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horizontal axis to enable measurement of all three components of the magnetic vector. This is achieved with a quartz screw driver, passing through a hole in the furnace and engaging in a notch on the specimen (after WILSON, 1962).

7. *Thermal demagnetisation apparatus*

Consists of six pairs of Helmholtz coils (two pairs along each axis) for compensating Earth's field and a non-magnetic furnace with platinum wire heating elements. The diameters of the outer pairs of coils are 220, 200 and 180 centimetres and those of the inner three pairs are 120, 100 and 80 centimetres correspondingly (Figure 3). The number of turns in the outer and inner pairs of coils along each axis is proportional to the fifth powers of their respective radii. The cancellation of the Earth's field at the centre of the coil-system is quite good and the residual field is of the order of 50 gammas or 0.1 percent of the Earth's field over a spherical volume of diameter 10 centimetres at the centre of the system. This set-up is used mainly for thermal demagnetisation of sedimentary rocks (ATHAVALE, 1969).

8. *Curie-balance*

The specimen in the form of a rock-chip or powder (magnetic fraction) is placed in a sample holder which is freely suspended in the pole-gap of a permanent magnet, having a field gradient of 1400 gauss per cm. The sample-holder can be encased in a cooling or heating device providing a temperature range from—150°C to 700°C. The field-gradient of the magnet pulls the specimen in one direction. This force is proportional to the saturation magnetisation intensity and the quantity of the sample. This force causes deflection of the movable part of a core-magnet moving coil system which is coupled with the sample holder. An automatic regulating device changes the current in the moving coil system so as to compensate the magnetic pull. This current is a proportional measure of the saturation magnetisation moment of the sample. The change in saturation magnetisation due to heating or cooling is recorded by proportionate changes in this current. The temperature changes are simultaneously recorded with a Pt-PtRh thermocouple embeded in the specimen holder.

The apparatus is calibrated by using standard samples. The Curie-temperatures and phase transition temperatures are recorded with an accuracy of $\pm$ 3%.

BULLETIN OF THE NGRI VOL. 8, NOS. 3 & 4 SEPTEMBER—DECEMBER 1970

Special Issue on NGRI's Contribution to Upper Mantle Project

HEAT FLOW STUDIES UNDER UPPER MANTLE PROJECT*

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Abstract

Terrestrial heat flow studies carried out during the Upper Mantle Project, in about 40 places located in the Pre-Cambrians and areas of Gondwana and Tertiary sedimentations in India are reviewed.

In the Pre-Cambrian areas, the mean thermal conductivity over large depth ranges has been found to be within narrow range of 7.26 to 8.43 m cal/cm sec°C, as a consequence of which a linear relation between surface heat flow and mean geothermal gradient in an area, has been observed. No correlations has been found between surface heat flow and mean conductivity of an area, either for hard rock areas or for areas of sedimentary cover.

A large variation of heat flow from 0.64 to 1.76 μcal/cm² sec has been observed in Pre-Cambrian areas. Three Pre-Cambrian orogenic regions of heat flow, significantly higher than the average for all shield areas of the world have been found, *viz.*, Singhbhum Thrust Zone, Khetri and Alwar copper belts of the Aravallis and the Agnigundala copper belt. It has been noticed that these regions of the Indian Pre-Cambrian have had orogenies during the Upper Pre-Cambrian and the surface rocks in these regions are generally of lower grade of regional metamorphism, as compared to shield areas where significantly lower heat flow values have been observed. The heat flow values in these regions together with few other high values in other Pre-Cambrian shield areas, do not support the earlier concept that the Pre-Cambrian shields are characterised by low heat flow values.

In the areas of sedimentary covers, the observed surface heat flow values range from 1.06 to 2.47 in the Gondwanas, while the heat flow in the Tertiary sediments of the Cambay basin is usually higher than the normal continental value. The likely causes of variations in the surface heat flow in the above regions are briefly discussed.

Introduction

The proposal of the International Upper Mantle Project for a programme of increased effort in solid-earth geophysical research gave a fillip to the activities of a small group set-up at the National Geophysical Research Institute for measurements of terrestrial heat flow throughout India. The group started with measurements in short horizontal holes in mines in 1963. With the fabrication of vertical bore hole logging equipment during 1965, the temperature measurements in bore holes were also commenced. So far 43 places have been covered by the group : 20 in the Pre-Cambrians, 15 in the

*NGRI Contribution No. 70-204

Gondwanas, 7 in the Tertiary Sediments of Cambay basin with 1 other. Temperatures were measured in vertical and inclined diamond cored holes drilled by various organisations (G.S.I., N.C.D.C., D.A.E., I.B.M. etc.), in the country for exploration purposes, in abandoned wells drilled by Oil & Natural Gas Commission, and in short horizontal holes located at different levels in two mines. Computation of heat flow also involves detailed study of the thermal conductivity of the rock formations. Thermal conductivity was measured on core samples obtained from the bore holes in which temperature measurements were made, except for the wells in Cambay basin, where core samples were obtained from various wells which encountered similar formations. At present heat flow values for 25 locations are published and at 18 other places they are in various stages of completion. In this paper the heat flow values measured during the Upper Mantle Project at the National Geophysical Research Institute, are reviewed. The details of individual measurements are not given, but reference is made to the original publication. The equipments used have been briefly described.

In addition to above, the Indian heat flow values are discussed in the light of the known geology, structure and tectonics of various areas along with the meagre data available on radioactivity of Indian rocks. In the end a brief account of the correlation of the thermal field with other geophenomena as attempted at the institute has been given. Terrestrial heat flow (Q) has been expressed in μcal/cm^2.sec throughout this paper.

Techniques of Measurements

The equipments used by us are described below.

Measurements of Temperature and Temperature Gradients

The temperatures were measured in bore holes at discrete depth intervals using calibrated thermistor thermometers connected to a three-conductor Vector Cable together with a Wheatstone bridge modified for compensation of lead resistance and a galvanometer coupled with a transistorized amplifier. The probe-cable assembly passes through a portable manualy operated pulley with a revolution counter attached (Figure 1). Four thermistor probes have been used. The one used for measurements in mines has been described by VERMA and RAO (1965). The other with 12 thermistors, housed and sealed in three stainless steel tubes of about 2.5 mm in diameter, in groups of four, connected all in series, with a total resistance of about 4000 ohms at 0°C and 1400 ohms at 25°C was constructed and calibrated by Dr. F. ROY at Harward University, Cambridge, Massachusetts. The construction details of this thermistor probe assembly are similar to those as given by ROY *et al* (1968). This probe dissipates approximately 10^{-4} watts without self heating of no more than 0.001°C. It has been used in areas where the temperatures are not likely to be more than 60°C. Two more probes each using only one Fenwal GB34P91 thermistor of resistance of about 4000 ohms at 25°C were fabricated and calibrated by the author*. One thermistor was housed in a thin diameter, stainless steel tube and the other was enclosed in a brass tube. The construction details of one of these, are shown in

*Gupta

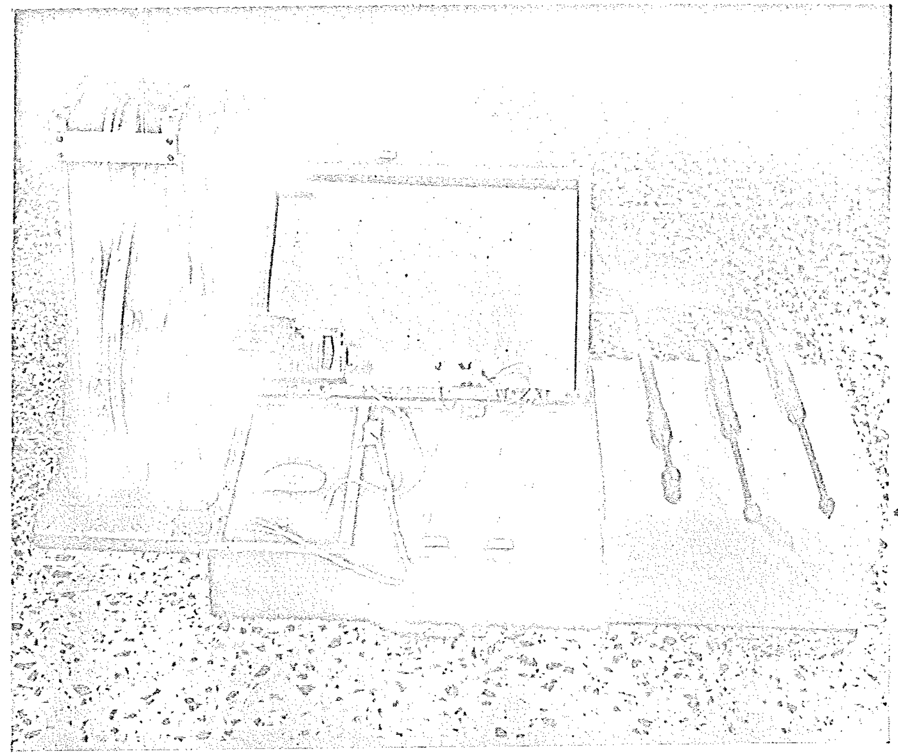

FIG. 1—Equipment for measurement of Geothermal gradients, showing thermistor probes, cable, pulley system and the bridge.

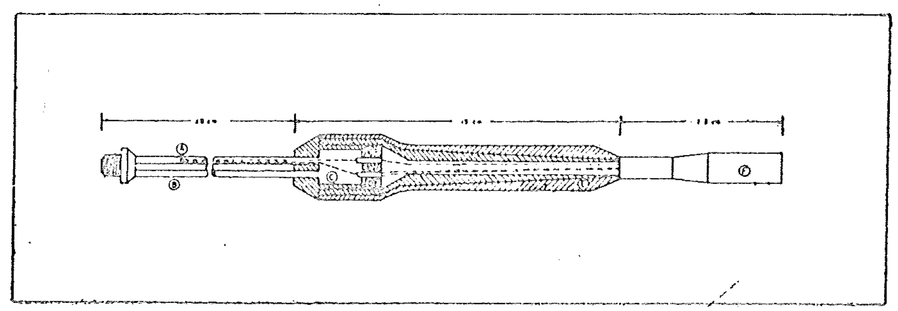

FIG. 2—Thermistor probe details :

A : 5-mm diameter, stainless steel tube silver brazed to housing.
B : Dummy stainless steel tube.
C : Stainless steel housing with 'O' ring.
D : Hylam bush with brass nipples.
E : Neoprene jacket vulcanized to connector cable and bonded to stainless steel housing.
F : Three pole water-tite connector, Mecca RM3FS. All connections covered with polyolefin heat shrinking tube. Cavity filled with neutral silicon oil.

Figure 2. These thermistors have a wider range of temperature and dissipate less amount of heat than as given above. These thermistor probes are usually calibrated and checked before and after the field trips. Although the absolute temperatures are not of much concern for the determination of heat flux, the temperatures obtained by these probes are accurate to within 0.02°C. The temperature gradients are usually accurate to within a few percent for small intervals of about 10 metres and to less than 1% for intervals of the order of 100 metres.

Measurements of Thermal Conductivity

Thermal Conductivity was measured by using divided bar method. The apparatus described by BENFIELD (1939) was modified by the author* so as to improve the precision and performance. In place of an electric heater at the top end of one bar, an arrangement for spraying of thermostatically controlled water at the ends of the bars, remote from the specimen, was used. System of applying axial pressure has also been modified, to ensure more uniform distribution of pressure at the contacts. In order to reduce the radial heat losses, the bars are insulated by U-foam and the whole apparatus is enclosed in an enclosure whose temperature is thermostatically controlled at the mean temperature of the two ends of the bars. The thermal contact resistance between the end faces of the bars in contact with the sample, and the sample, is reduced by using water and glycerine mixture or silicon grease. The conductivity of the brass bars is found by calibrating them against crystalline quartz.

With this type of apparatus, measurements have to be made on three or more discs to eliminate contact resistance, which involves lot of time, both in preparation of discs and measurements. Errors are also introduced in the measurements due to slight variation in conductivity values of the discs from the same core, on account of mineral compositional variations ; a varying contact resistance from disc to disc; and increasing 'parallel' arrangement of minerals with decreasing disc thickness. Therefore a need was felt to fabricate another apparatus in which the inherent defects of the Benfield's apparatus are eliminated by a proper design. The guard-ring divided-bar apparatus described by BECK (1957), though better in performance and accuracy, suffers from the same inherent shortcomings as those of the Benfield's apparatus. Another type of divided-bar apparatus was described by BIRCH (1950) which involves measurements on a single disc. The contact resistance is eliminated in this apparatus by the application of large axial pressure by a hydraulic jack. In order to reduce the time required for a measurement and improve the precision and performance, several modifications were introduced in this apparatus by the author*. The electric heater is replaced by a water jacket having spraying of water from a thermostatically controlled bath. Similar water jacket is provided at the lower end of the stack of discs. The water jackets are insulated from the pair of hemispherical thrust bearing by 6 mm perspex discs. Thermostatically controlled water at 40° and 35°C or 35° and 30°C is circulated through the jackets.

With this modification, the apparatus becomes a constant temperature difference type of divided bar apparatus, and the time to reach equilibrium is much reduced. The water jackets were coated with film of silcon grease so that the contact resistance is minimised, and a uniform temperature distribution is obtained over the copper discs containing the differential thermocouples. In order to reduce lateral heat losses, U-foam or cotton insulation is used arround the specimen and the reference discs. The lateral heat

*Gupta

losses from the stack of discs are further minimized by enclosing the apparatus containing the thrust-bearings and stack assembly in a steel-shield and maintaining it at the mean temperature of the two water jackets. So that, to avoid rapid exchange of heat from the steel-shield with the environment and to have a good constancy of its temperature, the whole apparatus along with the shield and the hydraulic jack is enclosed in a wooden-glass enclosure (Figure 3).

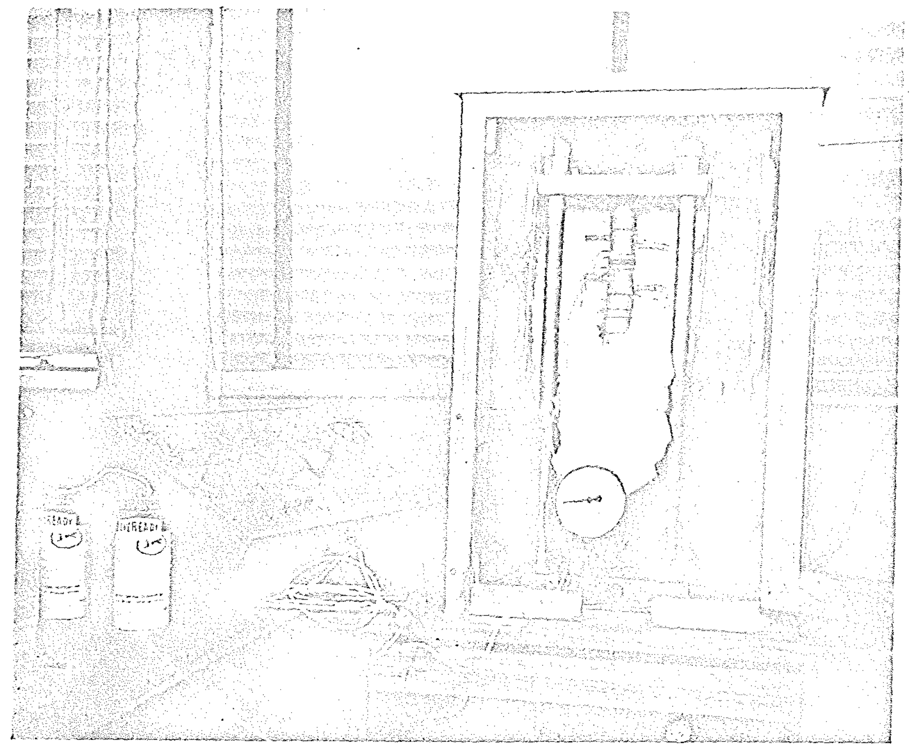

FIG. 3—Thermal conductivity apparatus

Lexan, a polycarbonate plastic supplied by Prof. Francis Birch of Harvard University, is used as a reference material. The reference discs of Lexan were calibrated against crystalline quartz. Prior to Lexan Crystalline quartz discs and calibrated serpentine discs were used as reference discs.

The specimen discs are saturated with water or oil under vacuum and coated with films of silicon grease before assembling the stack. After assembling the stack into a proper position it is subject to an axial pressure of about 1500 psi. After the system reaches stablility, temperature differences are measured by copper-constanton differential thermocouples along with a K-type potentiometer and sensitive galvanometer (Sensitivity 0.46 μv/mm deflection at 1m). This modified Birch-type divided-bar apparatus has been used since 1966, practically for all the thermal conductivity measurements.

The samples in the form of circular discs of diameter of 4.12 cm or 2.54 cm and thickness about 1cm are cut or cored from the core samples, with flat and parallel faces. The flat faces were ground parallel to within 0.03 mm and flat to within 0.01 mm.

Results and Discussions

Typical temperature profiles from various areas of exposed Pre-Cambrian rocks are shown in Figure 4, while those from areas of Gondwana and

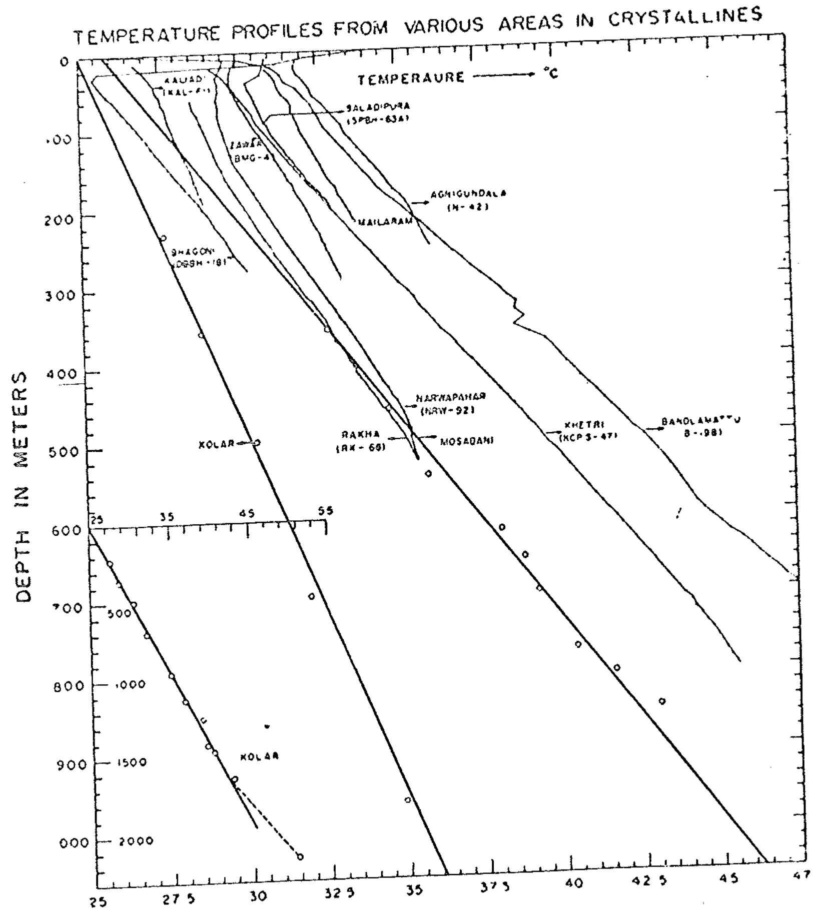

Fig. 4

Tertiary sedimentary covers are shown in Figure 5. Values of the average

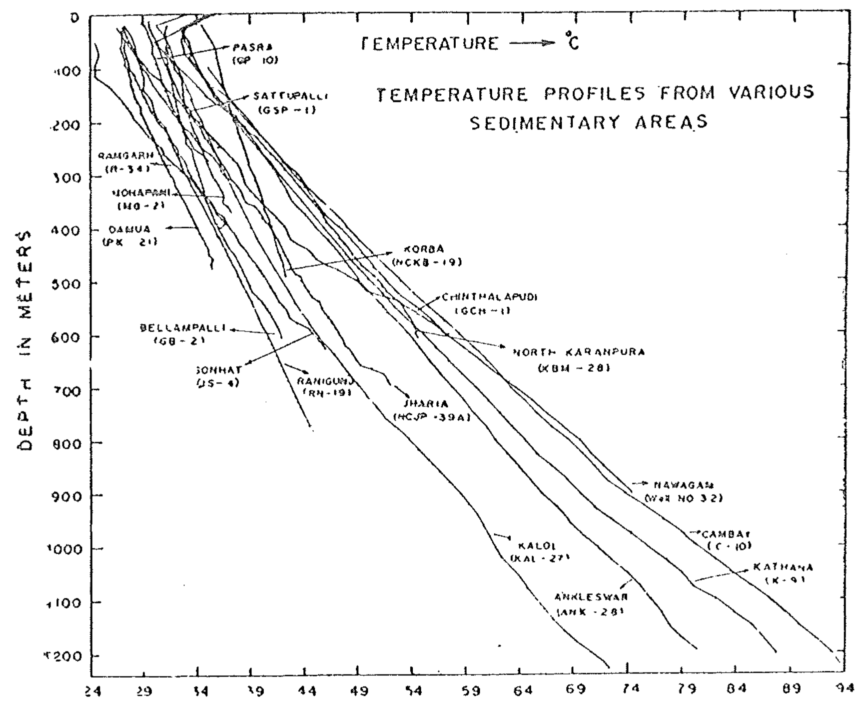

Fig. 5—Geothermal gradients in various parts of India

geothermal gradients for the various locations are shown in Figure 6. The gradients in the Pre-Cambrian rocks fall in two groups, one in range of 1.0 to 1.4 °C/100 m being observed in Dharwar System, Peninsular Gneisses, Aravalli System and Banded Gneissic complex (B.G.C.) of Rajasthan (Archaean) and while the other in the range of 1.7 to 2.5°C/100 m being observed in Delhi System, Singhbhum Thrust Zone, N.E. and N.W. margins of Cuddapah basin. Temperature gradients in general, are higher in the Cambay basin than the Gondwana basins and troughs.

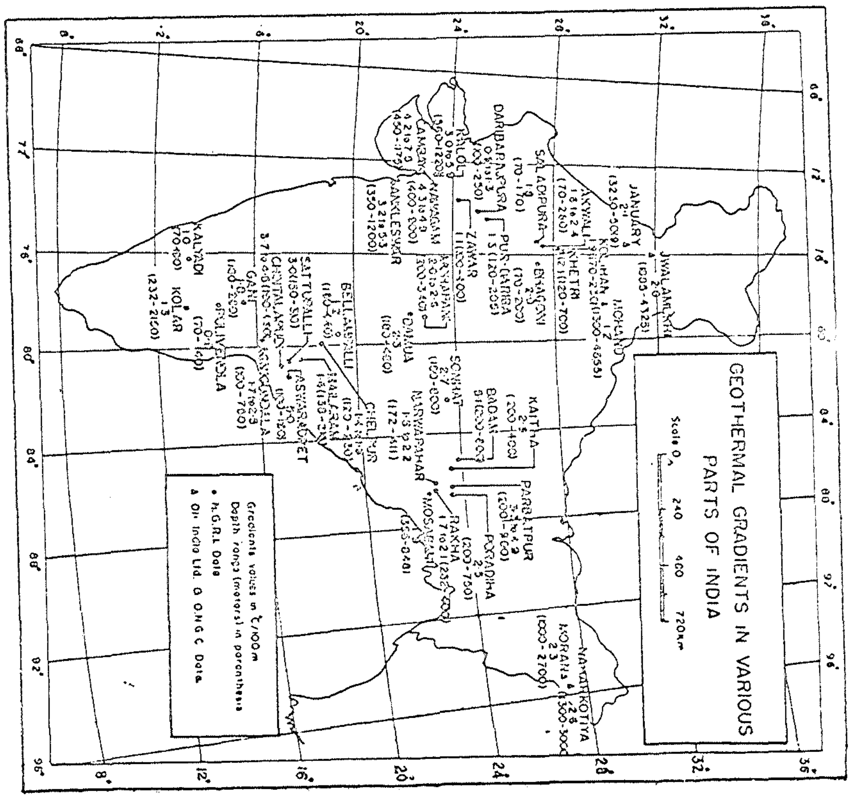

Fig. 6

Heat flow at 25 locations with mean conductivity, average gradients, method adopted for evaluation of heat flow, and the reference in which the individual measurements have been described in detail are listed in Table 1.

Table 1

Summary of Measurements of Gradients, Thermal Conductivity and Heat Flow

Locality	Lat. (N)	Long. (F)	Elevation metres	Depth Range metres	Conductivity mcal / cm sec°C	No. of samples	Gradient °C/km.	Heat flow μ cal/cm² sec.	Method	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Dharwar System										
Kolar Gold Field ..	12°55′	78°15′	835	232–2150	7.26	20	13.08	0.95*	G K**	Rao (1970)
Kalyadi ..	13°14′	76°09′	—	85–135	8.1	12	10.35	0.84	G K	Ngri Annual Report (1968)
Peninsular Gneisses										
Mailaram ..	17°43′	80°37′	137	138–216	—	—	—	1.10	MBP****	Rao *et al* (1970)
Cuddapah Basin										
Pulivendala ..	14°26′	78°14′		80–140	5.98	9	10.66	0.64	G K	Verma *et al* (1969)
Agnigundala ..	16° 2′	79°45′	—	68–252		22		1.23	B P	Ngri Annual Report (1968)
Delhi System										
Khetri ..	28°12′	75°56′	—	—	—	—	—	1.76	—	Gupta *et al* (1967)
S-47 ..			383	120–700	8.06	26	21.75	1.75	G K	
S-48 ..			381	150–300	8.63	8	20.26	1.75	G K	
				300–460	8.18	10	22.39	1.83	G K	
S-49 ..			364	150–300	8.31	8	20.62	1.71	G K	

Table 1 (*Contd.*)

Summary of Measurements of Gradients, Thermal Conductivity and Heat Flow

Locality	Lat. (N)	Long. (E)	Elevation metres	Depth Range metres	Conductivity mcal / cm sec°C	No. of samples	Gradient °C/km.	Heat flow μcal/cm² sec.	Method	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Bhagoni	27°17′	76°24′	—	74–221	—	—	—	1.4	M B P	Gupta *et al* (1970*a*)
Singhbhum Thrust Zone										
Mosabani	22°31′	86°28′	116	356–848	7.52	17	19.37	1.45	G K	Verma *et al* (1965)
Rakha	22°37′	86°23′	110	418–486	8.43	29	18.03	1.41	M B P	Rao (1970)
Narwapahar	22°42′	86°16′						1.50		Rao (1970)
(A)				351–432	8.54		17.21	1.47	G K	
(B)				225–411	7.12		21.76	1.54	G K	
Cambay Basin										
Kalol Oil Field	23°16′	72°30′				21		1.85		Gupta *et al* (1970*b*)
K-58			73.8	550–975		21		1.7	B P	
				975–1200				1.8	B P	
K-27			65.2	560–1000		21		1.8	B P	
				1020–1220				1.9	B P	
Nawagam Oil Field	22°50′	72°30′		400–900				1.9	B P	Gupta *et al* (1970*b*)
Kathana Oil Field	22°17′	72°48′	26.2	725–1200				2.2	B P	Gupta *et al* (1970-*b*)
Cambay Gas Field	22°23′	72°35′						2.3		Verma *et al* (1968)
C-10			11.9	875–975	3.3		74.9	2.5	B P	
				975–1125	3.5		65.7	2.3	B P	
C-36			12.2	850–1100	3.6	12	63.9	2.3	B P	
C-33			15.7	1025–1175	3.9		52.2	2.0	B P	
Ankleswar Oil Field	21°35′	72°55′						1.6	B P	Gupta *et al* (1970-*b*)
A-2			12.5	750–1200				1.7	B P	
A-28			13.0	500–1175		10		1.65	B P	
A-170			23.3	700–1200						
Gondwanas										
Godavari valley										
Bellampalli	19°12′	79°25′	198					1.06		Verma and Narain (1968)
29				110–180	6.42	11	15.79	1.01	G K	
52				100–150	6.34	12	16.56	1.04	G K	
				150–200	5.94		20.60	1.16	G K	
				190–240	7.74	4	12.76	0.99	B P	Verma *et al* (1969)
GB-2				280–360	6.33	9	16.19	1.02	B P	
				380–440	4.67	4	25.13	1.17	B P	
Chintalapudi	17°05′	81°00′	125					2.22		
Gch-1				200–540	5.19	(41)	42.80	2.19	B P	
Gch-3				130–270	5.23		43.42	2.32	B P	Rao *et al* (1970)
Gch-4				90–270	4.09		51.74	2.12	B P	

Table 1 (*Concld.*)

Summary of Measurements of Gradients, Thermal Conductivity and Heat Flow

Locality	Lat. (N)	Long. (E)	Elevation metres	Depth Range metres	Conductivity mcal / cm sec°C	No. of samples	Gradient °C/km.	Heat flow μcal/cm² sec.	Method	Reference
1	2	3	4	5	6	7	8	9	10	11
Aswaraopet ..	17°14′	81°13′	123	120-200	5.51	14	44.90	2.49	B P	Rao *et al* (1970)
Sattupalli ..	17°13′	80°48′	158	160-300	4.73	30	30.46	1.52	B P	"
Chelpur ..	18°23′	79°55′	200	170-230	6.98	15	17.85	(1.25)	G K	"
Venkatapur ..	18°16′	80°02′	229	130-180	8.36	9	15.56	(1.30)	G K	"
Pasra ..	18°13′	80°11′	146	180-250	7.70	25	26.14	(2.01)	G K	"
Damodar Valley										
Parbatpur (Jharia) ..	23°38′	85°19′		150-700	5.63	40	39.05	2.2	B P	NGRI Annual Report (1968)
Satpura Gondwana Basin										
Damua ..	22°14′	78°26′	836					1.46		Rao *et al* (1969)
				180-240	6.62	20	21.64	1.43	G K	"
				260-450	6.23		24.11	1.49	G K	"
Mohapani ..	22°45′	78°49′		260-450	5.44	24	21.72	1.18	B P	"

* Corrected for ventilation and past climatic effect values within brackets are of low reliability

** Heat flow obtained by the product of the least square gradient and the mean thermal conductivity.

*** Heat flow obtained calculated by Bullard method (1936)

**** Heat flow computated by taking refraction due to contrast of thermal conductivity into consideration, Hyndman & Sass (1966).

Relationship between Heat Flow Thermal Conductivity and Geothermal Gradient

The mean thermal conductivity of all the samples measured for an area versus heat flow for several regions of crystalline Pre-Cambrian rocks (excluding those from Cuddapah basin) is plotted in Figure 7 (*a*). The mean conductivity versus heat flow shows practically a null correlation. A similar result has been noticed for seven locations in the Gondwanas. This is in contradiction to studies of Horai and Nur (1970), where a significant relationship between the two quantities was found. It was suggested that the refraction of heat flux due to inhomogeneous conductivity and the proportionality between radioactive heat generation and thermal conductivity may be the possible explanations, for their observed correlation.

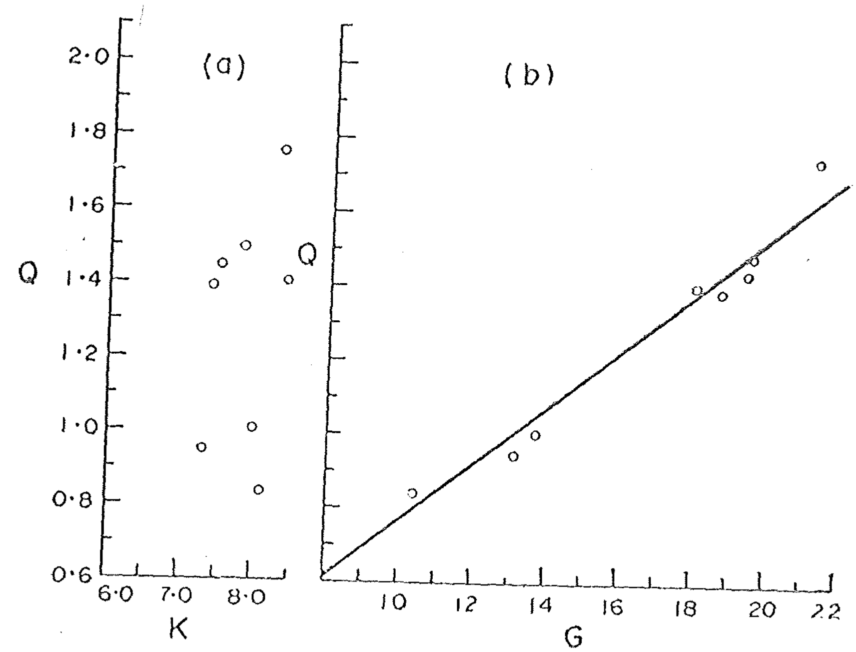

Fig. 7—(*a*) Heat flow Q (in μ cal/cm² sec), versus thermal conductivity K (in m cal/cm sec °C).
(*b*) Heat flow Q versus geothermal gradients, G (in °C/km) for Pre-Cambrian crystalline areas in India.

Samples for which thermal conductivity was determined for the Pre-Cambrian rocks in India, are mainly schists, gneisses, argillites, granites and phyllites. The mean conductivity values for different regions computed from the measurements, fall in a narrow range from 7.26 to 8.43, with a mean of 7.93 m cal/cm sec°C. This is in close agreement with a mean value of 7.82 ± 0.08 given by Birch (1950) for 117 samples of granite, quartz monzonite, quartz diorite gneiss and injection schists and gneisses. As a consequence of this heat flow versus average geothermal gradient shows a very linear relationship Fig. 7 (*b*) (coefficient of correlation 0.96). This suggests that, for the areas of exposed crystalline Pre-Cambrian rocks of the above types, the heat flow anomalies are more or less [illegible] by the geothermal gradient anomalies. This has some advan[illegible] approximate inferences can be made for the heat flow from gradi[illegible] [illegible]rements.

Variation of Heat Flow in Peninsular India

Large variation of surface heat flow has been observed in Peninsular India (0.64 to 2.49). Variations of the heat flow at the surface of the earth may be caused by one or more of several factors. Undoubtedly most of the heat arriving at the Earth's surface today is mainly due to the energy released by the decay of the radioactive elements Uranium, Thorium and Potassium in the earth. Regional differences in the amount of heat producing elements will thus produce regional variations in heat flow. The other causes for the variations of the surface heat flow may be, the presence of hot material injected into the crust or upper mantle at some time in the geologic past, and the tectonic activity. Factors such as slow underground water movement or refraction due to contrast of thermal conductivity may also cause variations in surface heat flow. These factors are not important, on a broad scale. Large variation of heat flow have been observed to occur over short horizontal distances and also over longer horizontal distance. In the first case the associated heat source must be within the crust and in the second case, the variations are very likely due to regional differences in the mantle.

The Peninsula is a *shield* area composed of geologically ancient rocks of diverse origin, most of which have undergone much crushing and metamorphism. Over these ancient rocks lie a few areas of Pre-Cambrian and later sediments and extensive sheets of horizontally bedded lavas of the Deccan Trap formation. The measurements so far made are located in the areas of exposed Pre-Cambrian rocks and areas of Gondwana (Upper Carboniferous—Middle Cretaceous) and Tertiary sedimentation. While the heat flow data shows the great variability within the Indian Peninsula, there are indications of some emerging pattern. The Pre-Cambrian shield is characterised by low to normal values with some high values that seems to be associated with higher concentration of radioactivity in near surface rocks. The Gondwanas are characterised by normal to high values (1.06 to 2.47). High value in one large area in the Gondwanas (Damodar valley coal fields) is probably of deep origin. The Cambay basin is characterised by generally higher values than the normal continental value. It appears that the differences in regional geology and tectonics of these geological provinces are reflected in their thermal field. The heat flow values have been discussed below seperately for the above geological units.

Areas of Exposed Pre-Cambrian Rocks

The Pre-Cambrian rocks occupy about two-thirds of Peninsular India. The regions in exposed Pre-Cambrian rocks, where heat flow measurements have been made, are the Dharwar Schist belt, the Peninsular Gneissed, the Aravalli mountain belt, the Singhbhum Thrust Zone, and the Cuddapah basin. The surface heat flow as observed in these areas has a large variation ; 0.64 to 1.76 with a mean value of 1.23 ± 0.32 sd. (Table 2). To the author's knowledge there are to date 64 reliable heat flow values published for various Pre-Cambrian shield areas of the world, whose mean is 1.05±0.39 sd. This mean is slightly higher than the mean (0.92) obtained by LEE and UYEDA (1965) for 26 Pre-Cambrian shield values.

Table 2

Arithmetic Average Heat Flow in Geological Provinces

Province	No. of observations	Range of gradients °C/km	Range of Mean conductivity m cal/cm °C	Heat flow μcal/cm²sec.	
				Range	Mean
1. Pre-Cambrian Shield..	10	10-22	6.0—8.6	0.64—1.76	1.23±0.32 s.d.
2. Gondwanas (Rift valleys (?) ..	7	20-45	4.09—7.74	1.06—2.49	1.73±0.25
3. Cambay Basin ..	5	43-65	3.5—4.0*	1.6—2.3	1.97±0.25
All values ..	22	..	..	0.64—2.49	1.56±0.5

* weighted mean conductivity

At present in the Indian shield, areas of Archaean rocks are characterised by low heat flow values. These areas are, Kolar, Kalyadi (Dharwar System) Mailaram (Peninsular Gneisses) (Table 1) and Zawar, Pur-Dariba, Rajpura-Dariba, Sideswar-kalan (Aravalli's, heat flow values as infered from measured geothermal gradients, (Figure 6), the knowledge of the rock types encountered, and the observed relationship between heat flow and geothermal gradients (Figure 7-*b*).

One probable explanation for the generally prevailing low heat flow in the shields as compared to younger continental area is known. It is that the Pre-Cambrian shields have been largely deprived of the radioactive sources of heat. They have been enriched in the lately formed crust. According to the present concept the continental crust has evolved through partial melting and regional metamorphism. HEIER (1965), HEIER and ADAMS (1965), and LAMBERT and HEIER (1967, 1968) have given evidence that partial melting and regional metamorphism in the crust cause an upward concentration of Uranium, Thorium and other elements, that do not readily fit into big pressure mineral lattices. A greater part of the heat producing elements from the top layers of the shield areas has been removed by erosional processes.

In the Cuddapah System (Proterozoic) of rocks, significantly lower (Pulivendala, S. W. Margin of the Cuddapah basin) and also relatively higher heat flow values, than the world average heat flow for the shields have been observed

At Pulivendala the lowest heat flow (0.64) has been observed so far in India. Though this value is from a shallow bore hole it is prorbable, as the bore hole passes mainly through basic rocks of low radioactivity. This low value indicates the extensiveness of the presence of the basic material due to the injection of old dykes and sills in the area. This is supported by the studies of regional geology and igneous activity (SEN and NARSIMHA RAO, 1967), gravity (QURESHY *et al*, 1968), gravity and magnetic (BALAKRISHNA *et al*, 1970) in the basin. All the above studies point towards a basic crust in the area. This value is similar to as observed at Kambadda (0.69) in the centre of the Kalgoorlie greenstone belt (altered basic and ultra basic rocks) by HYNDMAN and EVERETT (1968) and in the basic rocks of pyroxene granulite facies metamorphics of Fraser Range in the Australian shield (JAEGER, 1970).

The areas of significantly higher heat flow than the world average heat flow for the shields are,

(1) The Khetri copper belt of about 80 km length (Delhi System).

(2) The Bhagoni area of the Alwar copper belt (Delhi System).

(3) The Agnigundala copper belt, situated at the N.E. margin of the Cuddapah basin.

Significantly higher heat flow values than the mean for the shields have also been observed along the Singhbhum Thrust Zone (Table 1). The arcuate copper belt thrust zone developed nearly along the southern limit of the Singhbhum group rocks, towards the latter part of the Singhbhum Orogenic Cycle, (between c .1550 and c .850 m y). The thrust movements partly overlaped with the granitisation and granitic intrusions along this zone, leading to the development of biotite granite-gneises, soda granite etc., (Saha, 1970).

The initial measurements in the South African, Australian, Canadian, Ukranian and the Indian shields showed that these are characterised by significantly lower heat flow than younger continental areas. A number of significantly high values have been reported recently, in the Indian, Australian and the Canadian Pre-Cambrian shields. The present heat flow observations from these three shields cover a number of Pre-Cambrian geological provinces, while the values from the Baltic, Ukranian and African shields are from relatively small areas. It is likely that with more observations these shields may also reveal higher values. From the above it is clear that the present heat flow data for the Pre-Cambrian shields do not support the previously held belief that the Pre-Cambrian shields are characterised by low heat flow. Recent radiometric age data for the various Pre-Cambrian shields have delineated various orogenic cycles and the Pre-Cambrian shield areas have been sub-divided into various orogenic and structural provinces. The observation of a large range of heat flow values in the exposed areas of Pre-Cambrian rocks, therefore, is not surprising.

In the Pre-Cambrian shield areas, equilibrium conditions should normally prevail, the average surface heat flow depending primarily on release of heat due to radioactivity in the crust. Quantitative variation in such crustal radioactive heat generation will thus give rise to variation in surface heat flow.

While data on quantitative estimates of Uranium, Thorium and Potassium for magmatic rocks have long been available, the data on metamorphic rocks of which the Pre-cambrian shields are mostly composed has come up only recently. Estimates of mean concentrations for the Australian shield have been given by Lambert and Heier (1968) and for the Canadian shield by Shaw (1967) and Fahrig, *et al* (1967). The data is summarised in Table 3. Heat generation has been calculated using conversion factors as given by Roy *et al* (1968).

Systematic studies on Uranium, Thorium and Potassium concentration for Indian rocks have not been done except some sporadic studies by few workers. Some data has been recently reported and the same has been summarised in Table 3.

Table 3

Average Concentration of Radioactive Elements of Surface Rocks

Locality	Rock Type	No. of samples analysed	U (ppm)	Th (ppm)	K %	Heat generation. 10^{-13}cal/cm^{3}sec.	Reference
India							
Kolar Mines	Hornblende Schist	5	1.36	4.68	0.23	1.71	Pal *et al* (1967)
Kolar Mines	Altered hornblende Schist	6	1.98	6.3	0.23	2.35	,,
S. E. Mysore	Augen gneiss Banded gneiss	4 2	3.62	24.83	3. 8	7.34	Narayanaswamy *et al* (1969)
S. E. Mysore	Granite	6	7.65	54.98	4. 7	15.17	,,
S. E. Mysore	Pegmatite	6	11.90	1.73	4.75	8.76	,,
Singhbhum Thrust Zone.	Soda-Granite	—	7.8	21.2	1.70	8.83	Saha and Sankaran (1968)
-do-	Granodiorite	—	8.7	8.1	1.49	7.11	,,
-do-	Diorite	—	8.0	9.6	0.52	6.71	,,
-do-	Felspethic Schist Mica	—	7.0	—	2.53	6.50*	,,
-do-	Chlorite Schist (Copper mineralised)	5	19.4 (eu)	—	—	12.8	Gangadharam *et al* (1963)
Australia	W. Australian Shield	160	3.0	20.0	2.6	5.89	Lambert and Heier (1967)
Canada	Shield	32 (composite samples)	2.45	10.3	2.58	3.9	Shaw (1967)

* *Th* has been estimated by using $\frac{th}{u}$ ratio of 1.33, as obtained from other samples for the area

Geochemical and geophysical constraints necessitate that the content of heat producing elements decrease in some manner with depth, but the data on the actual variation of radioactive elements with depth are lacking. As mentioned earlier the studies of Lambert and Heier (1967, 1968) have given evidence that partial melting and regional metamorphism cause an upward concentration of Uranium and Thorium in the crust. Different models on the distribution of radioactive heat sources with depth have been considered by Hyndman *et al* (1968), Roy *et al* (1968) and Lachenbruch (1968). The latter two and Birch *et al* (1968), have also shown a remarkable linear relationship between heat flow and heat generation of the surface rocks in plutons from many regions (designated as heat flow provinces by Roy *et al*, 1968) in the United States.

Without much elaborating on the above, the heat flow in the three areas of high heat flow in Pre-Cambrian shield has been analysed below on the basis of general concepts that the heat coming from below the crust is nearly constant in stable continental areas, the radioactive elements are concentrated in top layers of the crust and that the variation in the surface heat flow within a geological province is due to different concentrations of radioactive heat producing surface layers.

Aravalli Mountain Belt

The heat flow in this mountain belt ranges from 1.76 to about 1. On the basis of above concepts several explanations are possible for the observed variation of heat flow in the Aravallis. It may be that the rocks of Delhi system which are about 6 km thick (PITCHAMUTHU, 1967) have high concentration of radioactive heat sources or that erosion of the underlying rocks of Aravalli system (and Raialo series where it is present) has been less and therefore the contribution to heat flow from the radioactivity of the top layers of Aravalli system is more. The top layers of the crust which contained more radioactive elements, have been eroded away in areas where the rocks of Aravalli system or B.G.C. are exposed on the surface thus rendering these areas depleted in radioactivity, compared to those areas on which Delhi's were deposited.

There is also evidence of some concentration of radioactive minerals in the rocks of Delhi System in Khetri copper belt and in the old copper working at Kho-Dariba (DAR, 1964). The rocks of Delhi system are regionally metamorphosed to greenschist facies, while the rocks of Aravalli system and B.G.C. are regionally metamorphosed to amphibolite facies (NARAYANASWAMY, 1966). If the rocks of Delhi System have higher concentration of radioactive heat sources than the rocks of Aravalli system and B.G.C., this will imply that the rocks of greenschist facies have higher concentrations of some, or all of the radioactive elements uranium, thorium and potassium, compared to rocks of amphibolite facies. This seems to be possible as significantly lower average concentrations of uranium and thorium have been observed in rocks of granulite facies than those of amphibolite facies (LAMBERT and HEIER 1968 ; and FAHRIG *et al*, 1967) Rocks of greenschist facies which are still lower in grade of metamorphism may contain more amounts of U and Th than the rocks of amphibolite facies.

Singhbhum Thrust Zone

This thrust zone is famous for its uranium mineralization in India. Here uranium mineralization is extended to more than 80 km long belt (DAR, 1964). There are a number of granitic bodies along the copper thrust zone (SAHA, 1970). Gravity studies suggest that granitic bodies in some parts near the thrust zone may have thickness of 3 to 9 km (QURESHY *et al*, 1970). The general grade of regional metamorphism of the rocks of thrust zone is of greenschist facies (SAHA, 1966). Using the radioactive data of SAHA *et al* (1968) (Table 2) for the main rock types of Singhbhum Thrust Zone and the mean heat flow value, 1.45 (Table 1), RAO (1970) has shown that this point falls near the linear curve of heat flow versus heat generation for the Eastern United States, as obtained by ROY *et al* (1968). The observation of high heat flow along the Singhbhum Thrust Zone is, therefore, consistent, with the general concepts mentioned above, the high heat flow anomaly being explained by a radioactive top layer of about 8 km thickness

Cuddapah Basin

The heat flow in the north-eastern margin of the Cuddapah basin at Agnigundala is 1.23. Recent temperature measurements in deep bore holes at Bundalamattu (about 10-12 km from the previous location) have indicated that the heat flow is likely to be of the order of 1.5, there. Granitic domes occur close to the mineral deposits and in a way the mineralisation itself follows the margins of granite plutons in the Agnigundala mineralized belt (ZIAUDDIN, 1964). From gravity studies a thickness of about 20 km of the massive granitic intrusion in Cuddapah formations of the eastern part of the basin has been infered by QURESHY *et al* (1968). Taking into account the average amount of heat generation of 6.7×10^{-13} cal/cm^3 sec for granites (HEIER and ROGERS, 1963), a granitic layer of even much lesser thickness than above will account for the observed surface heat flow. It is very likely that the infered granitic body thins out towards Agnigundala. A similar heat flow value of 1.28 in the Pre-Cambrian granitic rocks has been reported by JAEGER (1970).

Lingering tectonic and geological activity has also been reported in the above three Pre-Cambrian areas. The Aravalli mountain belt and the Singhbhum area have been known zones of crustal weakness, since their inception and evidence of continued mantle disturbance can be seen in volcanic activity of various ages and types. In the Aravalli region three orogenies are recognised *viz.,* Pre-Aravalli, Aravalli and Delhi. The Delhi orogenic cycle is the youngest and closed at *c.* 750 my. (MUKTINATH, 1967, and SARKAR, 1968). The existence of also three distinct orogenic cycles with closing dates at *c* 3200, 2700 and 850 my have been recognised in the Singhbhum region (SAHA, 1970 and SARKAR, 1968).

Aravallis were rejuvenated during the Post-Mesozoic times. Slow tectonic activity in the form of slow uplifts have been observed in the Ranchi plateau and Singhbhum Thrust Zone (SAHA, personal communication). The eastern half of the Cuddapah basin shows evidence of some folding and slight metamorphism. The disturbance along the eastern margin may perhaps be due to the rejuvenation of the Eastern Ghats in post-Cuddapah but Pre-Gondwana times, (KRISHNAN, 1960). QURESHY (1970) has observed an increase in gravity over the post-Mesozoic rejuvenated shield blocks (horst) in India and related the same to probable thickening and increase in density of the crust through incorporation of material from the upper mantle into the crust. The high heat flow at Khetri has been attributed by QURESHY to the rejuvenation of the Aravalli belt.

If the rejuvenation of the Aravallis has contributed significantly to the surface heat flow whether due to transfer of sub-crustal masses or through the generation of heat due to tectonic forces, high heat flow values would have been observed along the entire mountain belt, which is not so.

If these tectonic forces contribute significantly to the present surface heat flow in Singhbhum Thrust Zone and Agnigundala copper belt, then it would imply that the radioactivity of the crustal rocks of these granitic areas is very low, which is not likely to be the case. Therefore, it is most likely that the contribution to the present surface heat flow from the factors responsible for the rejuvenation of the above three regions is negligible. The perturbations introduced in the past have probably died away.

Areas of Sedimentary Cover

Heat flow has been measured in Gondwanas and the Cambay basin. During the Paleozoic and Mesozoic the peninsular shield appears to have suffered a great deal of tension resulting in the formation of Gondwana sedimentary basins and troughs. Most of these basins and troughs in India are believed to be rift valleys; the sediments outcroping along linear tracts and occupying tectonic troughs with faulted boundaries. The Cambay basin appears to have been formed as a result of down faulting of the traps ; the basic extrusives of Cretaceous-Eocene age, and subsidence of the basement during Cenozoic times.

The areas of normal heat flow observed in the Gondwanas are,

(i) The Satpura-Gondwana basin, located in the central part of the Peninsular India.

(ii) The central portion of the Godavari valley.

The heat flow values in the above regions are typical of continental platform regions and indicate normal conditions underlying these areas. The values range from 1.06 to 1.46 and compare well with those obtained in Gondwanas of other continents. GOUGH (1963) has reported values ranging from 1.31 to 1.57 in the southern Karroo system (Gondwana group in South Africa). HYNDMAN (1967) has reported three reliable values 1.20, 1.26 and 1.36 from Gondwanas of Queensland, Australia.

The values for Chelpur, Venkatapur and Pasra at the southwestern edge of the central portion of the Godavari valley are disturbed due to water movements (RAO *et al*, 1970).

Higher heat flow than the world average heat flow (1.65) (HORAI and SIMMONS, 1969), have been observed at the following areas ;

(i) Damodar valley coal fields region,

(ii) A small area in the southeast extension of the Godavari region *viz.*, Aswaraopet-Chintalapudi area.

(iii) The northern part of the Cambay basin, extending from Cambay to Kalol approximately in North-South direction.

Almost every coal field of the Gondwanas including those of Damodar and Satpura contains dykes and occasionally sills of dolerite and basalts and in most cases, this igneous material is definitely of Deccan Trap age (FOX, 1931). The intrusives are considered to be related to the Rajmahal traps, and contemporaneous with the Deccan trap efusives (Upper cretaceous to Eocene) (KRISHNAN, 1960). These intrusives do not seem to be the cause of the high heat flow in the Damodar valley, as heat flow is normal in the Satpura Gondwana basin, which also has been intruded by trap dykes and sills. Similar is the case for the Bowen River coal field of Australia which have also been intruded by several rhyolite dykes and sills and where normal heat flow has been reported. The high heat flow in the Damodar valley region is further supported by the presence of many hot springs in the region. Recent uplift with noticeable arching of the crust, indicating recent mantle disturbance has been reported in the Damodar valley coal fields. This suggests the deep cause of the high heat flow in the area.

The high heat flow at Chintalapudi and Aswaraopet (2.22 and 2.49) cannot be accounted for by very deep sources since heat flow at Sattupalli, 30 km to the North-west is normal (1.52). Various possibilities for the high heat flow in this area were examined in detail by RAO (1970) and RAO *et al* (1970). The high heat flow in the region may be attributed to a region in the basement of the valley, of anomalous heat generation of the order of 6×10^{-13} cal/cm³ sec elongated in the direction of Chintalapudi-Aswaraopet. Another alternative may be tectonic activity. Chintalapudi and Aswaraopet are located at the junction of two tectonic trends, the Eastern Ghats trend and the Godavari valley trend. Eastern ghats were rejuvenated during post-Mesozoic period. The heat flow values in the Godavari valley also seems to be characteristic of continental rift valleys. Both low (East Africa) and high (Baikal) heat flow values have been observed in other continents.

The various causes of heat flow in the northern part of the Cambay basin have been studied in detail by VERMA *et al* (1968) and GUPTA *et al* (1970). The anomalies (from a background of 1.1-1.2 μ cal/cm² sec) in the northern part of the Cambay basin, in the region extending from Cambay to Kalol can be attributed to igneous intrusion about 10-15 million years ago. This has been supported with other geological and geophysical surveys carried out in the basin by GUPTA *et al* (1970) and VERMA *et al* (1968).

Relationship of Heat Flow with other Geophenomena

Various results, obtained during the Upper Mantle Project have led to a clear understanding of the essential inter-relationship of geophysical and geological phenomena. Attempts have been made by various workers in the world to correlate the thermal field with, topography, the form of gravity field and the configuration of the geoid surface, seismic delay time, the age of tectogenesis, radioactivity of surface rocks, thermal conductivity of rocks, and with tectonic and geological provinces etc.

Data of statistical analysis of heat flow observations by LEE and UYEDA (1965), and POLYAK and SMIRNOW (1966) indicated the dependence of heat flow on the age of foldings. GUPTA (1967-*b*) indicated that the heat flow values of an area have a correlation with the age of the rocks and tectonic events. HAMZA and VERMA (1967) showed that the heat flow values decrease with the age of the basement rocks. The decrease of heat flow with age was found to be very nearly exponential, the rate of decay, (decay constant 4.2×10^{-10}) being close to that of disintegration of K^{40}. It is postulated that heat flow value for each region reflects the outcome of the latest magmatic or metamorphic activity in that region, which are responsible for the redistribution of *U*, *Th* and *K* in the underlying crust and Upper Mantle. The coincidence of the rate of decay of heat flow with age with that of K^{40}, supports the hypothesis that the primitive earth has had a composition close to that of chondritic mantle model as compared to that of terrestrial model. MAKARENKO *et al* (1967) and LUBIMOVA (1967) obtained similar results and showed that the analysis of heat flow distribution over the USSR territory is concerned with relationship of heat flow values and age of tectonic zones. For the very ancient areas of Pre-Cambrian crystalline shields, the heat flow values are minimum. They start to grow with rejuvenation of folding and attain maximum values, in areas of Cenozoic age. So, heat flow values decreases as age increases. LUBIMOVA (1969) has shown the closeness of the results of the above workers and concluded that the history of heat flow for certain section of the earth's crust is connected to the age of tectogenesis.

LEE and MACDONALD (1963), WANG (1965) and GIRDLER (1967) observed similarities between the patterns of distributions of heat flow and the geoidal undulations ; and found a correlation such that depressions on the geoid correlate with regions of high heat flow, while rises on the geoid, correlate with regions of low heat flow. They considered thermal expansion, through convective motion in the mantle, to explain the observed anomalies of heat flow and gravity. Using more heat flow data which is now available and picking out only the isolated 'lows' and 'highs' of the geoids a comparison of both the fields was made by GUPTA (1969). It has been found that almost a null correlation exists between heat flow and geoid undulations. HORAI and SIMMONS (1969) compared the spherical harmonic coefficients of the Earth's thermal and gravitational fields and have arrived at the same conclusion. This probably would imply that the density irregularities are not due to thermal expansion and contraction but due to chemical variations.

Conclusions

The concentrations of radioactive elements in the vicinity of various sites where heat flow has been measured in India, must be adequately determined before the interpretation can be pushed much further. However, the following general conclusions may be drawn from the heat flow studies in India.

1. The lowest surface heat flow (0.64) so far in India has been observed at Pulivendala (southwestern margin of the Cuddapah basin). Such very low heat flow can be observed in shield areas, where the basic portion of the crust has been exposed, due to deep erosion or in areas where a part of the crust has been extensively injected by basic or ultra basic material.

2. In the Indian shield, lower heat flow values (0.84 to 1.01 μcal/cm^{2}sec) have been observed in regions which suffered older orogenics in comparison to other parts of the shield where significantly higher heat flow (1.40 to 1.76 μcal/cm^{2}sec) has been observed. Thus the age of the orogenic event seems to be reflected in the thermal field of an area.

3. Areas of low heat flow in the Pre-Cambrian shield, probably represent the portions of the shield where radioactive heat sources were more concentrated by vertical segregation, in the top layers of the crust, and which have been probably removed by deep erosion ; thus rendering these regions much depleted in radioactive heat sources. It seems these regions represent deeper portions of the crust of higher grade of regional metamorphism.

4. Three belts of significantly higher heat flow than the world average heat flow for shield areas have been observed in the Indian shield. These are (1) The Singhbhum Thrust Zone, (2) The Khetri copper belt of about 80 km length and (3) The Agnigundala copper belt, situated at the NE margin of the Cuddapah basin. These high values do not support the previously held belief, that the Pre-Cambrian shields are characterised with low heat flow values.

5. The high heat flow values in the Pre-Cambrian shield have been observed in areas of surface or near surface granitic bodies or in areas where the surface rocks are likely to have an adequate amount of radioactive heat sources.

6. The heat flow studies in the Aravalli mountain belt indicate the possibility that the rocks (regionally metamorphosed) of green-schist facies may have higher concentration of some or all of the radioactive elements *U*, *Th* and *K* than the rocks, of amphibolite facies.

7. For the areas of exposed crystalline Pre-Cambrian rocks a linear relationship, has been obtained between the surface heat flow and the observed average geothermal gradients. This suggests that for the areas of exposed crystalline Pre-Cambrian rocks in India, the heat flow anomalies are more or less reflected by the geothermal gradient anomalies. This has some advantage, as approximate inference can be made for the heat flow from the gradient measurements.

8. Two areas of normal heat flow implying normal stable conditions underlying these areas have been observed and are (1) The Satpura Gondwana basin, located in the central part of the Peninsular India and (2) the central portion of the Godavari valley. From the above it seems likely that the present thermal field of the Gondwanas is not having appreciable effects from the intrusion of dykes and sills of dolerite and basalt, which are likely of Deccan Traps age.

9. Areas in the Gondwanas where significantly higher heat flow than the world average heat flow (1.65), have been observed are (1) The Demodar valley coal fields region and (2) A small area in the south-east extension of the Godavari region *viz.*, Aswaraopet-Chintalapudi area. Recent uplifts with noticeable arching of the crust, indicating recent mantle disturbance has been reported in the Damodar vally coal fields. This suggests the deep cause of the high heat flow in the area, and merit further geological and geophysical investigations from the point of view of the utilization of deep heat of the earth for economic purposes. This is further substantiated by the presence of various hot springs in the area.

10. The northern part of the Cambay basin, extending from Cambay to Kalol is associated with higher heat flow than the world average heat flow. The high heat flow in this region can be attributed to igneous intrusion in the crust about 10-15 million years ago.

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References

BALAKRISHNA, S., PAUL, P. A. and RAMANA RAO, A. V.—Gravity and Magnetic Investigations in South-western Region of Cuddapah Basin, *Abstracts Second Symp. U.M.P.*, Hyderabad, 1970.

BECK, ALAN. E.—A Steady State Method for the Rapid Measurements of Thermal Conductivity of Rocks, *J. Sci. Instr.*, 1957, **34**, 186-89.

BENFIELD, A. E.—Terrestrial Heat Flow in Great Britain, *Proc. Roy. Soc. London A.*, 1939, **173**, 428-450.

BIRCH, F.—Flow of Heat in the Front Range, Colorado, *Bull. Geol. Soc. Am.*, 1950, **61**, 567-630.

BIRCH, F. ROY, R. F. and DECKER, E. R.—Heat Flow and Thermal History in New York and New England ; in *Studies of Applachian Geology, Northern and Maritimes*, ZEN, E-AN, Whilte Walters and Hedley J. B. Ed.), Inter-science Publishers, New York, 1968, 437-51.

BULLARD, E. C.—Heat Flow in South Africa, *Proc. Roy. Soc. London A*, 1939, **173**, 474-502

DAR, K. K.—Some Geological Data on Atomic Energy Minerals in India *J. Geol. Soc. India*, 1954, **5**, 112-120.

FAHRIG, W. F., EADE, K. E. and ADAMS, J. A. S.—Abundances of Radioactive Elements in Crystaliine Shield Rocks, *Nature*, 1967, **214**, 1002-3.

FOX, C. S.—*Mem., Geol. Survey of India*, 1931, *LVIII*, 103.

GANGADHARAM, E. V., KAMESWAR RAO, K. and ASWATHANARAYANA, U.—Distribution of Radioactivity in Mosabani Copper Mine, *Economic Geology*, 1963, **58**, 506-514.

GIRDLER, R. W.—Earth Satellites, Terrestrial Heat Flow, Mantle Convection and the Location of Extensional and Compressional Features on the Earth's Surface, *Proc., Geol. Assn.*, 1967, 78(1), 165-178.

GOUGH, D. I.—Heat Flow in Southern Karoo, *Proc. Roy. Soc. London*, A., 1963, **272**, 230.

GUPTA, M. L., VERMA, R. K., RAO, R. U. M., HAMZA, V. M. and RAO, G. V.—Terrestrial Heat Flow in Khetri Copper Belt, Rajasthan, India, *J. Geophys. Res.*, 1967. **21**(16), 4215-20.

GUPTA, M. L.,—Relationship between Terrestrial Heat Flow and the Geoid Undulations, *N.G.R.I. Annual Report*, 1969.

GUPTA, M. L., VERMA, R. K., HAMZA, V. M., RAO, G. V. and RAO, R. U. M.—Terrestrial Heat Flow and Tectonics of Cambay Basin, India, *Tectonophysics*, 1970, **70**.

HAMZA, V. M. and VERMA, R. K.—The Relationship of Heat Flow with Age of Basement Rocks, *Bull. Volcanologique*, 1969, XXXIII-I, 123-52.

HEIER, K. S. and ADAMS, J. A. S.—Concentration of Radioactive Elements in Deep Crustal Materials, *Geochim. Cosmochim. Acta*, 1965, **29**, 53-62.

HEIER, K. S.—Radioactive Elements in the Continental Crust, *Nature*, 1965, **208**, 479-80.

HORAI, K.I. and SIMMONS, G.—Special Harmonic Analysis of Terrestrial Heat Flow, *Earth Planet. Sci. Lett.*, 1969, 6(5), 386-94.

HORAI, K. I. and NUR AMOS—Relationship among Terrestrial Heat Flow, Thermal Conductivity and Geothermal Gradient, *J. Geophys. Res.*, 1970, 75(15), 1985-91.

HYNDMAN, R. D. and SASS, J. H.—Geothermal Measurements at Mount Isa, Queensland, *J. Geophys. Res.*, 1966, **71**(2), 587-601.

HYNDMAN, R. D.—Heat Flow in Queensland and Northern Territory, Australia, *J. Geophys. Res.*, 1967, **72**, 527-539.

HYNDMAN, R. D., LAMBERT, I. B., HEIER, K. S., JAEGER, J. C. and RINGWOOD, A. E.—Heat Flow and Surface Radioactivity Measurements in the Pre-Cambrian Shield of Western Australia, *Phys. Earth Planet. Interiors*, 1968, **1**, 129-35.

HYNDMAN, R. D. and EVERETT, J. E.—Heat Flow in a Low Radioactive Area of the Western Australian Pre-Cambrian Shield, *Geophys. J. Roy. Astro. Soc.*, 1968, **14**, 479-86.

JAEGER, J. C.—Heat Flow and Radioactivity in Australia, *Earth Planet Sci. Lett.*, 1970, 8(4), 285-92.

KRISHNAN, M. S.—*Geology of India and Burma*, Higginbothams (Pvt.) Ltd., Mount Road, Madras-2, 1960.

LACHENBRUCH, A. H.—Geothermal Models for Sierra Nevada, *J. Geophys. Res.*, 1968, 73(22), 6977-89.

LAMBERT, I. B. and HEIER, K. S.—The Vertical Distribution of Uranium, Thorium and Potassium in the Continental Crust, *Geochim Cosmochim. Acta*, 1967, **31**, 377-99.

LAMBERT, I. B., and HEIER, K. S.—Geochemical Investigations of Deep Seated Rocks in the Australian Shield, *Lithos*, 1968, **1**(1), 30-53.

LEE, W. H. K. and MACDONALD—The Global Variation of Terrestrial Heat Flow, *J. Geophys. Res.*, 1963, **68**, 6481-92.

LEE, W. H. K. and UYEDA, S.—Review of Heat Flow Data, *Geophys. Monograph No. 8., Am. Geophys. Union*, 1965, 87-186.

LUBIMOVA, E. A.—Thermal History of the Earth, *Geophys. Monograph No.* 13., *Am. Geophys. Union*, 1969,63-77.

LUBIMOVA, E. A.—Terrestrial Heat Flow for the USSR and its connection with other Geophenomena, *14th IUGG General Assembly Abstracts*, *2-a*, 1967.

MAKARENKO, F. A., POLYAK, B. G. and SMIRNOV, Ya. B.—Thermal Regime of the Upper part of the Lithosphere, *14th IUGG General Assembly, Abstracts*, 1967, *2-a*, B-9.

MUKTINATH—Some Recent Mineral Development Work in the Aravalli Belt, Rajasthan, *Proc. Symp. on UMP, Hyderabad*, 1967, 363-91.

NARAYANASWAMY, S.—Tectonic Problems of the Pre-Cambrian Rocks of Peninsular India, *Symp. Tectonics, Bull. Indian Geophys. Union*, 1966, 77-94.

NARAYANASWAMY, S. and VENKATASUBRAMANIAN, V. S.—Uranium and Thorium Contents of Coexisting Gneisses, Granites and Pegmatics, *Geochim. Cosmochim. Acta*, 1969, 33(8), 1007-9,

NGRI—Heat Flow Studies in India, *Annual Report*, 1968-69, 56-62.

PAL, S., IYER, S. S. and VENKATASUBRAMANIAN, V. S.—Studies of Uranium and Thorium Contents and Potassium Rubidium Ratios of Certain Pre-Cambrian Rock Types, *Proc. Symp. on UMP*, Hyderabad, 1967, 146-54.

PITCHAMUTHU, C. S.—The Pre-Cambrian of India, *in The Pre-Cambrian*, Interscience Publishers, New York, 1967, 3, 1-96.

POLYAK, B. G. and SMIRNOV, YA. B.—Heat Flow in Continents, *Dokl. Akad, Nauk, SSSR*, 1966, 168(1), 1970-72.

QURESHY, M. N., KRISHNA BRAHMAM, N., ARAVAMADHU, P. S. and NAQVI, S. M.—Role of Granitic Intrusions in Reducing the Density of the Crust and other Related Problems as Illustrated from Gravity Study of the Cuddapah Basin. India, *Proc. Roy. Soc. America* 1968, 304, 449-64.

QURESHY, M. N.—Relation of Gravity to Elevation and Rejuvenation of Blocks in India, (To appear in *J. Geophys. Res.*, 1971, 76(2), 1970.

QURESHY, M. N., BHATIA, S. C., and SUBBA RAO, D. V.—Preliminary Results of Some Gravity Surveys in Singhbhum Area, *Second Symp. U. M. P. Abstracts*, Hyderabad, 1970.

RAO, R. U. M., VERMA, R. K., RAO, G. V. and GUPTA, M. L.—Heat flow at Damua and Mohapani, Satpura, Gondwana Basin, India, *Earth. Planet. Sci. Lett.*, 1969, 7(5), 406-12.

RAO, R. U. M., VERMA, R. K., RAO, G. V., HAMZA, V. M., PANDA, P. K. and GUPTA, M. L.—Heat Flow Studies in Godavari Valley, India, *Tectonophys*, 1970, **10**.

RAO, R. U. M.,—Heat Flow Studies in Kolar Schist Belt, Singhbhum Thrust Zone and Godavari Valley, India, *Ph.D. Thesis*, Andhra University, Waltair, 1970.

ROY, R. F., DECKER, EDWARD R, BLACKWELL, DAVID, D. and BIRCH FRANCIS—Heat Flow in the United States, *J. Geophys. Res.*, 1968-*a*, 73(16), 5207-21.

ROY, R. F., BLACKWELL, DAVID, D., BIRCH FRANCIS.—Heat Generation of Plutonic Rocks and Continental Heat Flow Provinces, *Earth and Planet. Sci. Lett.*, 1968-*b*. 5, 1-12.

SAHA, A. K.—Magma-Tectonics of the Northern part of Singhbhum Granite, A Resume, in Proceedings of the Symposium on Tectonics, *Bull. Indian Geophys. Union*, 1966, 3, 59-76.

SAHA, A. K.—Pre-Cambrian Geology of the Singhbhum Region, Lecture under University Grants Commission, *National Lectureship Scheme* (Cyclostyled notes), 1970.

SARKAR, S. N.—*Pre-Cambrian Stratigraphy and Geochemistry of Peninsular India*, Dhanbad Publishers, India, 1968.

SEN, S. N. and NARASIMHA RAO, CH.—Igneous Activity in Cuddapah Basin and Adjacent Areas and Suggestions on the Paleo-geography of the Basin, *Proc. Symp. U. M. P., Hyderabad*, 1967, 261-85.

SHAW, D. M.—*U*, *Th* and *K* in the Canadian Pre-Cambrian Shield and Possible Mantle Compositions, *Geochim. Cosmochim. Acta*, 1967, 31, 1111-13.

TILLING, R. I., and GOTTFRIED, DAVID.—Radiogenic Heat Production of Comagmatic Rocks, *5th Annual Meeting Am. Geophys, Union Abstracts, EOS*, 1969, 50(4), 315.

VERMA, R. K., RAO, R. U. M., and GUPTA, M. L.—Terrestrial Heat Flow in Mosabani Mine, Singhbhum District, Bihar. *J. Geophy. Res.*, 1966, 71(20), 4943-48.

VERMA, R. K., RAO, R. U. M., GUPTA, M. L., HAMZA, V. M. and RAO, G. V.—Heat Flow Studies in India, *Bull. Volcanologique*, 1968, *XXXIII*-(1), 69-88.

VERMA, R. K., GUPTA, M. L., HAMZA, V. M., RAO, G. V. and RAO, R. U. M.—Heat Flow and Crustal Structure near Cambay, Gujarat, India, *Bull. NGRI*, 1968, 6(4), 153-66.

VERMA, R. K., and NARAIN, HARI.—Terrestrial Heat Flow in India, *Geophys. Monograph No. 12, Am. Geophys. Union*, 1968, 22-34.

WANG, C. Y.—Some Geophysical Implications from Gravity and Heat Flow Data *J. Geophys. Res.*, 1965, 70. 5629-34.

ZIAUDDIN, MOHD.—Origin of the Agnigundala Ore Deposit, *J. Indian Geosci. Assn.*, 1964, 4, 107-112.

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Special Issue on NGRI's Contribution to Upper Mantle Project

THEORETICAL GEOPHYSICS RESEARCH UNDER UPPER MANTLE PROJECT*

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Introduction

The main objective of theoretical studies about upper mantle have been interdisciplinary integration of diversified geomagnetic, geothermic and tectonic information through common physico-mathematical procedures. These multivariable studies involve large scale geo-data in different fields and sophisticated models incorporating realistic values of inhomogeneities and anisotropies. Extensive use of numerical analysis and highspeed digital computers (IBM 1620 of RRL Hyderabad, and IBM 7044 of IIT Kanpur) had greatly helped carrying out tedious computations. While we statistically investigated coupled seismo-and thermo-tectonic correlations from the available large scale data, we also exploited powerful perturbation techniques, symmetric matrix methods and transform operators to develop more realistic models of the interior. The details of the investigations are projected under the following four major headings :

1 Earthquake energy balance and lateral geothermal gradients.

2. Effects of anisotropy and inhomogeneity on Love Wave propagation.

3. Symmetric matrix methods and isostatic compensation.

4. Contribution of shape deformation, and transient analysis in Geoelectromagnetics.

Earthquake Energy Balance and Lateral Geothermal Gradients

To understand near surface energetics of the earth it is necessary and of great importance to investigate the possible correlationship between the heat flow and seismicity. The available heat flow data has been analysed on the global scale to seek for such an association between lateral gradients of heat flow values and seismicity connected primarily with high magnitude earthquakes. The lateral cumulative thermal gradients have been calculated :

(*a*) in the regions where shallow earthquakes of magnitude higher than 8.5 have occurred during the period 1897-1956, and

(*b*) in the Atlantic, Indian and Pacific Oceans along latitudinal directions.

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