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Conductive heat flow in the Godavari sub-basin (Pranhita-Godavari valley), Indian shield and its significance

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ABSTRACT

The Godavari sub-basin (GSB) is a part of the Gondwana Pranhita – Godavari Valley (PGV) of the Indian Peninsular Shield, which is a major NW-SW lineament where sediments from Neoprotrozoic to Mesozoic are present.

The objective of this paper is three fold viz ; i) an examination and analysis of available measured heat flow values(HFU) of the GSB for hydro-geological perturbations and obtain the most probable true magnitude of conductive heat flow (CHF) value, in cases wherever it is possible, ii) to decipher the thermal characteristics of the GSB through a comparison of its CHF values with the other available heat flow data in its surrounding region of the Indian Shield, and iii) to infer the main deep thermal characteristics of the GSB through an examination of the results so obtained and the inferences from some reported geo-data of the GSB and PGV.

Based on our analysis we obtain; i) that the CHF values at three locations of the NW part of the GSB viz; Indaram, Godavarikhani and Bellampalli areas are 50, 52, and 49 mWm^{-2} respectively ,and ii) that the average CHF of the GSB is of the same order as the average HFU for the Chandrapur ,a NE sub-basin of the PGV (51mWm^{-2}) and the Wardha – Yavatmal Deccan Trap region (Av = 52mWm^{-2}), below which Gondwana sediments, likely extension of the PGV Gondwana rocks ,do occur. The CHF values of the GSB are similar to those that are reported for Proterozoic Bastar Craton, which lies towards NE of GSB and also similar to Mailaram high which is a large outcrop of Archaean- Proterozoic group of rocks in the SE sector of the GSB. Available data on Chemical analysis of thermal waters of the area showed their meteoric origin and association with sedimentary rocks and non-magmatic sources.

Based on these observations, presence of cooling magmatic bodies within the crust of GSB and a shallow Moho below it are strongly ruled out. Available geo-data (geological, gravity, seismic etc.) of GSB are in conformity with these inferences.

INTRODUCTION

It is a known fact that in sedimentary basins, sub-surface hydrological regime largely influences the geothermal gradients (Lachenbruch and Sass, 1977; Majorowies et al., 1984). Therefore it is often difficult to discern a correct value of the background conductive heat flow in sedimentary strata as those of GSB, where the river Godavari and its various streams flow and drain the area. Upward, downward as well as lateral forms of ground water movements disturb GSB`s thermal regime. It is therefore apparent that a meaningful interpretation of the heat flow data of the GSB needs careful examinations of most of the relevant parameters. Such an attempt is significant and important to decipher the true thermal characteristics of the PGV/GSB, for which opposing inferences have been drawn and reported. Utilizing the concept of magneto-thermometry and using MAGSET data Sarkar and Saha (2006) reported conductive heat flow 72.5 mWm^{-2} and thin lithosphere of thickness 57km in Godavari Valley. On the other side, based upon shear wave splitting analysis using SKS, SKKS and S waveforms recorded at eight broadband seismic stations within and in the vicinity of the Proterozoic Godavari rift system, Kumar et al. (2010) suggested the absence of a preferentially thinner lithosphere beneath the Godavari rift or anomalously high heat flow values.

We, therefore examined the available heat flow values (Rao et al., 1970; Gupta,1993; Gupta and Sharma, 2013) and made an attempt to analyse the available temperature logs and evolve a methodology to obtain (considering the hydrological perturbations to thermal regime) and infer, in cases where ever it has been possible, reliable magnitude of the CHF. Heat flow values in GSB are reported by Ravi Shanker (1988) also. However these have not been considered as most of these are based on employing an empirical relationship between heat flow and silica-temperature (silica dissolved in ground water) for which there is no physical basis, and for other reported values adequate information is missing. We also examined the heat flow data of the sub-provinces of the Indian shield, which occur around the GSB (Gupta, 1995; Gupta et al., 1993 and 1991; Roy Sukanta, 2008) so as to outline the general thermal characteristic of a broad region of the Indian shield.

We, thereafter briefly analyse the determined CHF of the GSB together with the available results of geophysical studies like gravity and magnetic, seismic etc. (Mishra et al., 1987; Sarma and Krishna Rao, 2005; Singh et al., 2012) mainly of the GSB, so as to see that how these conform to each other, to get a better insight into its thermal characteristics.

GENERAL GEOLOGY AND STRUCTURE OF PGV

The GSB is one of the three main sub-basins of Pranhita – Godavari Valley, which is a major lineament disposed in a NW-SE direction of Peninsular India. The GSB is of about 200km length and of about 50 km width. According to Raju (1986), PGV extends over a length of about 600 km and width of 50km in NW-SE direction from Chincholi ($21^0$30′N,$78^0$42′E) to Jangareddigudem ($17^0$08′N,$81^0$19′E). The southern limit of PGV is marked by the outcrops of the Gondwana sediments of the Krishna –Godavari coastal basin. Sediments from Neoprotrozoic to Mesozoic are preserved in it. Its geology, structure and tectonic framework have been discussed in detail by many workers of Geological Survey of India (Raja Rao, 1982) and the Oil and Natural Gas Commission of India (Raiverman et al., 1985; Raju, 1986). Longitudinally, the PGV consists of three sub-basins- the Chandrapur, Godavari (or the Sironcha) and Chintalpudi, which are separated by Asifabad ridge and the transverse Mailaram high. A prominent feature named as Chinur ridge (Figure -1), which represents an area of uplift, divides the Godavari sub-basin transversely into two half grabens, while parallel strike-slip boundary faults are prominent features near its south-western margin. North-east and south-west sides of PGV are flanked by the crystalline basement complex of Archaean age and sediments of Purana Group. Deccan Trap effusive and the Lameta beds of Cretaceous age occur towards the north-western side of PGV. Coastal Gondwana sediments of the Krishna- Godavari basin, limit the south - eastern boundary. The PGV is filled with the rocks of Purana Group

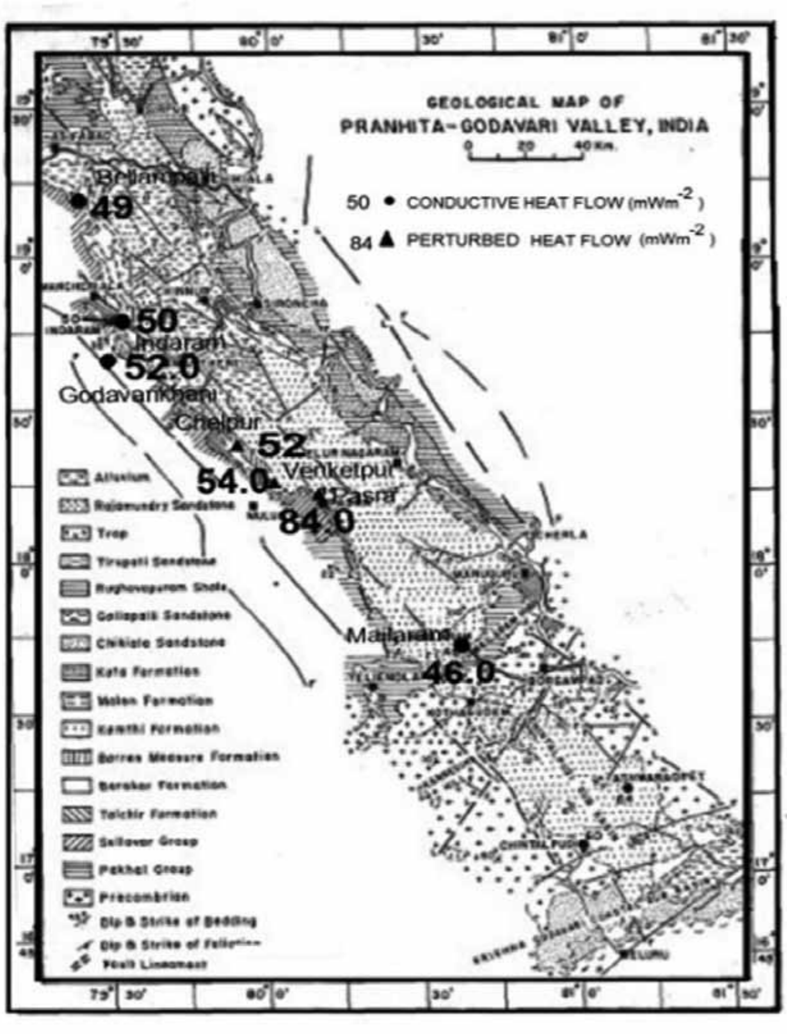

Figure 1. Geological map of Pranhita –Godavari valley, India, with heat flow values in its Godavari-Sub-basin

(Pakhal and Sullivan formations of Proterozoic age) and a complete sequence of rocks of the Gondwana systems. The Gondwana consists of two major sub divisions viz. (i) The Upper Gondwana (Triassic-Cretaceous) and (ii) the Lower Gondwana (Permo- Carboniferous).

The PGV rift developed along a pre-existing zone of weakness i.e. axial portions of Proterozoic Pakhal and Sullivan basins, which are set on continental crust along the contact between the Dharwar and Bastar cratonic blocks of the Indian Shield (Lakshminarayana and Sivaji, 2008). The evolution of Indian Gondwana basins, according to Mahadevan (2007) may be expected to have interacted largely with the shallow layers of the lithosphere, mostly the lower crust. This fact is evidenced by the presence of charnockitic rocks, which occur as exposed on the limbs of Godavari and Mahanadi basins.

HEAT FLOW DATA

Six heat flow values distributed along the western edge of the GSB, three in its NW part and three in its SW part and one value in an Archaean out crop near its SE edge at Mailaram are available (Rao et al., 1970; Gupta, 1993; Gupta and Sharma, 2013). The locations are shown in figure -1.

Heat Flow Data of NW Part

The reported measurements in the NW part of the GSB are from seven closely spaced boreholes at Indaram, three boreholes at Bellampalli and one deep borehole from Godavarikhani (Table -1). All these values are examined and analysed below.

Analysis of borehole Temperature and Heat Flow Data of Indaram:

In the presence of vertical water movement the total heat flow (Q) includes energy carried by mass movement as well as through conduction. For such a case (Lubimova et al., 1965), it can be shown that

$$-K\,(dt/dz) = Q - C\,\rho VT \text{ ----- } (1)$$

Where V= Velocity of the downward moving water
C = Specific heat capacity per unit mass of the moving water
ρ = Density of water
T = Temperature of the moving water
K =Thermal conductivity of the saturated rock

Normally as a result of continuous flow of heat from below and percolation of water, steady or near steady state thermal conditions are obtained below certain depths. If so, plots of heat flow (K (dt/dz)) versus temperature should yield various non-horizontal straight segments (for those intervals in which 'V' is more or less uniform). Keeping this in mind heat flow values (K(dt/dz)) for Indaram have been calculated in regular intervals of 40 m depth each and their plots against temperature are shown in figure 2. We see (Figure -2) that all the curves show various non- horizontal linear segments of more or less uniform heat flow with the magnitude of the average heat flow for the segments increasing with the temperature of the following deeper segments. These clearly demonstrate the decreasing effect of water percolation, due to its diminishing velocity with depth, on the sub-surface temperatures and consequently on the heat flow. The curves for the three deep bore holes SP-31, 32 and 33 show more or less vertical segments showing practically constant values of heat flow at higher temperatures i.e. at deeper depths.

Hydro-geological perturbations to sub-surface thermal regime due to downward moving ground water in a sedimentary basin, could become negligible below certain depth. It could be applicable in the following two cases: i) below the depth of fully saturated layers and or ii) below the layers where, the permeability becomes more or less negligible due to presence of a succession of permeable, semi-permeable and impermeable (?) sedimentary layers. Therefore, the velocity of percolating ground water would become more or less zero at certain depths. The litho-logs of boreholes of Indaram show such geological characteristics. The velocity of water percolation at Indaram has been estimated and reported by Gupta and Sharma (2013). They have reported that the velocity of water percolation at Indaram in top layers (70-150m) is around ~ $3.4\text{x}10^{-7}$ cm/sec, which decreases to ~$0.04\text{ x}10^{-7}$ cm/sec in the depths around 300 m and becomes more or less negligibly small for deeper levels. They (ibid) have further stated that the value of Peclet Number, which is the ratio of the heat transfer through convection to that of conduction, naturally becomes negligible at appropriate deep depths in the Indaram area. In Indaram case the deeper levels that are not influenced by ground water circulation may lie below ~ 300 m.

Considering the aforesaid, more or less uniform heat flow indicating conduction as the main mode of heat transfer occurs at deeper segments at Indaram. This aspect becomes further clear from figure -3, where heat flow values as calculated in large sections versus depth are plotted. The magnitude of variation of heat flow decreases with depth and after certain depths(~ 300 m) more or less uniform values occur for the three deep boreholes, SP-31,32 and 33. Such behaviour as in the case of temperature vs. heat flow plots, discussed earlier, reflects hydrological disturbances to the thermal regime due to downward ground water percolation, decreasing with depth and becoming negligible below ~300m.

Table 1. Heat Flow data in Godavari Sub- basin

S.NO	Location Coordinates, Lat(N), Long (E), Borehole No., (A)	Depth to which logged undisturbed period, (B)	Depth range (m) (C)	Temperature Gradient, mKm^{-1} (D)	Heat Flow, mWm^{-2} (E)
1	INDARAM , (18^0 48′N, 79^0 33′ E)	_______	395to 580	_______	50.0
1.1	SP-33 (18^{0}48′05″N 79^{0}13′27″E)	585 m 28 days	71.0-127.0 128.0-193.0 198.0-225.0 227.0-285.0 285.0-395.0 395.0-450.0 450.0-488.0 488.0-520.0 520.0-580.0	6.2 11.8 13.9 14.9 17.9 17.5 22.1 49.1 20.1	17.3 33.4 39.6 42.2 45.5 49.5 49.6 50.4 50.6
1.2	SP-32 (18^{0}48′25″ N, 79^{0}33′26″E)	512 m 30 days	70.0-112.6 112.6-154.6 154.6-190.7 230.0-270.0 273.0-293.0 293.0-313.0 314.5-430.0 434.5-450.0 450.0-488.0	3.8 8.4 11.3 14.3 15.6 19.5 17.1 21.8 23.0	10.7 20.9 30.8 40.5 44.8 46.3 49.5 50.4 50.6
1.3	SP-31 (18^{0}45′51″N, 79^{0}33′32″E)	450 m 4 days	88.5-130.0 133.0-212.0 215.0-279.5 281.0-300.0 320.0-390.0 390.0-430.0 430.0-450.0	8.9 15.2 15.8 21.8 17.6 19.7 20.4	25.4 36.5 44.8 50.6 50.0 50.5 50.5
1.4	SP-37 (18^{0}48′48″N, 79^{0}33′49″E)	300 m 2 days	131.5-160.0 173.5-195.0 230.0-260.0 260.0-300.0	8.5 11.6 15.2 21.3	24.1 32.9 38.0 40.0
1.5	SP-43 (18^{0}48′28″N, 79^{0}33′49″E)	280 m 3days	96.0-127.0 127.0-250.0 250.0-280.0	9.0 12.2 14.9	25.5 32.3 39.5
1.6	SP-40 (18^{0}49′14″N, 79^{0}32′43″E)	170 m 8days	120.0-150.0 150.0-170.0	11.1 14.8	30.2 30.2
1.7	SP-35 (18^{0}47′48″N, 79^{0}33′51″E)	150 m 10 days	70.0-107.0 110.0-146.0	6.29 9.90	17.8 28.0
2.	Godavarikhani (18^{0}40.2′N, 79^{0}30′E)	540 m 5 days	280.0-320.0 320.0-360.0 360.0-400.0 400.0-440.0 440.0-480.0 480.0-520.0	- - - - - -	42.0 50.0 51.0 42.0 52.0 52.0
3.	Bellampalli (19^{0}12′N, 79^{0}25′E)				
3.1	GB 2	440 m 3 days	190.0-240.0 280.0-360.0 380.0-440.0	12.76 16.19 25.13	41.4 42.7 48.8
3.2	BH 29	180 m 14 months	110.0-180.0	15.79	42.0
3.3	BH 52	310 m 8 days	100.0-150.0 150.0-200.0	16.56 20.60	44.0 48.6
4.0	Chelpur,GC.15 (18^{0}23′N, 79^{0}55′E	230 m 36 hours	120.0-170.0 170.0-230.0	13.83 17.85	46.8 52.3
5.	Venkatpur,GV.5 (18^{0}15.5′N, 80^{0}02′E,	180 m 30 days	130.0-150.0	15.56	54
6.	Pasra (18^{0}13′N, 80^{0}10.5E)	250 m 7days	110.0-180.0 180.0-250.0	19.28 26.14	65 84
7.	Mailaram (17^{0}43′N, 80^{0}37′E)	285 m (inclined) 36 hours	138.0-216.0	14.7	46

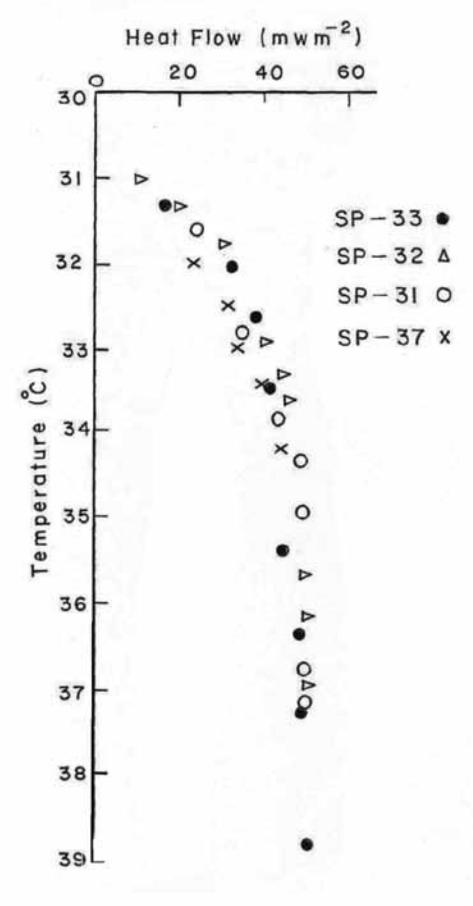

Figure 2. Heat flow v/s temperature in boreholes, Indaram area of Godavari Sub-basin, India.

The heat flow data, based on the arguments presented above, can be separated in to two categories (i) those influenced by downward ground water movement and those (ii) more or less undisturbed by its influence. The data from the first four shallow boreholes SP-35, 37, 40 and 43, mainly fall in the first category. The data from the boreholes SP-31, 32 and 33 fall in both the above mentioned categories. The magnitude of heat flow is more or less uniform at deeper depth intervals, with an average value of 50 ± 10% mWm^{-2}, which can be taken as the magnitude of the conductive heat flow for the Indaram area.

It is worth noting that in the GSB the relief of the water table is low, as indicated by the small values of hydraulic gradients. Considerable anisotropic permeability occurs on a regional scale and small aquifers are mostly bounded by highly impervious layers of coal and shales etc. These facts when considered together even for two and three dimensional cases as modelled by Smith and Chapman (1983) and Woodbury and Smith (1985), point out that the hydro-geological perturbations to the heat flow in the lower depth intervals of the boreholes SP-31, 32, and 33 are negligibly small.

Heat Flow at Godavarikhani Area

The logic as outlined for Indaram area and the knowledge gained has been used to analyse the thermal data for Godavarikhani and Bellampalli areas. Thermal logging data from a borehole to a depth of 540 m is available for Godavarikhani (Table - 1). Heat flow values (Q) as calculated, using measured thermal conductivity data (Rao et al.,1970), in small depth sections of 40m intervals are given in table 1. The values show a general increasing trend with depth in the magnitude of Q, with a constant value of 52mWm^{-2} between depth intervals from 440 to 520 meters. The Q value is more or less of the same order (~50mWm^{-2}) in an upper depth section from 300-400m depth. There is a dip in the calculated Q value for 400-440 m depth section. The reported litho log of the borehole show a thick section (11m out of 40 m ; ~27.5%) consisting of sandy shale formation. However, in the temperature profile there is no corresponding kink and appropriate increase in the temperature gradient for this depth section. We in view of these facts, ascribe that the decrease in heat flow value between 400-440m depth is not real. It is the result of an error caused due to the poor control on the

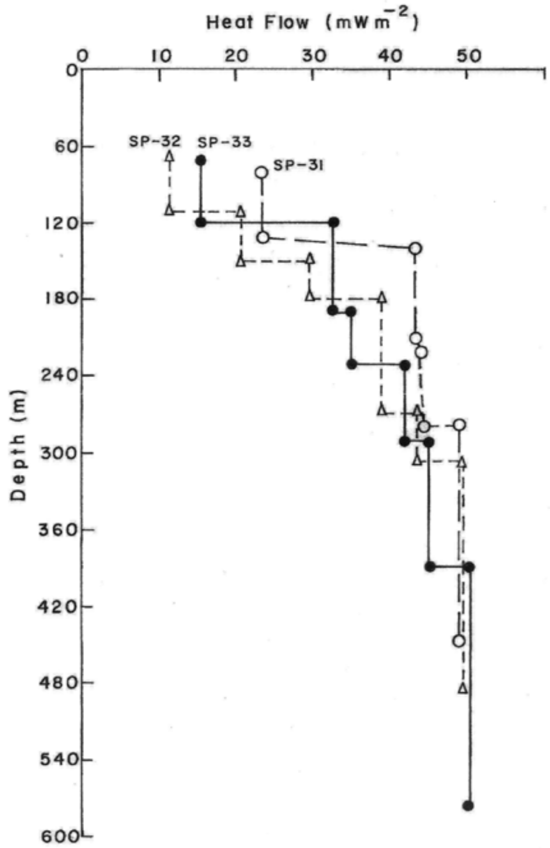

Figure 3. Heat flow v/s depth in boreholes, Indaram area of Godavari Sub-basin, India.

thermal conductivity data of the formations encountered in this depth section. The results as discussed above clearly show that the magnitude of conductive heat flow for the Godavarikhani area of the GSB is 52mWm^{-2}.

Heat Flow at Bellampalli:

Heat flow values from one deep and two shallow boreholes are available (Rao et al., 1970; Table - 1) .The data show increase of the magnitude of heat flow with depth. However, the data of boreholes 52 and GB -2 show values of same order (~49 mWm^{-2}) after encountering zones where sledge, clay stone, shales and coal, (semi- impermeable and impermeable (?) formations) occur together with sand stones. Keeping in view , the analysis of the thermal data of Indaram, the heat flow values (as obtained for depth intervals, 150-200 m for borehole 52 and 380-440 m for GB-2), most probably represent the true conductive heat flow (49 mWm^{-2}) for Bellampalli.

Heat Flow Data of the Southern Part of the Godavari Sub-basin

Four heat flow values are available in this part of the basin (Figure -1, Table - 1). Out of these one value of magnitude 46 mWm^{-2} is at Mailaram, which is a site located towards the SE corner of the sub-basin on an Archaean outcrop as a basement high, and the other three values are near the western margin of the southern part of the GSB in Gondwana sediments at Chelpur, Venkatpur and Pasra. These three values are from shallow bore holes (maximum depth up to 250m) and show a wide range of values varying from 52 mWm^{-2} to 84 mWm^{-2} (Rao et al., 1970).

DISCUSSION AND CONCLUSION

The GSB is considered as a graben/ half graben developed on Proterozoic platform of Indian shield during Permo-Carboniferous period. The measured temperature data and calculated heat flow values in six sites have been examined for hydro geological perturbations.

The upper sub-surface sedimentary strata below the heat flow sites consists of mainly of loose sandstone at the top followed by layers of sandstone, shale ,clay, clay stone, coal and their combinations. In such formations, overall permeability of the subsurface layers, due to occurrences of successions of permeable, semi-impermeable and impermeable (?) layers are likely to get reduced to more or less zero at certain deep depths.

Analysis of data of temperature logs, calculated heat

Table 2. Surface Heat Flow Data from nearby regions of Godavari Sub- Basin, India.

S.No	Area	Co-ordinates Lat(N),Long(E),	Depth Range, m	Temperature Gradient, mKm^{-1}	Heat Flow, MWm^{-2}	Reference
1.	Chandrapur basin					
1.1	Agarzari	$20^0$04.31′N, $79^0$19.5′E	130-220	16.5 to 21.3	50	Gupta,**1993**
1.2	Durgapur	$19^0$58.7′N, $79^0$20.7′E	70-250	13.0 to 16.0	52	-----do-----
2.	Bastar Craton					
2.1	Malanj- Khand	22°01′33″N, 80°43′33″E				Gupta et al.,1993
		MDN-1	281-651	16.0	54	
		MDL-4	241-433	15.3	51	
		MDL-7	172-422	15.3	52 **Av.=52±2.1**	
2.2	Mogra	21°10′42″N, 80°04′00″E MGH-18	170-248	13.5	52	-----do-----
2.3	Bodal	20°30′4″N, 80°45′57″E BDL 168 BDL 169 PL --1	206-530 203-643 151-198	23.8 23.8 23.1	67 63 63 **Av.=64**	-----do-----
3.	Peninsular Gneiss					
3.1	Hyderabad	17°25′02″N, 78°33′11″,E NGRI-1	90-115 125-160	11.2 11.1	38 37.8	Gupta et al., 1987
3.2	Jedimetla	17°30′52″N, 78°28′40″E WDS-1	30-210	12.9	44.0	-----do-----
3.3	Vikarabad	17°18′26″N, 78°08′40″E VK-1	30-65	10.9	37	------do-----
4.0	Deccan Trap region					
4.1	Yavatmal 3 locations	~ 20°N, ~ 78°E	144 to 192	24.0 to 41.7	49 to 66, Av=52	Roy ,2008
4.2	Wardha area 4 locations	~21°N, ~78°E	192-204	29.1 to 43.1	48 to 71 Av = 62	----do------

flow values in discrete intervals, plots of heat flow vs. temperature (Figure -2) and heat flow vs. depth (Figure -3) from closely spaced seven bore holes at Indaram, has resulted in fixing the probable depth range (~ 300m), which is not influenced by ground water circulation. From that depth range downwards, the convective heat transfer gets reduced to more or less zero .As such, one can safely conclude that below that depth range the heat transfer is due to conduction alone. Lateral flow of sub-surface water in such deep layers naturally becomes insignificant. The near uniformity of the obtained heat flow values for the region confirms the efficacy of the present study in resolving heat transfer-water circulation connectivity, with depth. CHF values of more or less of constant magnitude ~50mWm^{-2} have been obtained from data of three deep boreholes SP-33, SP-32 and SP-31, for the Indaram area (Table -1).The knowledge gained from the processing of the Indaram heat flow data has been used to analyse the data of the other two locations viz, Bellampalli and Godavarikhani of the NW part of GSB also. The CHF values for these two locations are 49 mWm^{-2} and 52 mWm^{-2}, respectively. We infer that the NW part of the GSB is characterised with more or less uniform conductive heat flow values around 50 mWm $^{-2}$ (Table - 1).

The available heat flow data of the SW part, which are from shallow bore holes (maximum depth~ 250 m) show large variations (47 to 84 mW m $^{-2}$; Table -1) .The values at Chelpur and Pasra show increasing magnitude of heat flow (Q) with depth. The magnitude of Q between depth interval of 180-250 m at Pasra is (84 mW m^{-2}) significantly higher than at Chelpur (Q = 52.3 mW m $^{-2}$, at a depth interval of 170-230 m). These two heat flow sites are located within an area of ~65 sq km (Rao et al., 1970). Such a significant variation in deep CHF, considering the geotectonics of the area, most likely, is caused by hydro geological perturbations, as these two Q values along with that of Venkatpur lie very close to parallel strike- slip boundary faults in the region.

The CHF of ~50mWm^{-2} in the NW part of the GSB imply, i) absence of a cooling crustal intrusive body below it, and ii) absence of a shallow Moho. Available geo-data of the GSB/PGV, as outlined later extend support to such inferences.

Distribution of surface heat flow in a sedimentary basin is of very complex nature and is controlled by many factors, including crustal structure, composition and other parameters of the basin. The Godavari rift, as suggested by Qureshy et al. (1968) developed along a zone of weakness inherited from the Archaean progenies. Khatri (1994) demonstrates the existence of Block Tectonics in many regions of the Indian Shield including Godavari graben where a major strike-slip fault exists in NW-SW direction. According to Mishra et al. (1987) parallel strike-slip fault system (PSSFS) on the western margin and a deep seated fault north of Bhadrachalam along the Mailaram 'high' do occur in the PGV. The PSSFS of the PGV might have developed and reactivated also in response to continued convergence between India and Asia (Rao, 2002). Intraplate stresses often reactivate old strike-slip faults and propagate them laterally and vertically into unfractured rocks (Woodcock and Schubert, 1994). These faults seem to play a very important role in controlling the various geo-properties and processes , including the large variations observed in the magnitude of surface heat flow at certain parts of GSB and the formation and manifestation of thermal and cold water springs occurring north of Mailaram 'high' and also its shallow seismic activity .However ,it is very likely that in certain parts of a sedimentary basin favourable geo-structures occur where the thermal regime is perturbed by water movement at shallow depths and unperturbed at deeper depths. It is the case with the north-western sector of GSB, where heat flow values free from geo-hydrological perturbations, representing the magnitude of the true conductive heat flow (49 - 52 mWm^{-2}) could be determined.

Numerous low temperature (29 °C TO 44 °C) springs occur in a small area (17° 56′- 18° 08′ Lat. x 80° 39′ - 80°45′ Long.), south eastern part of the GSB, since ancient times. These emerge through fissures and joints in Kamthi (Lower Gondwana) sandstones and conglomerates close to Kamthi Vindhyan boundary. Thermal waters of temperature 33-39 ^{0}C have been encountered in some exploratory boreholes drilled for coal and ground water and also inside the Mangru Coal Mines (17° 55′ 45″ N, 80° 44′ 25″ E).

Studies of the chemical analysis of thermal and cold waters collected from this part of the GSB from , i) two known thermal springs (temp 44 - 41°C) near Buga village, ii) five cold water springs (Temp. 30 - 29 °C) ,iii) two bore holes drilled for coal at Pagadaru (where water flowed out at a temperature of 39 °C from a depth of 244 m in one bore hole and at a temperature of 33 °C from a depth of 214 m in an another bore hole) and iv) also of hot water that was oozing out in Mangru coal mines at depths around 180 m (have been reported by Saxena and Gupta (1982, 1985). Saxena and Gupta inferred a) that the thermal waters (TW) of the GSB are more or less of similar chemical character and have low concentrations of dissolved solids and are associated with sedimentary rocks, b) these water are formed due to circulation of the meteoric water to appropriate shallow depths and thereby get heated up to moderate temperatures around 80-90 °C (estimated reservoir temperature), and c) Presence of high concentrations of Mg and Mg/Ca ratio in these waters point out that these are not associated with high temperature rocks .We conclude that most probably these waters draw the heat from non-magmatic sources .

The quantitative analysis of the gases collected from the above mentioned thermal systems of GSB, as carried out by gas chromatograph (Saxena,1987) has also shown the meteoric origin of these thermal waters.

The above mentioned thermal manifestations of GSB occur north of Mailaram High, which is a large outcrop of Archaean-Proterozoic group of rocks in the SE sector of

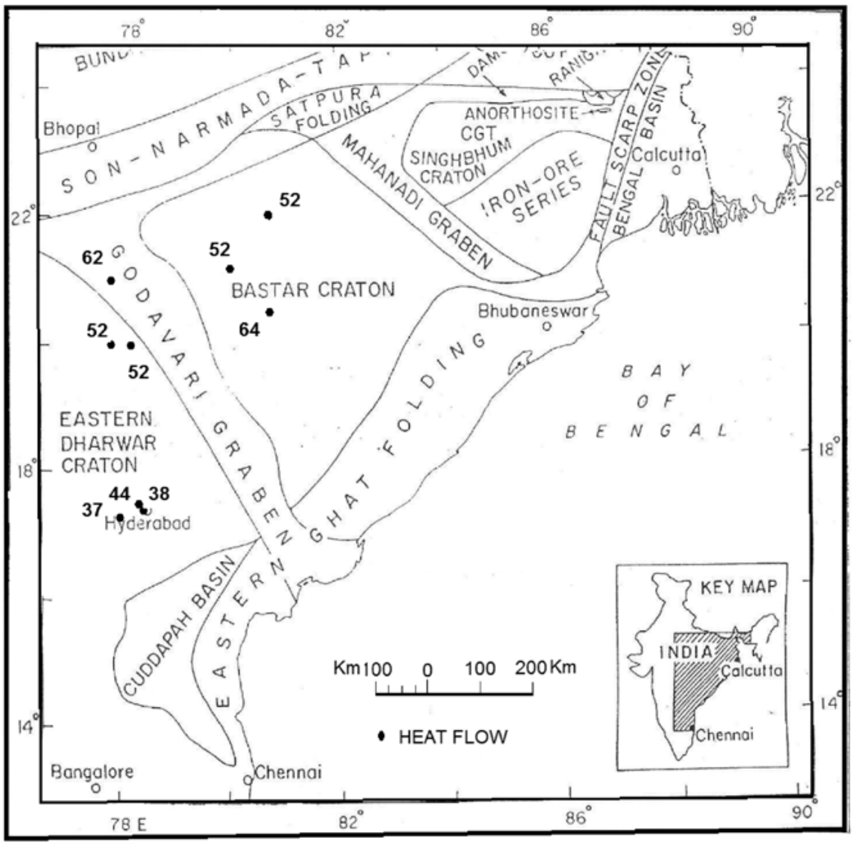

Figure 4. Heat flow values in some surrounding regions of Godavari Sub-basin, India.

the GSB. The chemical analysis of thermal waters of this area shows the same inferences as of GSB (Saxena and Gupta (1982, 1985). One measured heat flow value of 46 mWm^{-2} has been reported in Mailaram (Rao et al., 1970).

Based on P-receiver function studies, Singh et al., (2012) have reported occurrence of a thickened crust (38.7 and 41.2 km) as estimated for the two stations of GSB , and a faster (mafic) lower crust along with a weak Moho within the Godavari rift. The mafic lower crust has been inferred due to mafic under plating within the crust from the mantle during the extensive phase of rift formation, there by supporting the studies of Biswas (2003) that the Godavari rift does not show evidence for igneous intrusions and the inference of Mahadevan (2007) that the evolution of Indian Gondwana basins remained passive unattended by any magmatic episodes, until the culmination of the basin development. Based on gravity and magnetic studies, Sarma and Krishna Rao (2005) inferred absence of basic bodies in the sediments of GSB. Rao (2002) has advocated that the Godavari rift is a non-volcanic passive rift which has been frequently reactivated by compressive and external events.

A comparison of the magnitude of conductive heat flow of GSB with heat flow values from its surrounding provinces and sub-provinces of the Peninsular India (Table - 2, Figure - 4) have been made. We noticed that the average heat flow values in the NW sector of GSB , and in the Chandrapur sub-basin of PGV and also in Wardha Valley-Yavatmal area are of the same order (Table -1 and 2, Figure - 4). Wardha is one of the tributaries of Pranhita River, which is a tributary of Godavari River. According to Mall et al. (2002) the Gondwana sediments, which occur below the Deccan Traps in the Wardha Valley could be the extension of Pranhita- Godavari Gondwana rocks.

The GSB is situated at the tectonic join between the Proterozoic Bastar, (also called as Bhandara) Craton (which lies towards NE of GSB) and the Archaean Early Proterozoic Eastern Dharwar Craton (EDC) (which lies towards SW of GSB).

The average heat flow value from sufficiently deep bore holes in Bastar Craton is 56 mWm^{-2} (Gupta et al., 1987) , which is of the same order as in the northern part of GSB. The average heat flow in EDC is 40mWm^{-2} (Gupta et al., 1991; Gupta, 1995, 2012). Heat flow in GSB is higher than in the EDC. The magnitude of the unperturbed heat flow (conductive heat flow) of the GSB (49-52 mWm^{-2}) determined at three sites in the NW part is of the same order as of Proterozoic terrains of Indian and various other Shields (Nyblade and Pollack, 1993).

Based on the above discussion, we infer that the magnitude of deep conductive heat flow in three NW locations of GSB and the one at Mailaram do not suggest the presence of a deep heat flow anomaly in the GSB region .This result/ observation provides, thereby, a strong support to the inference that there is absence of igneous intrusions in the GSB.

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