GEOTHERMAL FIELDS OF INDIA: A LATEST UPDATE

O.P. PANDEY and J.G. NEGI

Theoretical Geophysics Group
National Geophysical Research Institute
Uppal Road, Hyderebad 500 007 (India)

Key words: India, Intermediate temperatures. Tatapani, Puga, Heat flow. Thermal springs.

Abstract:
In a global tectonic context. India is not particularly well placed as far as geothermal energy is concerned. However, due to the anomalous nature of some segments of ita lithosphere, it does contain **a** number of geothermal areas with temperatures in the range of 30°C to 100°C. Most of them **are** of intermediate temperature type and **occur** along certain tectonic boundaries. The Moho boundary and asthenosphere at some of these places **are** shallow and associated with high sub-crustal heat flow and temperature gradients. The most promising geothermal areas include (1) Puga-Chhumathang, Manikaran. Tapoban etc. in NW Himalaya, (ii) Konkan, Cambay and Bombay offshore, (iii) Tatapani **(M.P.)**, **(iv)** Gondwanic grabens, and (v) volcanic areas of Andaman-Nicobar chain. Deep seated reservoir temperature are reported to be between 100°C and 250°C. Total geothermal power potential, as assessed by a number of geoscience organisations, is of the order of 2000 MW to 10,000 MW. However. proper infrastructure has to be built to commence power generation **on** a commercial basis. Presently, attempts are being made to install **experimental** power plants of 20 KW to 1 MW capacity at a feu locations. India's new emphasis on multi-dimensional development of non-conventional energy in an open economy, for the growing energy needs of 900 million people, may accelerate rapid utilisation of available geothermal fields.

1. INTRODUCTION

The Indian subcontinent and its adjacent offshore region form one of the most interesting areas of the colliding plate **zones**, containing diversified **geological** units varying in **age** from Quaternary to early Archeans. It is the only continent which **has** travelled a distance of about 9000 km within **a** short span of less than 50 Ma during the post-Pangea break-up period. Scars of the long journey are reflected in the form of a degenerated lithosphere (Pandey and Negi, 1987). particularly along the western margin. First. along this margin, continental breakup of Madagascar occured about 80 Ma before present. it was followed by break-up of the Seychelles Island from India at about 65 Ma, when world's largest flood volcanic eruption **(Decca"** Traps) took place. India is the only continent which **came** into contact in its journey with four hot spots (Kerguelen, Reunion. Marion and Crozet) between 117 Ma and 65 **Ma** after its break-off from Antarctica (Raval, 1993). It is thus not surprising that Indian subcontinent became much warmer, thinner, relatively **non** rigid and less viscous compared **to** other continental lithospheres (Negi et al., 1986). It is not seismically stable and in large parts, uplifting and vertical crustal motion are still taking place. **The** above mentioned factors have contributed to the formation of geothermal areas in India.

Traditionally, geothermal resources occur world wide along plate boundaries, young orogenic areas and volcanic belts associated with active subduction like New Zealand, Japan. Mexico, Indonesia etc. However, due to the warmness of the thermal lithosphere, India does contain large number of promising geothermal areas. In fact, there are almost more than 300 **known** thermal springs in the country (Figure 1). The Indian continent also contains number of high heat flow **areas** (Figure 2). Many thermal spring localities **are** situated **over** plutonic intrusions, volcanic paleo-channels. areas of recent crustal movements and hydrothermal convective systems. They contain abundant quantities of thermal/gaseous fluids and thus **have** the potential for geothermal energy exploitation. Some thermal springs may **have** deep reservoir temperatures beyond 200-250°C. The **paper** presents the latest update on geothermal energy scene in India and provides suggestions for future work.

2. DISTRIBUTION AND STUDY OF GEOTHERMAL SIGNATURES

Thermal springs of the Indian subcontinent (temperature **range** of about 30°C to 100°C), occur in groups along certain major tectonic trends, plate boundaries, continental margins and rifted structures (Figure 1). These springs are mostly of nonvolcanic type and thus, form intermediate to low grade exploitable resources. Geotectonically, they could be grouped in the following broad regions:

(i) **NW-SE** Himalayan **arc** system with continuation to Andaman Nicobar Island,
(ii) Son-Narmada-Tapti lineament and its surroundings.
(iii) West **coast** continental margin end adjacent regions,
(iv) Parts of Gondwana grabens, and
(v) Regions of Delhi folding.

Detailed research and exploration programs to **assess** the geothermal potential of the country were started mainly after 1973-74, by various organisatians, more particularly, the Geological Survey of India and the National Geophysical Research Institute (NGRI), Hyderabad. They collected significant amount of geothermal data. Presently, the exploration work is being continued mainly by the central and northern divisions of the Geological Survey of India. Geological, geophysical, geochemical and geohydrological exploration studies **were** followed by exploratory drilling of **bore** holes at a number of potential thermal zones to **assess** possible **power** generation. It is estimated that the total geothermal resources of the country could provide 2000 MW to 10,000 MW of electricity. These estimates are tentative and appear to be on the high side and need confirmation through deep geophysical exploration and drilling. As **a** matter of fact. India is at the experimental stage of power generation. The present paper has drawn substantial information

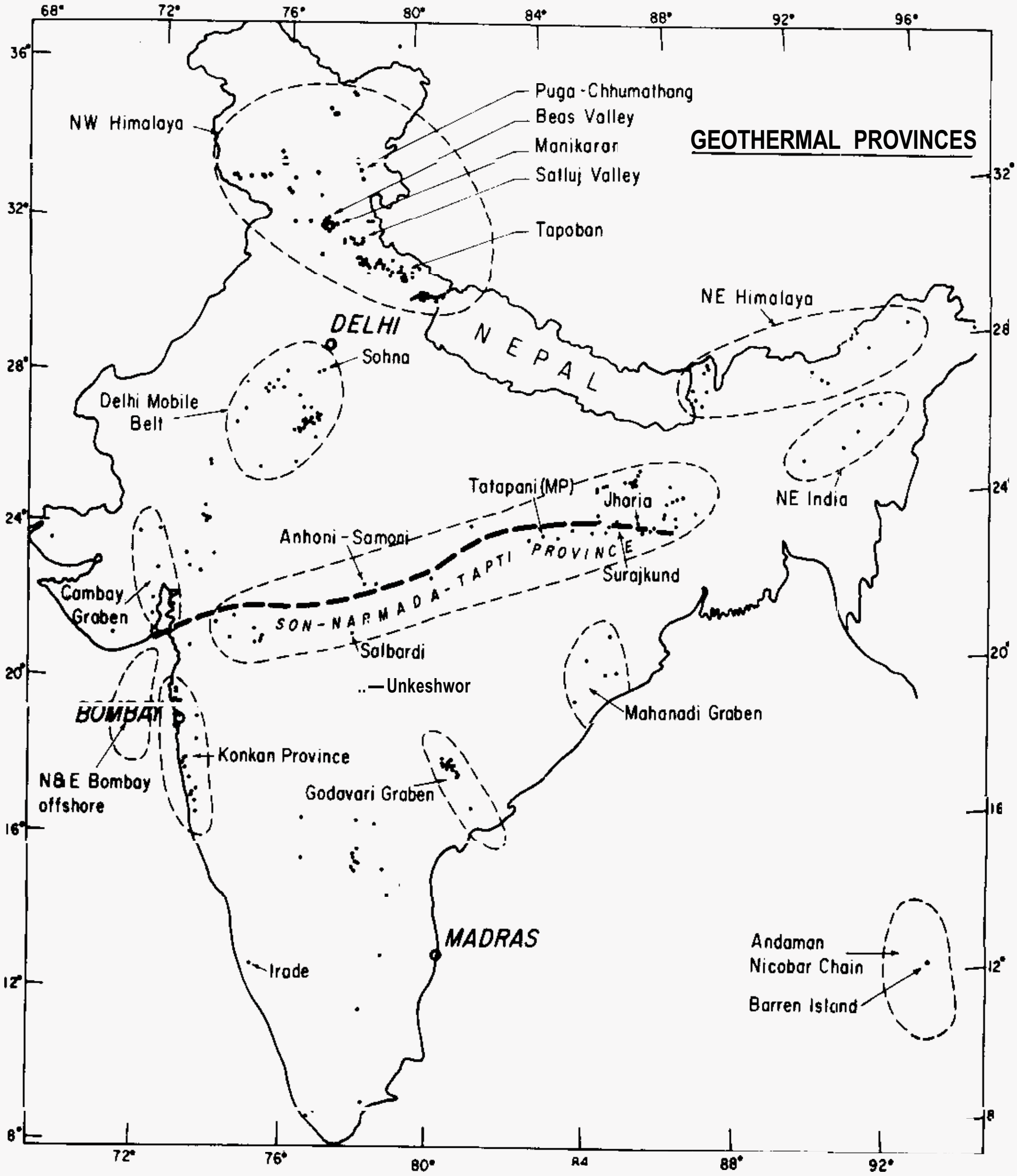

Figure 1: Geothermal provinces of India. as deduced by geotectonic. geothermal and terrestrial heat flaw data. Distribution of thermal spring localities (as listed in Ravi Shanker et al., 1991) are shown by solid dots. Son-Narmada-Tapti lineament is represented by thick broken line.

from excellent recent reviews on geothermal resources by Gupta (1992, 1994), Gupta et al. (1988). Karve (1994), Pitale (1994), Ravi Shanker et al. (1991), Sarolkar (1994) and Sharma (1993, 1994) etc.

3. TERRESTRIAL HEAT FLOW

In many instances, conductive heat transmission from the earth's interior plays an important role in the formation of potential geothermal fields. Its magnitude and distribution gives us a direct measure of the thermal state of the lithospshere. In India, systematic heat flow measurements were started in the early 1960s by NGRI, Hyderabad. Presently. there are altogether about 100 hear flow measurements. They vary from 26 to 107mW/m , indicating presence of large scale subsurface inhomogeneities. Heat flow is particularly high in the certain parts of (i) Cambay graben, (ii) Bombay offshore region, (iii) Konkan geothermal province, (iv) Narmada-Son lineament, (v) Jharia coal field, (vi) Godavari valley, and (vii) Aravalli mobile belt. Interestingly. in these areas, the asthenosphere lies et shallow depths of 30 to 75 km (Negi et al., 1987). The regional distribution of heat flow is shown in the heat flow map of India (Figure 2).

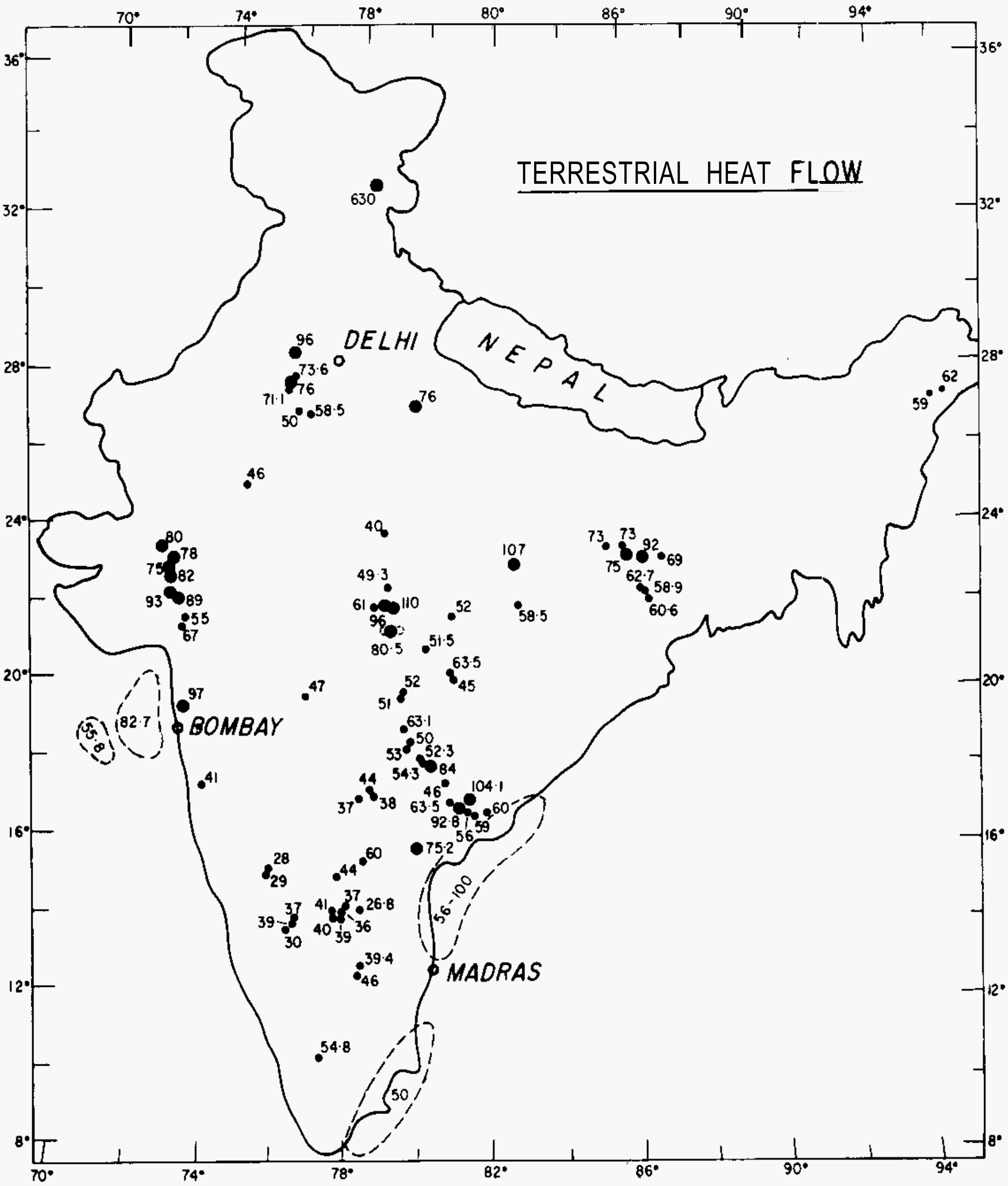

Figure 2: Distribution of terrestrial heat flow values (mW/m^2) in India based on data collected from various sources. large solid dots indicate high heat flow values while low to normal values are indicated by small dots.

4. POTENTIAL GEOTHERMAL FIELDS

4.1. Himalayan Province

This region contains a large number of hot springs (numbering more than 100), situated mainly in the NW Himalayan region. near the Indo-Eurasian plate boundary. Temperatures in some of the springs reach the boiling point. These regions have been extensively surveyed and exploration work is almost complete (Ravi Shanker, 1991). The details of different areas are as follows:

Puga-Chhumathang area

This area is situated about 180 km ESE of Leh in the Ladakh district of the state of Jammu and Kashmir. Magmatic/granitic intrusive activity during last few million years have been the sources of thermal energy. There are a number of connected primary and secondary faults which govern movement of thermal waters at several places. The Hottest thermal spring at Puga shows a temperature of about 84°C and at Chhumathang about 87°C. Here, temperature gradients exceed 100°C/km. In some depth sections, temperature gradients reverse for short distances but reach as high as 7°C/m at Chhumathang and 5.8°C/m at Puga (Figure 3A). Maximum discharge from a single spring is about 15 litls.

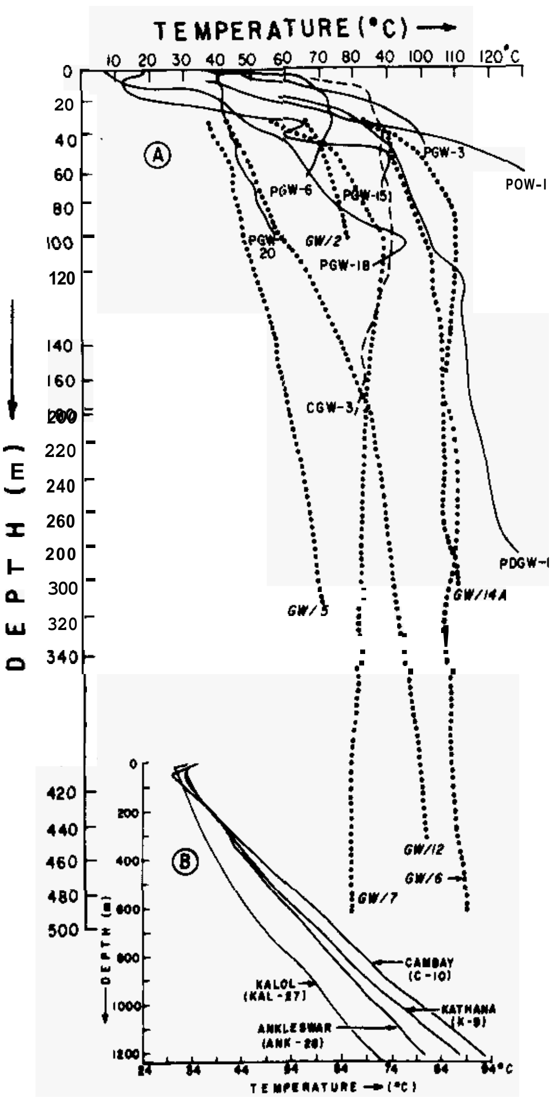

Figure 3: Temperature-depth profiles in Puga (PGW - 1, 3, 6, 15, 18, 20; PDGW - 1). Chhumathang (CGW - 3) and Tatapani, M.P. (GW - 2, 4A, 5, 6, 7, 12) geothermal wells (figure A) and some areas of Cambay graben (Figure B). Data source for respective figures are Ravi Shanker et al. (1991) and Gupta and Rao (1970).

In the Puga region, all thermal manifestations are confined to the eastern part of the valley in an area of about 4 sq km where the hot thermal zone is characterised by low resistivity of about 5-30 ohm m. Based on magnetatelluric recordings, two dimensional resistivity structure of the Puga field has recently been delineated (Singh and Nabetani, 1995). The survey confirms the presence of a low resistivity zone, possibly representing a geothermal reservoir situated between 1 and 3 km depth. Large numbers of drill holes (about 34) have been drilled reaching a maximum depth of 385 m. Some drill holes yield steam (10-15%) at a temperature around 140°C and pressure of 2-3 kg/cm^2. Some wells discharge water-steam mixture at 125°C. The Maximum discharge reported from a single hole is about 30 tonnes/hr. Metallic ion analysis of the gas from Puga borehole GW23 indiates large concentration of Cu, Zn and Cs. The concentration of Cs in thermal spring deposits are of the order of 750 to 1800 ppm (Sharma, 1994). At a deeper level, reservoir temperatures are estimated to be between 180°C and 260°C. Geothermally formed epidote in borehole PDGW1 substantiate this view. The estimated heat flaw in the Puga region is 630 mW/m^2 (Gupta et al., 1988).

In Chhumathang, the thermal region is mainly spread over the right bank of Indus river where several thermal springs emit H_2S bearing hat water. Six bore holes, to a depth of 221 m, have been drilled here. Most of them discharge a water-steam mixture mixture with a maximum temperature of 109°C. The reservoir temperature is between 160°C and 200°C.

Beas and Parbati Valleys

These areas are situated in the Kulu region of Himachal Pradesh. There are 8 thermal springs in the Beas valley where the main activity is distributed on both sides of the river. Thermal manifestations extend for about 70 km with temperatures in the range of 30°C to 57°C. 18 boreholes (50 - 500 m) are drilled here. All drill holes along the river bed indicate thermal artesian conditions at shallow depths. Maximum discharge from a borehole is about 350 lit/minute at 36°C. The reservoir temperature estimates are around 140 ± 20°C at deeper levels. based on chemical and isotope thermometries.

Similarly. a 40 Km area of the Parbati valley contains six thermal springs with a temperature range of 21°C to 90°C. 19 boreholes (57 - 707 m) are drilled here. Manikaran geothermal field is the most promising in the region and covers a linear zone of about 1.5 km. It has been extensively studied. Exploratory drilling at Manikaran reveals lateral flow of hot water and reversal of temperatures at depths. Thermal discharge from drill holes is about 96 tonnes/hr. The temperature of the thermal water discharge from Manikaran bore wells is 86°C to 94°C. The maximum temperature recorded in a bore hale is 101°C. Th reported reservoir temperature is between 186°C and 202°C for Manikaran, 170°C for Jan, 100°C for Kasol and 150°C for Khirganga (Gupta et al., 1979).

Thermal artesian flow in the above regions largely depends on seasonal hydrological cycles. Analysis of gas samples reveal the dominance of CO_2. Age of the Manikaran water is calculated to be 11000 yr based on carbon-14 dating (Sharma, 1994).

Satluj and Spiti valley

This region of Himachal Pradesh contains 12 thermal localities where temperatures vary from 23°C to 73°C, the hottest spring being at Tapri where thermal water is of NaCl type. Five exploratory bore holes were drilled to a maximum depth of 183 m. Significant thermal manifestations occur at Chuza-Sumdo (23-59°C) and Tatapani (32-61°C). The highest discharge from a single spring is 3.3 lit/s. The base temperature, as deduced from NaKCa and Silica thermometries, range from 110°C to 212°C.

Tapoban region

Tapoban area lie8 in the Alaknanda valley of the Chamoli district (U.P.) and contains about a dozen springs with the highest temperature being 65°C. Five shallow (50 - 52 m) and 4 medium depth (291 - 728 m) bore holes are drilled here during 1975-1990. Two drilled holes (291 and 431 m deep) discharge thermal fluids (11-13 lit/s) at a temperature of 80°C to 90°C. However, another deep borehole discharges hot water (16 lit/s) with a lower temperature of 63°C and pressure of 7 kg/cm^2. The estimated reservoir temperature is 180 ± 20°C. Young acid magmatic intrusions are expected here. No reversal of temperature **curve** with depth is noted here upto about **Mom.** Chemically, the thermal water is of $CaMgHCO_3$ type, with tritium values ranging from 21 to 27.4. The gaseous emanations are predominantly composed of CO_2 (Sharma. 1994).

Other localities

There are several other spring **areas** in the NW Himalayan region. At least three hot springs are located in the Nubra valley (Ladakh. J & K). Among them, Pananik thermal spring (34" 47', 77' 32') with temperature of 65°C to **76°C,** appears to be most promising. Its cumulative discharge is 600 lit/minute. Expected base temperature is 180°C **(Gyan** Prakash and Aggrawal, 1989). Similarly, **a** few springs are reported from Ravi valley (Chamba District, H.P.). Here, the Awas thermal Spring (58°C) discharges at the rate of 40 litlminute. Further. **a** number of thermal springs ***are*** also located in the Bhagirathi, **Darma** and Madhya Maheshwari valleys of Uttar Pradesh.

Bhagirathi valley (Uttar Kashi District) contains six of them. **Gangnani** thermal spring (30" 54', 78' 41') shows a temperature of 62°C and discharge of 450 lit/minute. This region experienced ***a*** disastrous earthquake in 1991, which significantly affected the thermal activity. Post earthquake geothermal study indicate rise in temperature from 35°C to 45°C at Bhukki thermal spring (30" 52', 78" **39'),** while drop from 50°C to 27°C at Songarh thermal spring **(Sharma,** 1993, 1994). **The** highest temperature spring (80°C) in the Darma valley (Pithauragarh district) is at Dar (30° **04',** 80° 30') which discharges at the rate of 700 lit/minute. Geothermal manifestation in this valley extend for **over** 5 km. The base temperature are expected to be less than 140°C (Sharma, 1993, 1994). In the Madhya Maheshwari valley, thermal springs have **a** maximum temperature of 94°C (Sharma and Absar, 1991).

4.2. **Son-Narmada-Tapti** lineament **and** surroundings

This is one of the most important lineament/rifted Structure of the sub-continent. It **runs across** the country in an almost east-west direction (Figure 1). It has **a** long history of tectonic reactivation. large scale vertical movements and crustal extension associated with magmatism. It Contains 46 known thermal spring areas, the most promising one being those situated at Tatapani and Salbardi. Geothermal activity is strongest at Tatapani. The details are as follows:

Tatapani thermal area

This region is situated in Surguja district of Madhya Pradesh. Strong thermal anomalies,with spring temperatures of **50°C** to 98°C, occur in an area of about 18 km^2 around the Tatapani hot spring. Here, temperature gradients are 81 ± 36°C/km (Figure 3A) while heat flow is 219 ± **87** mW/m^2. The **ares** of thermal anomaly is likely to extend much beyond the known zone. Telluric field studies (Harinarayana et al., 1988), carried out in **a** 150 sq km area, indicate the presence of an anomalous zone extending in ***a*** east-west direction **near** the hot springs. EM Modelling **of** the data indicates the possible presence of **a** conductor *(50* ohm m) (or hat water fracture zone) at **a** depth of about 400 m. A number of bore holes **have** been drilled **here.** GW/Tat - 25 and 26 are the latest holes yielding 200-300 lit/minute of water at about 100°C (Sarolkar, 1994). Bore hole Tat-26 has **a** geyseric discharge. Well testing operations suggest thqt pressure at the bottom may **be** about 32-45 kg/cm . A deep reservoir is likely to occur at a depth **range** of 1 and 3km. It may be ideal **for** the commercial exploitation of **power.** Reservoir **temperatures** at these depths are expected to be 112 ± 30°C at 1 km end **230** ± 40°C at 3 **km.**

Salbardi region

This region includes parts of Betul district of Madhya Pradesh and the Amaravati region of Maharashtra. It is structurally located at the faulted junction of the **Satpura** horst and part of the Tapi-Purna graben. Thermal spring temperatures are much lower here (38-42°C) despite temperature gradient of the order of 65 ± 8°C/km. Reported base temperature is 110°C.

Anhoni - Samoni area

This region is located **along** the southern **part** of the lineament situated in the district of Chhinduara and Hoshangabad (M.P.). Anhoni hot springs, with **a** temperature of 30°C to 42°C, **are** aligned along **a** prominent fracture zone running through the area. A few boreholes to **a** depth of 635 m have been drilled here to study the temperature regime and the rock sequences at depths. Inflsmable **gases** (80% methane) were encountered in borehole ANH-2 (drilled to a depth of 262.1m) (Pitale, 1993). The borehole encountered interlayered basic sills and volcanic tuffs within the Talchir shales and mudstones, underlain by basic intrusive rock. A thick dolerite dike is contemplated below this region. Thermal logging indicates **a** temperature of 53.2°C at surface and 55°C at a depth of 210 m, where reversal of temperature occurs. Bottom hole temperature is 52.3°C. Another bore hole ANH-1 (drilled to a depth of 635.26 m) has free flowing thermal **water** at **a** temperature of 50.5°C. The temperature gradient is reported to be **58'** Clkm in this well.

Unkeshwar

Unkeshwar thermal field is situated 1 **km** south of the **Penganga** river. in the Nanded and Yeotmol district of Maharashtra **(Karve,** 1994). Geothermal activity is in the form of hot springs spread **Over** an area of 10 sq km, with temperatures of 30°C to 42°C. Reported reservoir temperature is about 100°C.

4.3. West **Coast geothermal** province

This is **a** large anomalous. rifted, continental margin of the Indian Peninsula and is associated with one of the world's largest flood volcanic eruption. The region encompasses **a** braod, high heat flow area termed as the west coast thermal anomaly (Negi et al., 1992). The region covers **parts** of the **Cambay** graben, the Bombay offshore and the Konkan coast (Figure 4). A large asteroidal impact appears to have taken place in this region. **near** Bombay offshore, just before **Decca"** volcanism (Negi et al., 1993) and to **have** caused **an** unusual gravity anomaly.

Cambay graben

Cambay is ***one*** of the major oil producing areas of India, containing Tertiary sediments which overlie basic lava flows. The **graben,** crossed by several deep-seated faults, appears to **have** originated due to extensional forces. In connection with oil, this basin **has** been studied extensively with large numbers of deep wells drilled to evaluate end extract hydrocarbons. The Moho in the region lies at an extremely shallow depth of 21 ± 3 km (Singh et al., 1991) beneath which the asthenosphere (~1250°C isotherm) has upwarped to a depth **as** shallow as 40 km. Heat flow is high **(average** 83 mW/m^2) in the northern part of the graben where temperature gradients reach **more** than 70°C/km (Figure 3b) in certain **zones** with a lower temperature of 63°C and pressure of 7 $kgfcm^2$. The estimated reservoir temperature is 180 ± 20°C. Young acid magmatic intrusions are expected here. No reversal of temperature curve with depth is noted here upto about 500m. Chemically, the thermal water is of $CaMgHCO_3$ type, with tritium values ranging from 21 to 27.4. The gaseous emanations are predominantly composed of CO_2 (Sharma. 1994).

Other localities

There are several other Spring areas in the NW Himalayan region. At least three hot springs are located in the Nubra valley (Ladakh, J & K). Among them, Pananik thermal spring (34° 47', 77° 32') with temperature of 65°C to 76°C, appears to be most promising. Its cumulative discharge is 600 lit/minute. Expected base temperature is 180°C (Gyan Prakash and Aggrawal, 1989). Similarly, a few springs are reported from Ravi valley (Chamba District, H.P.). Here. the Awas thermal spring (58°C) discharges at the rate of 40 lit/minute. Further, a number of thermal springs are also located in the Bhagirathi, Darma and Madhya Maheshwari valleys of Uttar Pradesh.

Bhagirathi valley (Uttar Kashi District) contains six of them. Gangnani thermal spring (30" 54'. 78' 41') shows a temperature of 62°C and discharge of 450 lit/minute. This region experienced a disastrous earthquake in 1991. which significantly affected the thermal activity. Post earthquake geothermal study indicate rise in temperature from 35°C to 45°C at Bhukki thermal spring (30° 52', 78" 39'), while drop from 50°C to 27°C at Songarh thermal spring (Sharma, 1993, 1994). The highest temperature spring (80°C) in the Darma valley (Pithauragarh district) is at Dar (30° 04', 80° 30') which discharges at the rate of 700 litlminute. Geothermal manifestation in this valley extend for over 5 km. The base temperature are expected to be less than 140°C (Sharma, 1993, 1994). In the Madhya Maheshwari valley. thermal springs have a maximum temperature of 94°C (Sharma and Absar, 1991).

4.2. Son-Narmada-Tapti lineament and surroundings

This is one of the most important lineament/rifted Structure of the sub-continent. It runs across the country in an almost east-west direction (Figure 1). It has a long history of tectonic reactivation. large scale vertical movements and crustal extension associated with magmatism. It Contains 46 h o w thermal spring areas, the most promising one being those situated at Tatapani and Salbardi. Geothermal activity is strongest at Tatapani. The details are as follows:

Tatapani thermal area

This region is situated in Surguja district of Madhya Pradesh. Strong thermal anomalies,with spring temperatures of 50°C to 98°C, occur in an area of about 18 km^2 around the Tatapani hot spring. Here, temperature gradients are 81 ± 36°C/km (Figure 3A) while heat flow is 219 ± 87 mW/m^2. The ares of thermal anomaly is likely to extend much beyond the known zone. Telluric field studies (Harinarayana et al., 1988), carried out in a 150 sq km area, indicate the presence of an anomalous zone extending in a east-west direction near the hot springs. EM Modelling of the data indicates the possible presence of a conductor (50 ohm m) (or hat water fracture zone) at a depth of about 400 m. A number of bore holes have been drilled here. GW/Tat - 25 and 26 are the latest holes yielding 200-300 lit/minute of water at about 100°C (Sarolkar, 1994). Bore hale Tat-26 has a geyseric discharge. Well testing operations suggest that pressure at the bottom may be about 32-45 $kgfcm^2$. A deep reservoir is likely to occur at a depth range of 1 and 3km. It may be ideal for the commercial exploitation of power. Reservoir temperatures at these depths are expected to be 112 ± 30°C at 1 km and 230 ± 40°C at 3 km.

Salbardi region

This region includes parts of Betul district of Madhya Pradesh and the Amaravati region of Maharashtra. It is structurally located at the faulted junction of the Satpura horst and part of the Tapi-Purna graben. Thermal spring temperatures are much lower here (38-42°C) despite temperature gradient of the order of 65 ± 8°C/km. Reported base temperature is 110°C.

Anhoni - Samoni area

This region is located along the southern part of the lineament situated in the district of Chhinduara and Hoshangabad (M.P.). Anhoni hot springs. with a temperature of 30°C to 42°C, are aligned along a prominent fracture zone running through the area. A few boreholes to a depth of 635 m have been drilled here to study the temperature regime and the rock sequences at depths. Inflamable gases (80% methane) were encountered in borehole ANH-2 (drilled to a depth of 262.1m) (Pitale, 1993). The borehole encountered interlayered basic sills and volcanic tuffs within the Talchir shales and mudstones. underlain by basic intrusive rock. A thick dolerite dike is contemplated below this region. Thermal logging indicates a temperature of 53.2°C at surface and 55°C at a depth of 210 m, where reversal of temperature occurs. Bottom hole temperature is 52.3°C. Another bore hole ANH-1 (drilled to a depth of 635.26 m) has free flowing thermal water at a temperature of 50.5°C. The temperature gradient is reported to be 58° C/km in this well.

Unkeshwar

Unkeshwar thermal field is situated 1 km south of the Penganga river. in the Nanded and Yeotmol district of Maharashtra (Karve, 1994). Geothermal activity is in the form of hot springs spread Over an area of 10 sq km, with temperatures of 30°C to 42°C. Reported reservoir temperature is about 100°C.

4.3. West Coast geothermal province

This is a large anomalous, rifted. continental margin of the Indian Peninsula and is associated with one of the world's largest flood volcanic eruption. The region encompasses a braod. high heat flow area termed as the west coast thermal anomaly (Negi et al., 1992). The region covers parts of the Cambay graben, the Bombay offshore and the Konkan coast (Figure 4). A large asteroidal impact appears to have taken place in this region. near Bombay offshore, just before Deccan volcanism (Negi et al., 1993) and to have caused an unusual gravity anomaly.

Cambay graben

Cambay is one of the major oil producing areas of India, containing Tertiary sediments which overlie basic lava flows. The graben, crossed by several deep-seated faults, appears to have originated due to extensional forces. In connection with oil, this basin has been studied extensively with large numbers of deep wells drilled to evaluate and extract hydrocarbons. The Moho in the region lies at an extremely shallow depth of 21 ± 3 km (Singh et al., 1991) beneath which the asthenosphere (~1250°C isotherm) has upwarped to a depth as shallow as 40 km. Heat flow is high (average 83 mW/m^2) in the northern part of the graben where temperature gradient. reach more than 70°C/km (Figure 3b) in certain zones

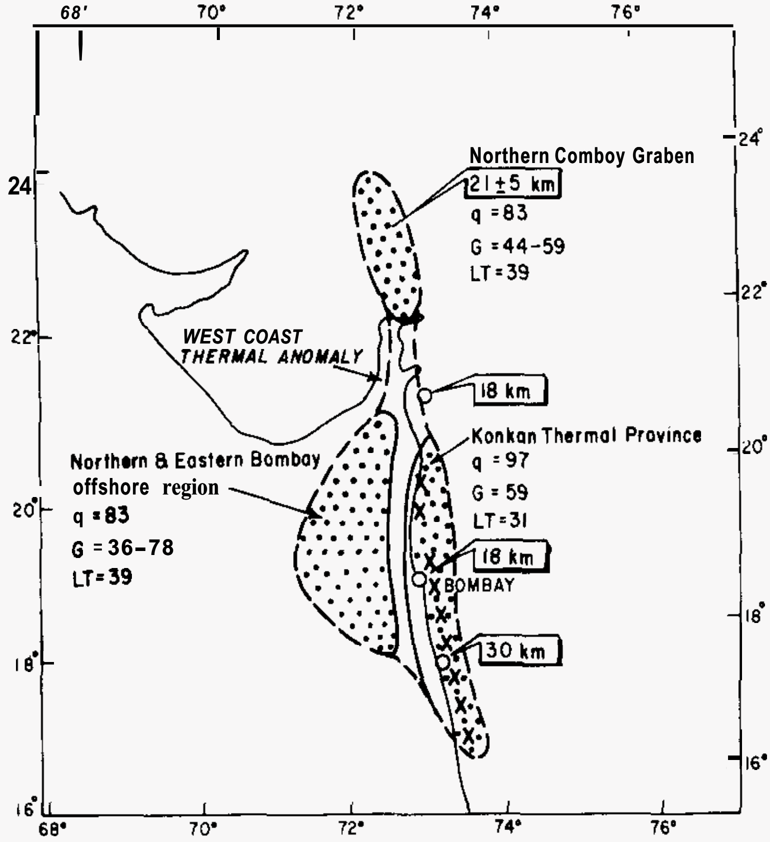

Figure 4: Heat flow (q in mW/m^2),geothermal gradient (G in °C/km) and lithospheric thickness (LT in km) variations beneath the regions of the west coast thermal anomaly zone. Figures in box indicate crustal thickness. Geothermal springs are represented by crosses.

(Gupta, 1981). A large positive gravity anomaly indicates the presence of **a** young basic intrusion (Miocene-Pliocene age) below this region. In the course of drilling, hot water with **stem was** encountered in bore holes Cambay-15 and Kathana-4. Steam discharge **was** estimated to be about 3000 Cu m/day. At 3 km depth. in situ temperatures **are** estimated to be as high as 175 ± 25°C based on drill hole data.

Northern and Eastern Bombay offshore

This is another oil bearing region situated south of the Cambay graben (Figure 4). In this region, **average** heat flow and temperature gradients are about 83 mW/m^2 (Negi **et** al.,1992) and 36 to 78°C/km (Pande et al., 19841 respectively. The *Moho* is extremely shallow (about 20 km) and below it melting conditions occur at around 40 km. The expected temperature at a depth of 3 km **can** be about 175 ± 50°C.

Konkan geothermal province

The konkan region is located in **a** narrow belt between the western ghats and the **west** coast of India. About 60 thermal springs **with** temperatures ranging **from** 34°C to 71°C cluster in 18 localities and extend for a distance of about 300 km (Figure 4). A number of springs border the dolerite dike intrusions. and show close association with tectonic movements. Thermal manifestations are strongest at Unhavre (Khed), where the spring temperature is 71°C and cumulative discharge is 14.5 lit/s.

Telluric and Magnetotelluric (MT) studies carried out in the northern part *of* this region (Harinarayana and Sarma, 1991) indicate **a** prominent telluric current low in **a** N-S direction. Modelling results indicates the presence of two distinct conductors; one at **a** depth of 400 m (20 ohm m resistivity) and another at 1500 m (4 ohm m resistivity). The latter conductor may possibly represent **a** hot water **zone**. Six holes, ranging in depths from 100m to *500* m, **have** been drilled here. In Ganeshpuri, where 4 holes **have** been drilled, the temperatures of the discharge is between 42°C and 59°C. Temperature gradients are 47°C/km **at** Unhavre to 59°C/km at **Tural** and Ganeshpuri. The surface heat flow is estimated at Ganeshpuri to be about 97 mW/m^2 (Gupta et al.. 1988). The reservoir temperatures could be around 110 ± 20°C. The 1250°C isotherm is expected at just above Moho depth.

4.4. **Sohna** thermal region

Sohna thermal area is located in the Gurgaon district of Haryana (Figure 1). Thermal activity is concentrated in **a** tectonic depression formed by down-faulting of **a** central block lying between two anticlinal ridges belonging to the Delhi mobile belt. Neotectonic activities are expected here. Systematic exploration commenced here in 1973-74 and the region is now well explored. Thermal springs have temperatures from 24°C to 46°C. Several boreholes **have** been drilled here to **a** depth of 547 m. The maximum temperature recorded in these bore holes is 55°C. Shallow geothermal surveys indicate large variation in temperature gradients from 30 to 220°C/km. Base temperature is reported to be 100°C.

4.5. Thermal field of Eastern and NB region

There are altogether 51 thermal spring localities with temperature range of 35°C to 88°C in the eastern region provinces of Bihar, Orissa, West Bengal and Sikkim. **So** far, very little exploration work has been done here. Landsat data analysis (Perumal et al.. 1989) suggests that most of the hot springs of the Bihar and West Bengal are located at the intersections or **convergences** of four or more lineaments. **The** hottest temperature (88°C) is found at Surajkund (Hazaribagh, Bihar). Estimated base temperatures in the different thermal spring areas range from 90° to 150°C. Similarly, the NE region (Assam, Meghalaya, Arunachal Pradesh, Nagaland, Manipur. Mizoram end Tripura) also contain **a** number of thermal areas **whose** temperatures vary from 35°C to 54°C. Systematic geophysical **work** is yet to be carried out.

4.6. Southern India

Over 30 thermal spring localities are **known** to occur here. **However,** very little is reported about them except for the springs in the Godavari valley, Agnigundam and Irade (Puttur). Agnigundam spring has **a** surface temperature of 62°C, while the base temperature is indicated to be more than 120°C. Irade also has **a** similar reservoir temperature (120°C).

Godavari graben

The graben is **a** tectonically active **zone** with hydrocarbon and coal-bearing Gondwana formations. Many thermal springs with temperatures ranging from 30°C to 62°C occur here. Artesian hot water conditions are found in some wells. **The** southern part of the graben and its extension into offshore **areas** have been extensively studied in connection with oil exploration. Maxim reported heat flow from the graben is 104 mW/m^2. Temperature gradients are also higher at about **45°C/km** in certain segments of the graben. Thermal water chemistry of the Godavari valley indicate average reservoir temperature of around 100°C to 150°C.

4.7. Damodar valley basins

These coal bearing Gondwanic basins **are** situated in the northeastern part of India and contain **number** of hot springs. Jharia and Ranigunj are the most prominent basins. Thick coal seams are found here. The area is crossed by number of faults. sills and basic intrusions. Hot springs temperatures are up to **80°C,** while reservoir temperature is estimated at 100 ± 20°C (Gupta, 1994). **The** measured **average** heat flow in this basin is 74 mW/m^2 while the temperature gradient at Jharia is about 40°C/km. The 1250°C isotherm is expected at **a** depth of 55 km (Negi et al., 1987). Recent uplift and crustal upwarping has been reported from these coal fields. **The** source of the thermal anomaly is definitely deep. Underground **mine** fires are **common** in various parts of the Jharia coal field. This is **a** potential geothermal region for power generation using suitable technology.

4.8. Andaman-Nicobar region

This island chain in the Bay of Bengal is tectonically active. Thermal effect of continued subduction of the Indian plate can be **seen** in the form of active volcanism. The young volcanism (few years to a million year) is recorded in the Barren and Narcondam islands. High temperatures, steaming ground and thermal spring activity are found at Barren Island. Multidisciplinary study in this Island **was** carried out in 1992 after the volcanic eruptions of 1991. Fumarolic discharge is found to have **a** temperature of 100°C to **more** than 500°C. **Some** gas samples from this discharge show high concentration of Na. Ag. Cs, Li. Rb and Zn (Sharma, 1993). Magma chamber appeared to be situated at a **very** shallow depth to the vest of the Island. Base of the crater may **have** a temperature of 500°C (Absar et al., 1993). This region has geotectonic similarity to the Taupo Volcanic Zone of New Zealand and thus could turn out to be one of the **most** promising exploitable thermal fields. Detailed exploration work is recommended.

5. BNERGI ASSESSMENT AND EXPLOITATION

Since the late 1960s, **a** number of organisations, particularly the Geological Survey of India and NGRI, explored promising geothermal regions with the sole aim of power production. **As** per Gupta (1994), total **stored** heat potential **in** India is about 40 X 10^{18} cal, which is equivalent to 27.6 billion barrels of petroleum. Other studies **have** estimated **power** potential from thermal areas to be of the order of 2000 MW (Gupta. 1992, 1994) to even 10,000 MW (Ravishanker et el., 1991). These are only preliminary estimates and need to be verified through deep exploration and assessment programmes.

As **a** matter of fact, Indian performance to date has been very dismal as far as power production from geothermal area is concerned. Although some serious attempts have been made, commercially, **we** are still not producing power. **For** example, **a** 5 KW geothermal binary cycle pilot power plant has been successfully test run to its optimum capacity in September. 1992 at the Manikaran geothermal area. It utilised the discharge from boreholes MGW-2 and 8. Further **a** binary cycle **power** plant of **20 KW** is planned for the Tatapani field (M.P.) and of 1 MW for the Puga valley in Ladakh. Recently. it has been decided to utilise thermal discharge from **AGW-6** drillhole (700 lit/minute at 68.5°C) at Tapoban for green house forming (Sharma, 1994). An attempt has also being made to find gold in geothermal discharges of Badrinath, Tapoban and Gangnani thermal springs, but the concentration was found to be less than 100 ppt (Sharma. 1993).

The primary reason for the indifference to the geothermal power appears to be the abundant availability of traditional **resources.** Even presently. only coal based power plants (to some extent wind power also) **are** being encouraged to meet the increasing power demands, using private sector participation. The **main** handicap, however. could be the intermediate to low grade potential of our geothermal resources. We really cannot compare **our** **resources** with those of the geothermally **success**ful countries like New Zealand, U.S.A., Italy. Mexico and Japan etc. What **we** could do is to follow countries like China, where a number of binary power plants have been installed to utilise low temperature discharges. In India, barring only **a** few. almost all the geothermal fields may have base temperatures exceeding 100°C, thus they should be suitable for fueling binary power plants.

Further, there are **a** large number of deep bare holes drilled in hydrocarbon bearing sedimentary basins. Not all of them are production wells. In many of these wells. measured temperatures exceed **100-150°C** at 2 to 4 km depth. For example in the Cambay graben. these temperatures have been recorded even in the depth ranges of 1.5 to 3 km. These sedimentary basins may **have** suitable thermal reservoirs at these depths. If so, these deep boreholes can be successfully utilised for geothermal power generation by hydro fracturing and using commercially available single bore hole geothermal energy extraction-system-technology. This technology can also be used in shallow high temperature wells.

Down-hole coaxial heat exchanger system could suitably be used for areas like the Jharia coal field where underground mine fires are prevalent in many localities. If possible, the concept of a closed circuit power plant, requiring generators to be buried at depths, can also be used for extracting geothermal energy (Gupta, 1992).

6. CONCLUDING REMARKS AND RECOMMENDATIONS

In India, geothermal exploration work, until now has comprised detailed reconnaissance and evaluation limited to areas of NW Himalaya and certain parts of central and western India. In other areas, only limited information is available and detailed work needs to be expedited. Commercial power generation has not yet commenced, although attempts are being made. Large scale availability of cheaper energy resources like coal, oil. nuclear fuel, wind energy etc. seems to have hampered the growth of geothermal energy exploitation.

Intermediate temperature resources could definetely used for power generation, specially those occuring at Puga-Chhumathang, Parbati valley and other areas of NW Himalaya. the Tatapani region (M.P.), areas containing the west coast thermal anomaly zone, Barren and Narcondam islands, and parts of Godavari and Narmada valley coal fields. In these and many more areas thermal reservoir temperatures are expected to be between 100 to 250°C. But again, these estimates are baed on chemical data only.

The occurrence of deep reservoirs has not yet been proved by deep exploration and drill hole data. There is an urgent need to carry out detailed deep resistivity, telluric and magnetotelluric studies in potential geothermal areas to help define the existence of deep seated thermal reservoir. If that is accomplished, then this work should be followed by deep drilling to establish resource quality and quantity. Lack of expertise in deep drilling is also a problem. Hence, such technology should be purchased so as to drill to depths of up to 3 km in those geothermal areas where expected temperatures could be in the vicinity of 200 ± 50°C.

Apart from power production. the use of geothermal resources should be encouraged for commercial and industrial purposes. Successful beginnings were made at the Puga. Chhumathang and Manikaran areas. Vast potential exists in other areas too. Recently. the government of Himachal Pradesh finalised the plans for direct utilisation of geothermal heat. in selected areas, for tourism and health resorts. Other geothermal agencies should be convinced to do the same. Programmes, involving the extraction of minerals of economic importance. should also be encouraged. There is an urgent need for a "centralised body" which can take initiatives and coordinate all the aspects of geothermal resources development. The energy potential must be critically assessed, particularly for those reservoirs which are expected to lie at the deeper depths of 1 to 3 km.

ACKNOWLEDGEMENTS

We are extremely thankful to Drs. Hari Narain, M.L. Gupta, U.L. Pitale. Ravi Shanker and S.C. Sharma for discussions and providing useful papers and to many other geoscientist8 whose work has been referenced. but which could not be included in the text due to page limitations. We are also thankful to Messrs Ch. Ramaswamy and Shyam Vaidya and Mrs. B. Padmavathi for their continuous help in the preparation of the manuscript. The permission accorded by the Director. National Geophysical Research Institute, Hyderabad to publish this work is gratefully acknowledged.

REFERENCES

Absar, A., Jangi, B.L., Pandey, S.N., Srivastava. G.C. and Singh, J.R. (1993). Geothermal and volcanological studies at Barren Island volcono, Andaman and Nicobar Islands. Rec. Geol. Surv. Ind. vol.126 (pt.8), pp.218-219.

Gupta, M.L.. (1981). Surface heat flow and igneous intrusion in the Cambay Basin, India. J. Volcan. Geoth. Res., vol.10, pp.279-292.

Gupta, M.L. (1992). Geothermal energy and its prospects in India. In: Power directory, C.P. Moraes (Ed.), Astra Publishers Fvt. Ltd.. Bombay, pp.157-165.

Gupta, M.L. (1994). Geothermal resources of India: Geotectonic associations, present status and perspectives, In: Terrestrial heat flow and geothermal energy in Asia, M.L. Gupta and Y. Makato (Eds,) Oxford and KBH Pub. Co. Pvt. Ltd., Delhi, pp.311-330.

Gupta. M.L. and Rao, G.V. (1970). Heat flow studies under upper mantle project. In: NGRI's contribution to the upper mantle project, Spec. Issue, Bull. Natl. Geophys. Res. Instt.. vol.8, pp.87-112.

Gupta, M.L., Kumar, R. and Singh. S.B. (1979). Present day knowledge of the Parbati valley geothermal field. Geoviews, vol.VI, pp.III 83-99.

Gupta, M.L., Sharma, S.R. end Sundar, A. (1988). Geothermal gradients and terrestrial heat flow in various metallogenetic and energy resources provinces of India. Proc. 5th International Bureau of Mining thermophysics, New Delhi, pp.127-133.

Gyan Prakash and Aggarwal, R.K. (1989). Geothermal exploration in Nubra Valley, Ladakh district, Jammu and Kashmir. Rec. Geol. Surv. Ind., vol.122 (pt.8), pp.236.

Harinarayana, T., Singh, S.B., Sarma, S.V.S. and Verma, R.K. (1988). Electrical structure across Tatapani hot spring from telluric field investigations. In. workshop on deep electromagnetic Exploration. NGRI, Hyderabad (India), pp.V-4.

Harinarayana, T. and Sam. S.V.S. (1991). Telluric and magnetotelluric field studies over Konkan geothermal province, West coast of India, Part I, Modelling of the Telluric field anomaly. Proc. Int. Sym. workshop on Deep Electromagnetic Exploration, I.I.T., Kharagpur (India), pp.1-10.

Kerve, A.E. (1991). Geothermal investigation and assessment of thermal spring of Unkeswar. Nsnded and Yeotmal Districts of Maharashtra. Rec. Geol. Surv. Ind., vol.127 (pt.6), pp.89-92.

Negi, J.G., Pander, O.P. and Anraral. F.K. (1986). Super mobility of hot Indian lithosphere. Tectonophysics, vol.131, pp.147-156.

Negi. J.G.. Agrawal, P.K. and Pandey, O.P. (1987). Large variation of curie depth and lithospheric thickness beneath the Indian subcontinent and a case for magnetothermometry. Geophys. J. R. Astr. Soc., vol.88, pp.763-775.

Negi, J.G., Agrawal, P.K., Singh, A.P. end Pandey, O.P. (1992). Bombay gravity high and eruption of Deccan flood basalts (India) from a shallow secondary plume. Tectonophysics, vol.206, pp.341-350.

Negi, J.G., Agrawal, P.K., Pandey, O.P. and Singh, A.P. (1993). A possible K-T boundary bolide impact site offshore near Bombay and triggering of rapid Deccan Volcanism. Phys. Earth Planet. Int., vol.76, pp.189-197.

Pande. D.K., Misra, K.N. and Sharma, S. (1984). Source bed history of Bombay offshore region. In: Oil and Gas fields, Roc. 27th Int. Geol. Cong., Moscow, vol.13, pp.211-244.

Pandey, O.P. and Negi. J.G. (1987). Signals of degeneration of the subcrustal part of the Indian lithosphere since the break-up of Gondwanaland. Phys. Earth Planet. Int., vol.48, pp.1-4.

Perumal. N.V.A.S.. Tewari, S.G. and Mahadevan, T.M. (1989). Delineation, discrimination and mapping of lineaments from landsat analysis and their correlation with aeroradiometric and geophysical data. Mem. Geol. Soc. Ind., vol.12, pp.156164.

Pitale, U.L. (1993). Geothermal division an overview. Rec. Geol. Surv. Ind., vol.126, (p.6), pp.173.

Pitale, U.L. (1994). Projects 10 and 15: Geothermal investigations. an overview. Rec. Geol. Surv. Ind., vol.127, (pt.6), pp.87-88.

Raval, U. (1993). Fast movement of the Indian plate. buoyancy due to plume and warm asthenosphere. Proc. perspectives and prospects in geosciences towards the new industrial policy, Indian Geophys. Un.. Hyderabad (India), pp.104-114.

Ravi Shankar, Guha. S.K., Seth. N.N.. Muthuraman, K., Pitale, U.L., Jangi, B.L., Prakash. G., Bandyopadhyay, A.K. and Sinha, R.K. (1991). Geothermal Atlas of India. special publication No.19. Geol. Surv. India, 144 pp.

Sarolkar. P.B. (1994). Subsurface geological studies in Tatapani geothermal field, district Surguja (M.P.). Rec. Geol. Surv. Ind.. vol.127 (pt.6), pp.147-151.

Sharma, S.C. (1993). A note on the progress of the work done in geothermal investigations in GSI. NR, from the period February 1992 to March. 1993. CGPB sub committee 15 (Pers. Comm.).

Sharma, S.C. (1994). Work carried out during the period May. 1993 to May 1994. CGPB sub committee 15 (Pers. Comm.).

Sharma, S.C. and Absar, A. (1991). Monitoring of thermal springs of upper Parbati and Madhya Maheshwari valleys, Himachal Pradesh and Uttar Pradesh, Rec. Gel. Surv. Ind., vol.124 (pt.8) pp.179.

Singh, A.P., Pandey, O.P., Agrawal, P.K. and Negi. J.G. (1991). Anomalous crustal and lithospheric structure beneath Cambay basin, India. Proc. First. Int. Sem. Exploration Geophysics in Nineteen Nineties, vol.1, pp.304-312.

Singh, R.P. and Nabetani, S. (1995). Resistivity structure of Puga geothermal field, Proc. World Geoth. Cong. Florence (Italy) (in press).