HEAT FLOW *MAP* OF INDIA – AN UPDATE

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SUMMARY : The Heat Flow Map of India (Ravi Shanker, **1988)** has been updated. Five different heat flow zones identified earlier have been further constrained. They broadly reflect the ongoing geodynamic processes operating underneath the Indian Sub-Continent which are responsible for geotectonic, geomorphic, magmatic and seismic histories during Tertiary and Quaternary.

1. INTRODUCTION

The first version of the Heat Flow Map of India (Ravi Shanker, **1988)** incorporated systematic heat flow studies by the GSI, conducted in over 200 bore holes drilled for geothermal, mineral and groundwater exploration. In addition, 60 heat flow values published fiom NGRI; and those by Panda **(1985) fiom** various petroliferous basins in India have also been used. The relationship between heat flow and dissolved silica in thermal and non-thermal groundwater (Swanberg and Morgan, **1978)** was modified to suit Indian studies to estimate the order of magnitude terrestrial heat flow. In large parts of alluvial areas, after the credibility of this indirect method was established (Ravi Shanker, **1988),** it was found that the geochemically established heat flow values were **3-15** $\mathbf{mW/m^2}$ **(≤ 10%)** less than those calculated by conventional methods.

During the last **10** years, a large number of additional heat flow values have been generated which are utilised in this presentation.

2. ADDITIONAL HEAT FLOW DATA

Table-1 gives additional heat flow data generated since **1988.** The data used in preparing the first version of the Heat Flow Map of India (contained in Table-2 of Ravi Shanker, **1988,** pp. **92-103),** along with the additional data have been used to prepare the new version of the Heat Flow Map (Fig. 1). While retaining the overall character and shape, the boundaries between the various heat flow zones are now better constrained, particularly, in the central, western and northwestern part of the Indian Peninsula. Moreover, data density in alluvial plains of Punjab, NW of Delhi, has increased.

The Heat Flow Map of India identifies 5 Heat Flow Zones (HFZ), numbered I to V.

3. RELATIONSHIP OF CRUSTAL STRUCTURE AND TECTONISM TO HEAT FLOW ZONES IN THE PENINSULA

The Indian subcontinental plate, after getting detached from its Gondwana partners in early Cretaceous **(–130** Ma) moved very rapidly resulting in substantial thinning and heating of its lithosphere (Negi et *al.*, **1986;** Pande, **1996;** Ravi Shanker *et al.*, **1998).** It started actively subducting underneath the Asian and Burmese Plates at differential rates with intense ophiolitic activity **(105-65** Ma) at the interplate boundary. Accumulation of compressive stresses with variable disposition of principal axes during the course of rotational movement of the Indian plate, resulted in conjugate sets of tensional regimes and zones of heating (or even partial melting). Consequently, many interplate rifts and associated basins were generated on the Indian plate, such as, Sone - Narbada - Tapti (SONATA) zone, Cambay graben-western continental margin and Krishna, Godavari, Mahanadi, Bengal and Cauvery basins.

The outpouring of Deccan basalt **(65±2Ma)** probably coincides with the culmination phase of these events. The continental collisional phase of the on-going geodynamic processes resulted in episodic uplift of the Himalayas during Tertiary and Quaternary times **(Himalayan** Orogeny). This has given rise to the present-day geomorphic configuration of the Indian sub-continent and resulted in intense fragmentation of the Indian Shield. This, in turn, controls all neotectonic features, contemporary tectonism, the present phase of geothermal activity and distribution of heat flow values.

Table - 1 Additional Data on Heat Flow in Parts of India

Number as in Map	Area	Heat - flow (mW/m²)		Data Source*
		Measured Conventionally	Geochemically Estimated	
	PUNJAB			A
P-1	Hoshiarpur		57 (n=4)	
P-2	Ropar		66 (n=8)	
P-3	Sangrur		58 (n=9)	
P-4	Bhatinda		50 (n=3)	
P-5	Faridkot		49	
P-6	Patiala		66 (n=4)	
P-7	Ludhiana		69 (n=3)	
P-8	Jalandhar		56 (n=5)	
P-9	Kapurthala		65 (n=4)	
	BUNDELKHAND			A
167	Jhansi-Jarar	41		
	KILLARI AREA			B
168	Killariwadi-Osmanabad	36 (n=3)		
	NASIK-AHMEDNAGAR-PUNE			B
169	Kopargaon-Shajapur-Deothan	39 (n=3)		
170	Srirampur	36		
171	Sangmaner-Taharabad	64 (n=4)		
172	Rahuri-Sheogaon	38 (n=5)		
173	Ahmadnagar	43		
174	Mata Pimpri	47		
175	Bhandi	48		
176	Sidhatek-Nirgude	42 (n=2)		
177	Loni Deokar - Malwadi	39 (n=3)		
178	Gotoundi	46		
179	Vakilbasts	38		
	YEOTMAL			B
180	Satephal-Digras-Ami-Loni-Sadoba	56 (n=7)		
181	Saykheda	38		
182	WARDHA	61 (n=3)		B
	HARYANA			C
183	Tosham	96 (n=4)		

* Data Source : A : This study, B : Sundar et *al.*, 1990, C : Roy et al., 1996

It is seen that regions along the convergent plate boundary and all major intraplate rifts/grabens are also the major zones of geothermal activity. The latter, in general, are long, narrow active tectonic features extending to several hundred kilometres in length and several tens to a couple of hundred kilometres in width. They are characterised by high gravity, positive isostasy, higher temperature gradients and heat flow, shallowing of magnetic crust and elevated Curie point and solidus of basalt isotherms. In addition, a typical five-layered crustal velocity structure, thinning of the crust, shallowing of the upper mantle in the median part like many other mid-continental rifts are other characteristics of these zones (Ravi Shanker, 1991). In general, they are traversed by several cross faults, which have been displaying strong neotectonism and moderate seismicity.

It has been established that these zones are characterised by a 5-layered crustal velocity structure. It is postulated that it is the fourth layer with P-wave velocities ranging between 7.1 and 7.6 km sec^{-1} and density around 3.02 g cm^{-3} (Ravi Shanker, 1991a; Singh and Meisser, 1995; Singh, 1997) which controls the crustal and thermal structures of these zones of variable dimensions. This layer is generally restricted to the axial portions and does not extend to the shoulder areas of the rifts/grabens. In the SONATA zone, which serves as a model on account of being the most thoroughly studied geothermally anomalous rift, the fourth layer has a maximum, thickness of 16 km with its top lying at depths of 7 to 23 km. It is shallowest in the western part (around 73°E longitude) and shows gradual deepening eastward, being deepest around 80% longitude (Ravi

Shanker, 1991a). Such zones have also been recognised along other rifted basins (Kaila and Sain, 1997).

The fourth layer has been variously interpreted as a zone of intense upper mantle - lower crust interaction producing highly anomalous hot upper mantle with temperatures exceeding basalt solidus (Ravi Shanker, 1991a), also as solidified magma chambers (Bhattacharji et *al.*, 1994) and as large scale magmatic underplating (Singh and Meissner, 1995; Singh, 1997) or asthenospheric uparching (Negi et *al.*, 1992; Pande, 1996; Kaila and Sain, 1997) prior to Deccan Trap extrusion around (65±2Ma).

In our opinion, geodynamic and magmatic processes that operated over 65 Ma ago would not be thermally active now and consequently, may have no influence over the contemporary heat flow regime. The Heat Flow Map (Fig. 1) reflects the present day distribution of heat flow values. It is inferred that in the peninsular part, the heat source for geothexmally anomalous zones may probably be related to the fourth layer. Magma chambers with roots in the fourth layer, generated during late Tertiary to early Quaternary times and yet to equilibrate with the surroundings, may explain the source of heat for some rather enigmatic thermal manifestations of the peninsular part.

This postulation gets support from the study conducted in the Tattapani geothermal area in SONATA zone (HF'Z-I) where the latest thermal event of 35000-38000 BP (mean age 36796 yrs) with equilibration temperature of about 150°C has been identified (Thussu et *al.*, 1994). Many such events may be present at shallow crustal levels, each supporting an active hydrothermal system.

An important off-shoot of our study is the suggestion that differential thermal structure within the Indian Shield provides the first order motive force for lateral and vertical movements of various fault-bounded blocks, which, in turn, may be responsible for neotectonism, contemporary tectonic movements and seismicity (Ravi Shanker, 1995, 1996).

4. THERMAL MANIFESTATIONS IN RELATION TO HEAT FLOW ZONES

Heat Flow Zone (HFZ) - I runs along the convergent boundaries of the Indian plate with the Asian and Burmese plates in the north and *east,* respectively. In addition, within the SONATA lineament (Ravi Shanker, 1991a) HFZ-I occurs as a small linear high. HFZ-I hosts India's most promising geothermal areas, *i.e.* Puga, Chhumathang and Tattapani (Ravi Shanker, 1991b). Temperatures in excess of 150°C are expected in these areas within accessible depths. Prospects of power generation are bright at Puga Chhumathang and Tattapani too may probably sustain binary-cycle plants.

HFZ-11 exists on the convex side of Zone-I all along the convergent plate boundary in northern and eastern parts of India. In the Himalayan region it mainly covers the area to the north of the Main Central Thrust (MCT), hosting more than 100 hot spring localities, the bulk of which are concentrated in its northwestern section. Beda, Tapri, Manikaran, Tapoban and Vashist are some of the important geothermal prospects of this zone. With the exception of Beda and Tapri, where temperatures in the vicinity of 150°C are possible, other geothermal areas have reservoir temperatures of 110 to 130°C. A 5 Kw binary plant was test-run at Manikaran.

HFZ-II is also identified in the axial part of ENE-WSW trending SONATA Rift Zone, active down faulted regions of Cambay graben, along the western coast of India as well as in Godavari, Mahanadi and Cauvery basins. Here too, it is characterised by numerous hot springs and large areas of hot groundwater, which indicate feed temperatures in the vicinity of 120°C.

HFZ-III exists on the convex side of Zone-I1 parallel to plate boundaries. In the Himalayan region it is bounded by the Main Boundary Fault (MBF) and MCT. It also envelops the Zone-I1 in SONATA Zone, Cambay graben, West Coast belt, Jodhpur, Bikaner - Nagpur basin and parts of Mahanadi, Damodar, Godavari and Cauvery basins in peninsular regions including adjoining off-shore areas. Temperatures between 100-150°C have already been recorded up to 3500 m depth in this zone in the Cambay graben.

HFZ-IV and V are areas of normal and below normal global heat flow, respectively, covering large parts of the Indian peninsula and its Archean/Palaeo-Proterozoic nuclei. Surprisingly and most unexpectedly, the subnormal heat flow Zone-V is located in the foothills of the NW Himalayan region. A high hydraulic gradient flushing out the heat laterally and preventing vertical heat flow is a possible reason for this (Ravi Shanker, 1996).

In addition, four en-echelon zones of HFZ-III are seen along Aravalli-Delhi mountain regions, which is a major tectonic zone with distinct evidences of neotectonic activity.

5. DISCUSSION

Anomalous thermal structure, confined particularly to grabens, is one of the significant characteristics of the peninsular part of India. Various explanations have been offered in this regard but authors, based on their studies in the

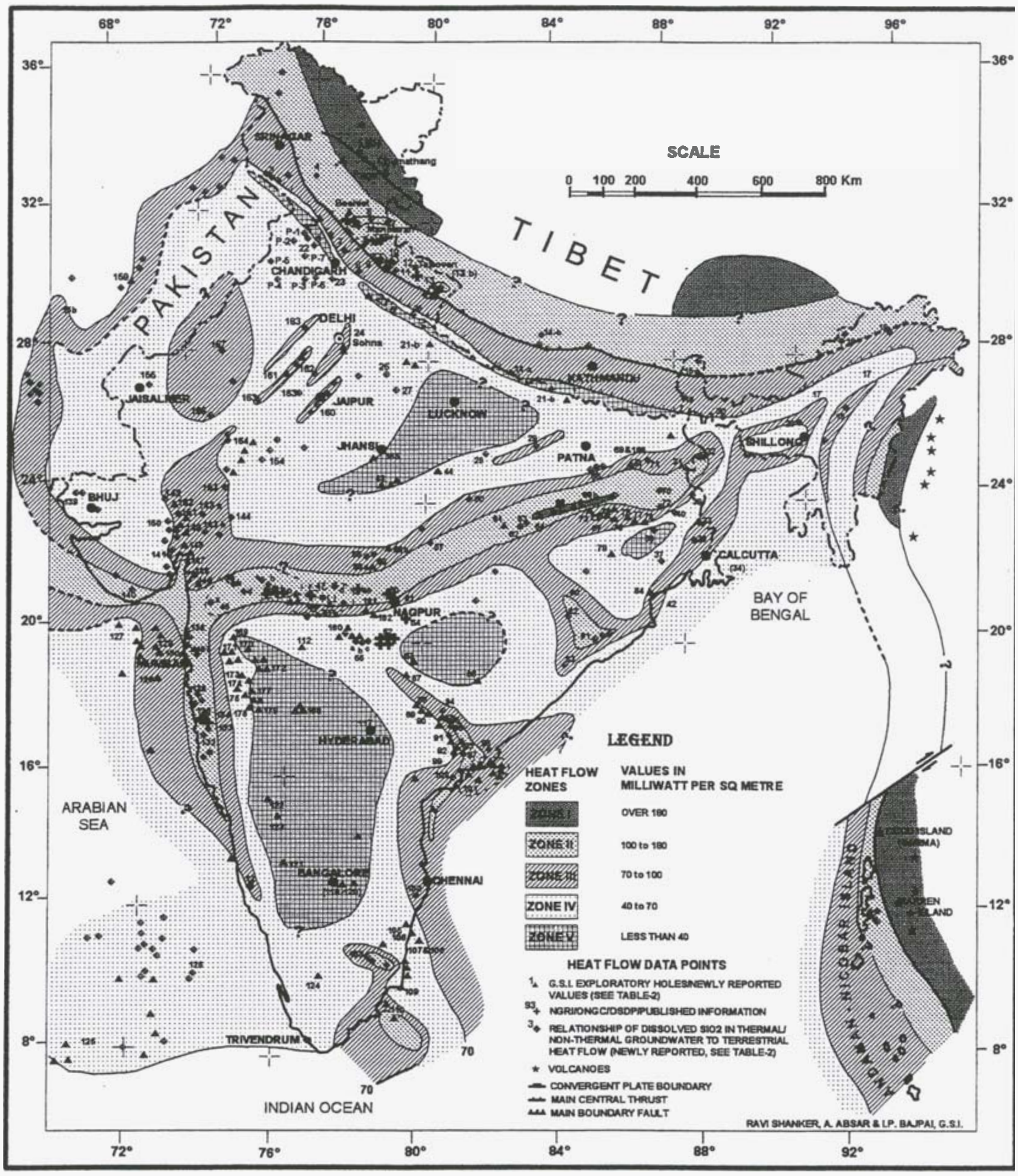

Figure 1. Heat Flow Map of India (modified from Ravi Shanker, 1988). Puga, Chhumathang, Tattapani geothermal areas and active volcanoes of Narcondum and Barren Island lie in HFZ-I. Manikaran, Tapri, Beda and Tapoban geothermal areas are particularly worth mentioning in HFZ-II.

SONATA zone, are of the opinion that relatively high heat flow zones in peninsular grabens are directly related to the fourth crustal velocity layer.

Various models have been proposed to explain the Himalayan Geothermal Belt (HGB). Toksoz and Bird (1977) consider shear heating on the crustal thrust plane mainly within the Indian plate as the possible cause. Bird (1978) explains the anomalously high crustal heat beneath the HGB through upwelling of hot asthenosphere more towards the underthrusted Indian plate. Hochstein and Regenauer-Lieb (1998), however, have their zone of heat generation due to plastic deformation within the upper part of the crust, more into the Tibetan area. Spilled over heat, though, is inferred to disseminate through the southern area.

As in the case of Yangbajing, Tibet, some additional source of heat in the form of a cooling granitic pluton (Hochstein and Regenauer-Lieb, 1998) needs to be invoked for the Puga-Chhumathang geothermal systems, practically lying on the Indus Suture Zone, the ophiolite-marked boundary between the Indian and Asian plates. A 3.5 Ma old granitic phase is recorded at Chhumathang (Ravi Shanker et al., 1976), which is intruded by still younger, pegmatites, aplites, quartz and quartz-fluorite veins. The magmatic activity in the Puga - Chhumathang zone is thus indicated to have continued to fairly late in the Quaternary times. Continuation of HFZ in the east corresponding to the boundary between the Indian and Burmese plates, on the other hand, is marked by Recent volcanism at Narcondum and Barren Islands.

As far as distribution of heat flow values within the Himalaya (HFZ-I, II & III) are concerned, our purpose is served by all the three models of heat generation though we would have liked the heat generation zone of Hochstein and Regenauer-Lieb to extend little bit more into the Indian plate to explain rather anomalous hot spots at Tapri and Beda (SiO_2 concentrations similar to that at Chhumathang) which are somewhat difficult to be explained by the heat spilled - over from the north.

6. CONCLUSIONS

The revised version of the Heat Flow Map of India is still the first step towards understanding the thermal structure underneath the Indian sub-continent There are still many gaps and the map has to be periodically updated and refined as additional and more reliable data pours in.

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