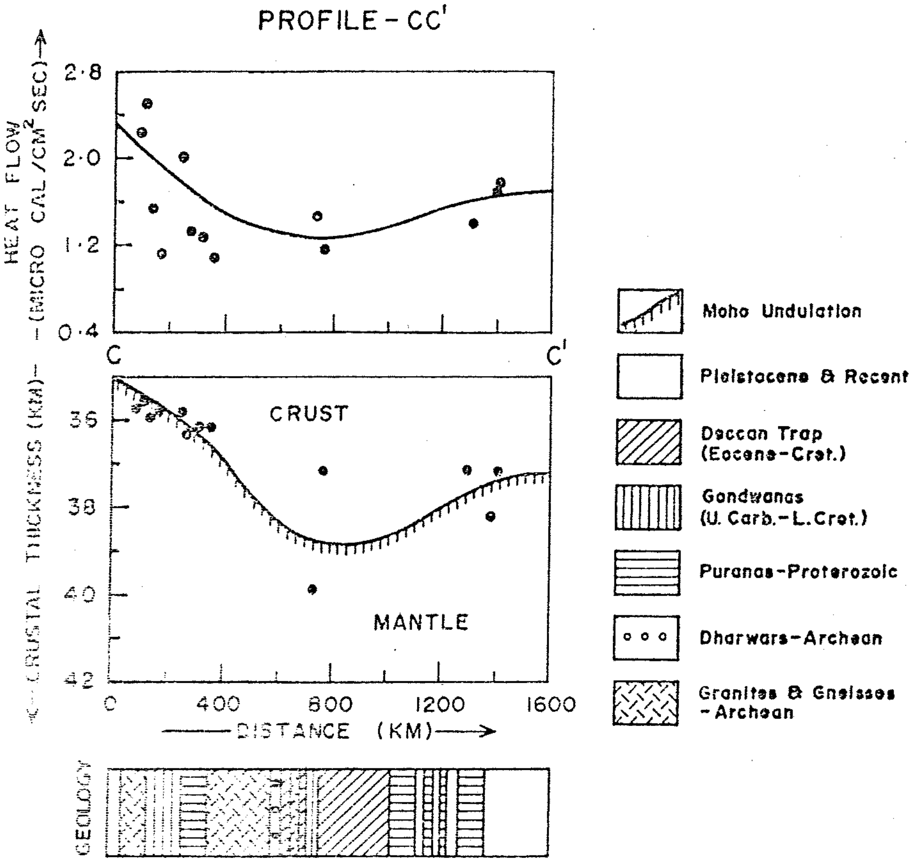


FIG. 8. Heat flow, crustal thickness and geological cross-section along the profile CC′ (Fig. 1).

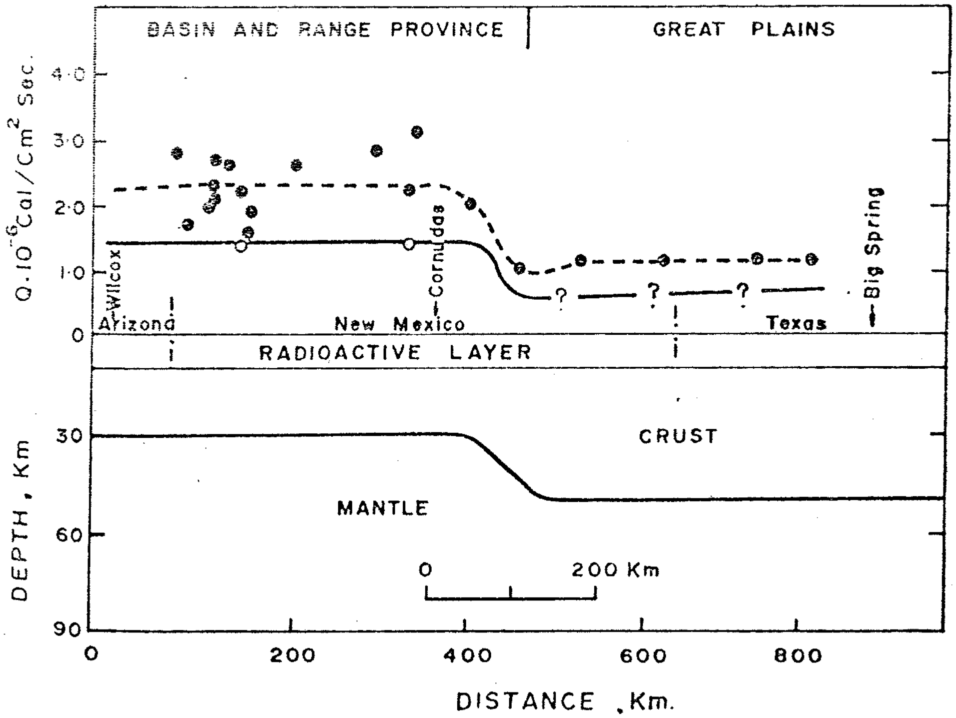


FIG. 9. Heat flow profile from Wilcox (Arizona) to Big Spring (Texas). The solid circles are the measured values whereas open circles represent 'reduced' values (After Roy *et al.* 1972).

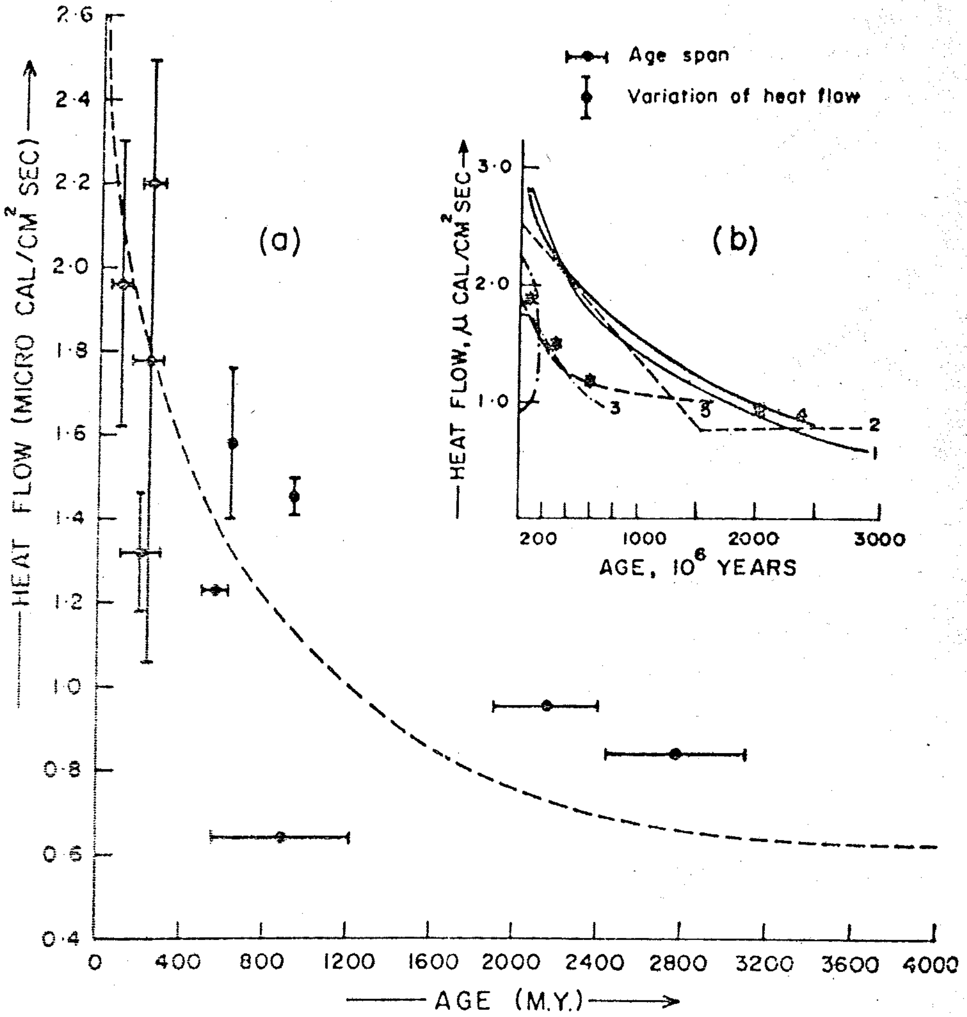


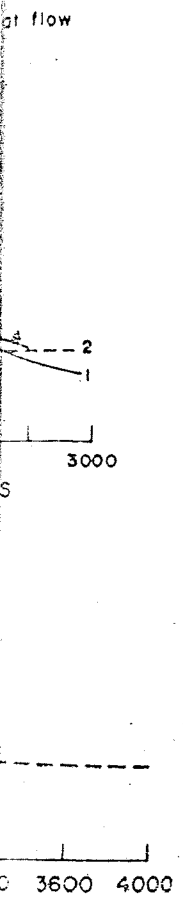
FIG. 10. The correlation of heat flow with the geological ages. (a) Illustrates results of present study on Indian region, and (b) results of similar studies by other investigators (mainly from Lubimova 1969): asterisks, Lee & Uyeda (1965); (1) Verma *et al.* (1967); (2) Lubimova (1967); (3) Makarenko, Polyak & Smirnov (1967); (4) Hamza & Verma (1969); (5) Kutas (1972).

studies for other places. For the sake of comparison, an inset is also inserted in Fig. 10 summarizing corresponding results on global scale from other studies.

From such a widely observed behaviour, it appears that the contribution to heat flow from the upper mantle is more through younger formations (characterized, in general, with smaller crustal thickness and high heat flow) than to the older formations (as featured by larger crustal thickness and low heat flow).

(c) *The Bouguer anomaly*

Recently number of studies, particularly using satellite observations, have been made to relate the global gravity field with surface heat flow (Lee & MacDonald 1963; Wang 1965; Girdler 1967; Horai & Simmons 1969) but no clear picture seems yet to emerge. Further, in such approaches much less attention has been paid to the correlation of heat flow with Bouguer gravity anomaly on either regional or global



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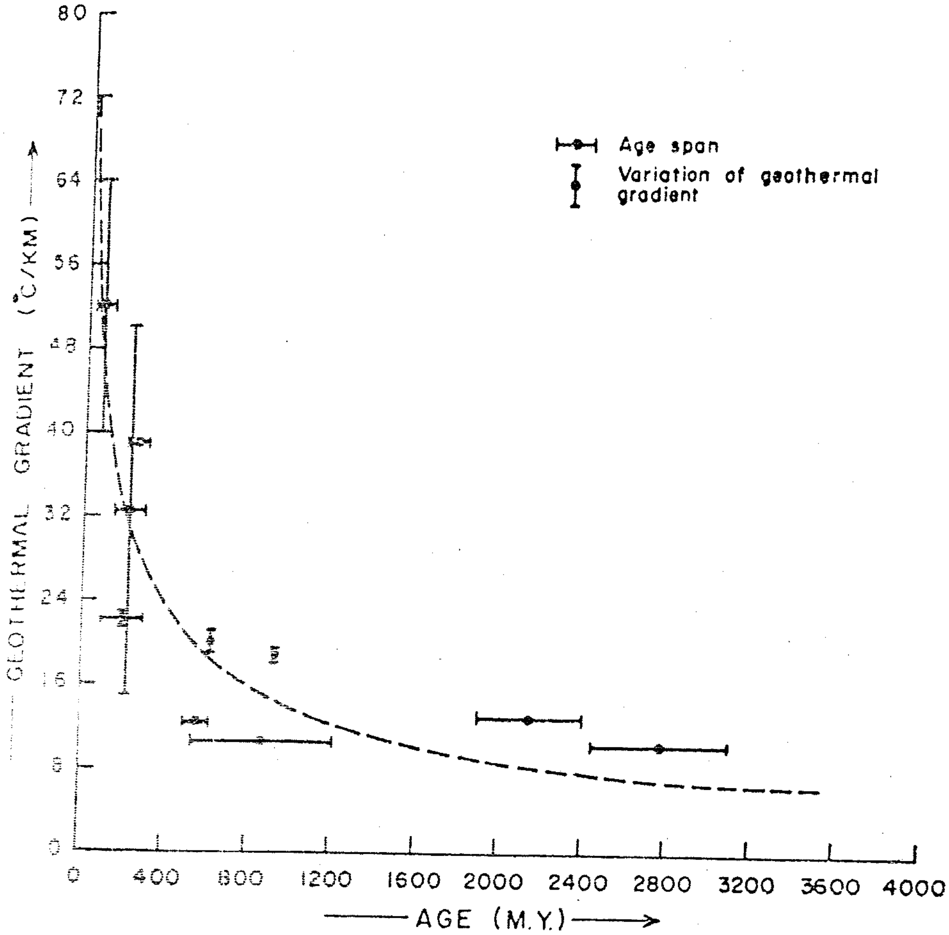


FIG. 11. Correlation of geothermal gradient with the geological age.

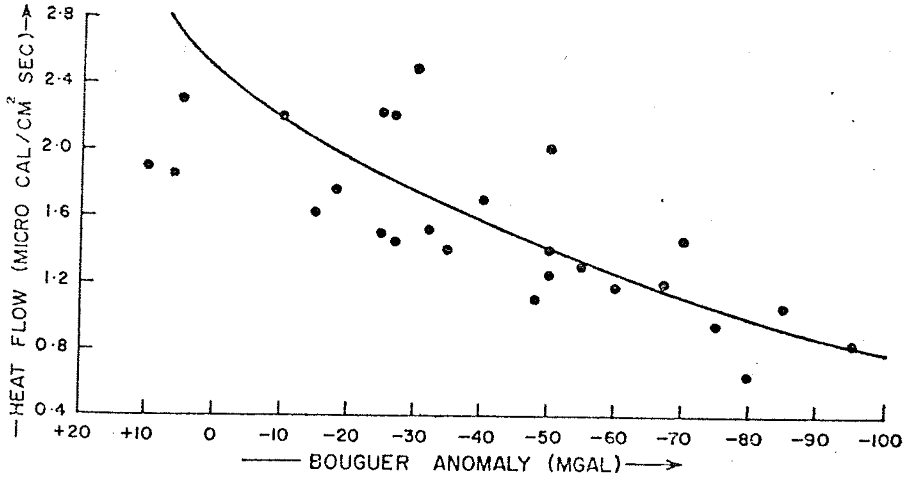


FIG. 12. Heat flow versus the Bouguer anomaly.

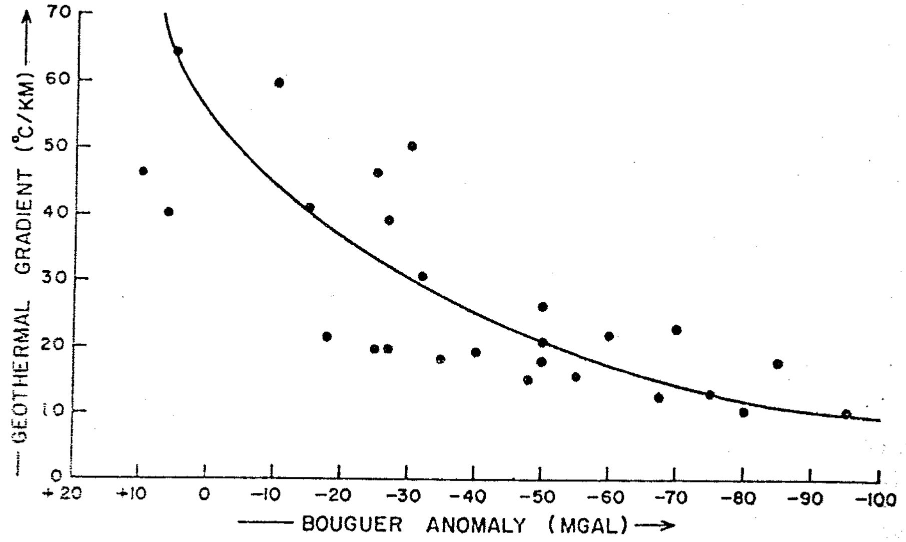


FIG. 13. Variation of geothermal gradient with the Bouguer anomaly.

scales apart from the work by Kresl & Novak (1970). The significance of this type of investigation may be that

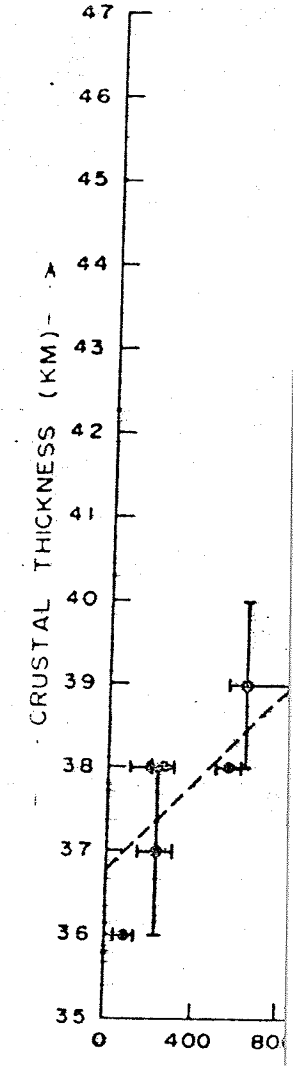
(i) the major steady-state geodynamic processes are dominated by the gravitational field, and

(ii) evolution of geological units depends on complex physico-chemical processes at depth involving thermal expansion and partial differentiation that modify the density distribution, giving rise to the density irregularities and disturbance of the gravitational equilibrium, reflected in the observed gravity field patterns.

Further according to Van Bemmelen (1967), gravity anomalies reflect the progressive stages of crustal evolution and are also closely linked with the thermal regime. We thus try to examine a possible relation between the geothermal and Bouguer anomalies over the Indian subcontinent. Gravity values have been taken from Gulatee (1956), Sengupta (1967), Qureshy *et al.* (1968a, b) and Qureshy (1971). The results are shown in Figs 12 and 13, which show approximately exponential decrease of both the geothermal parameters (namely, heat flow and geothermal gradient) with increase in the amplitude of negative Bouguer anomaly.

4. Discussion of the results

Crustal thickness and geological age. In the present study, we have examined the correlation of geothermal parameters with topography, crustal thickness, geological age and Bouguer gravity anomaly and in view of the results obtained, it might be reasonable to correlate geological age directly with the crustal thickness. Results of such an analysis (for 10 selected provinces of Fig. 1) are shown in Fig. 14, which depicts a linear increase in conformity with the observations of Woollard (1972) for the North American and Meissner (1970) for European continents as may be noted from the inset of Fig. 14. Further from this finding and those expressed in Figs 10 and 11, one expects that both heat flow and geothermal gradient should decrease with the increase in crustal thickness, as indeed is obtained from the analysis presented above (Figs 4 and 5).



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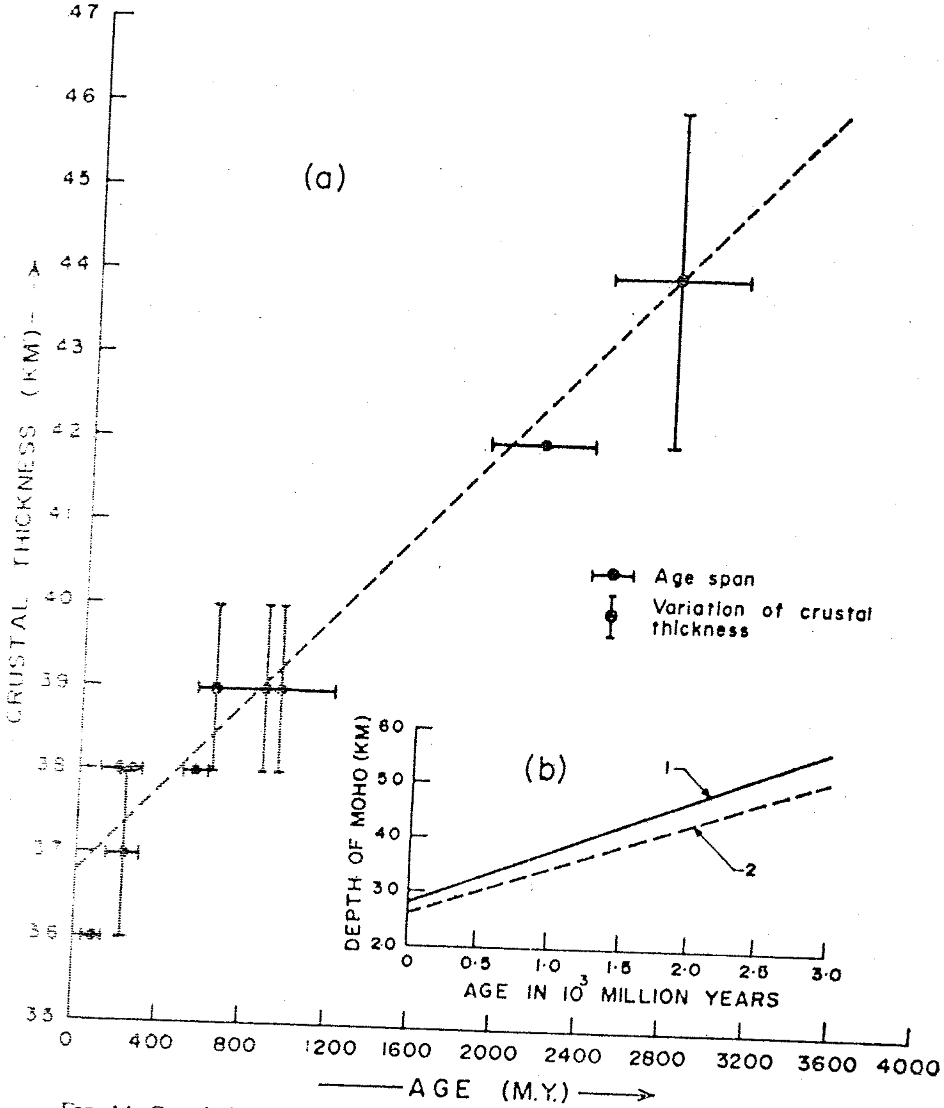

FIG. 14. Correlation of crustal thickness with the geological age. (a) Is derived from the studies over Indian region, and (b) from other studies: (1) North America (Woollard 1972); (2) Europe (Meissner 1970).

Sources of heat flow. Such a result does not seem explicable, if only the contributions from crustal radioactive sources are taken into account (which are known to be predominant mostly in the uppermost layers). Further, the zones of high heat flow, namely, (i) Cambay basin, with possible extension up to Khetri beneath the Aravallis, (ii) Jharia coal field area in Damodar valley, and (iii) South eastern portion of Godavary valley (Fig. 1) also do not appear to be associated with high radioactive concentrations, suggesting that deeper causes (mainly from the upper mantle), contribute significantly to the measured geothermal anomaly. This is supported by the observation that elevated topography and large crustal thickness are correlated with downgoing isotherms within the Earth and vice versa (Warren *et al.* 1969; Roy *et. al.* 1972).

Thus the observed heat flow may generally be assumed to be composed of a contribution from the radioactive sources of the upper crustal rocks to which is added that from the deeper physico-chemical processes (Tikhonov *et al.* 1969, 1970; Roy *et al.* 1972). The latter may be due either to thermal expansion, phase transformation, successive differentiation or partial melting etc. Among these, partial melting may be more probable as it is also thought to cause the horizontal heterogeneities, convection cells and rise of isotherms. In some cases (active and unstable younger regions), however, the amount of heat contributed from the interior, may be more than the crustal radioactive contribution, and it depends on the depth of the inner source and the temperature conditions of the Earth's mantle and crust (Clark & Ringwood 1964; Birch 1966; Von Herzen 1967; Warren *et al.* 1969). It might, thus, be surmised that isotherms, rising up from the partial melting zone in the upper mantle might also act as an additional source for the observed high heat flow zones, as is supported by the studies of Lubimova (1966, 1969), Tikhonov *et al.* (1969, 1970) and Beloussov (1972).

The protocontinental growth. It may be of interest to view these correlations of the geothermal field in the light of the protocontinental nucleation hypothesis, wherein it has been argued (Naqvi, Rao & Narain 1974; Negi & Pandey 1976b) that the Indian continental crust has been formed by the welding of the oldest protocontinents (or nuclei). These protocontinents are presumed to consist of $3 \cdot 0 \times 10^9$ y old separate prototype crust, characterized by low heat flow (0·64–1·76), large negative Bouguer anomalies (−50 to −100 mgal) and greater crustal thicknesses (40–50 km). As one moves outward from the central and primary portions of these nuclei, one gradually comes across younger active zones, which correspond to relatively high heat flow, small negative Bouguer anomalies and lesser crustal thicknesses. Thus, during the growth of nuclei, loss of heat might be implied from the fact that low values of heat flow measured over central portions is characteristic of all continental shields (Rao & Jessop 1975).

5. Concluding remarks

Utilizing the data for the Indian region, the above analysis tries to emphasize—to some extent quantitatively—the statistical correlation between the geothermal parameters and other crustal parameters and to stress the role of deeper sources like the partial melting zone in the build-up of heat flow values. It is hoped that further systematic and detailed investigation on both regional and global aspects, on these lines, will provide better physical insight into geothermal processes.

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