GEOTHERMAL FIELDS OF INDIA: A LATEST UPDATE

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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 its 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) the Puga-Chhumsang, Manikaran, Tabopan etc. in NW Himalaya, (ii) Tatanpani (M.P.), (iii) Gondwana grabens, and (iv) volcanic areas of Andaman-Nicobar chain. Deep seated reservoir temperatures are reported to be between 100°C and 250°C. Total geothermal power potential, 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 MW to 1 MW capacity at a few 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-Ranaea 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 occurred 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 (Deccan Traps) took place. India is the only continent which came into contact in its journey with four hot spots (Keniguela, Reunion, Martin and Cretas) between 117 Ma and 65 Ma after its break-off from Antarctica (Rayal, 1989). 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., 1988). 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 30 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 non-volcanic 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 organisations, one 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 geophysical geological 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...
A TOPOGRAPHIC MAP TYPISH

Figure 1: Geothermal provinces of India as defined by geoscientific, geothermal, and terrestrial heat flow data. The regions of high heat flow are shown as shaded areas, the archipelago lies at shallow depths.

1. Peninsula
2. Wehnert et al. (1979)
3. Negi et al. (1991)
4. Negi et al. (1994)
5. Negi et al. (1995)

Negi et al. (1991, 1994, 1995) provide a comprehensive review of geothermal resources in India. However, the map shows the distribution of thermal areas in India, and the distribution given by Negi et al. (1991) is shown as shaded areas.

In many instances, the heat flow is an important tool in geothermal exploration. Negi et al. (1991) mention that in the Narmada lineament, the heat flow is about 5 W/m², indicating the presence of large-scale subsurface geothermal provinces. The regional distribution as shown in the map is indicative of the presence of large-scale geothermal resources in India.

Pre-1950, the archipelago lies at shallow depths, and the regional geothermal provinces are indicated by shaded areas. The map also shows the Narmada lineament, which is a significant geological feature in India.
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-Chumathang area

This area is situated about 180 km ESE of Leh in the Ladakh district of the state of Jammu and Kashmir. 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 Chumathang 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 Chumathang and 8.8°C/m at Puga (Figure 3A). Maximum discharge from a single spring is about 15 litls.
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 Ωm. Based on magnetotelluric recordings, two dimensional resistivity structure of the Puga field has recently been delineated (Singh and Vahetani, 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 (10-154) at a temperature around 140°C and pressure of 2-3 kg/cm². Some wells discharge water-steam mixture at 125°C. In the Puga borehole 0512 indicates large concentration of Cu, Zn and As. 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 150°C and 240°C. Geo-thermally induced episteme in borehole POW-1 substantiates this view. The estimated heat flow in the Puga region is 630 mW/m² (Gupta et al., 1988).

In Chumathang, the thermal region is mainly spread over the right bank of Indus river where several thermal springs emit H₂S bearing hot water. Six bore holes, to a depth of 221 m, have been drilled here. Most of them discharge a water-steam mixture with a maximum temperature of 109°C. The reservoir temperature is between 160°C and 200°C.

**Basal and Parbatli Valleys**

These areas are situated in the Kulu region of Himachal Pradesh. There are 8 thermal springs in the Basal 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 75°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 380 l/sec at 55°C. The reservoir temperature estimates are around 140°C to 20°C at deeper levels. based on chemical and isotope thermometries.

In the Parbatli 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 hole is 101°C. Th reported reservoir temperature is between 186°C and 202°C for Manikaran, 170°C for Jan, 100°C for Tashi and 150°C for Khirangla (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 CO₂. Age of the Manikaran water is calculated to be 11,000 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 Chura-Sumdo (23-59°C) and Tatapani (32-63°C). The highest discharge from a single spring is 3.3 l/sec. The base temperature, as deduced from NaCl and Silica thermometers, range from 110°C to 212°C.

**Tapoban region**

Tapoban area lies in the Alaknanda valley of the Chamoli district (U.P.) and contains about 12 deep type 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 m) and one deep discharge thermal fluids (11-13 l/sec) at a temperature of 80°C to 90°C. However, another deep borehole discharges hot water (16 l/sec).
with a lower temperature of 63°C and pressure of 7 kg/cm². The estimated reservoir temperature is 180 ± 20°C. Young acidic magmatic intrusions are expected here. No reversal of temperature curve with depth is noted here upon Mom. Chemically, the thermal water is of Ca(HCO₃)₂ type, with tritium values ranging from 21 to 27.4. The gaseous emanations are predominantly composed of O₂ (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, Panikhat thermal spring (41° 47', 77° 32') with temperature of 65°C to 76°C, appears to be most promising. Its cumulative discharge is 600 l/min. Expected base temperature is 180°C (Gyan Prakash and Agrawal, 1989). Similarly, a few springs are reported from Bari valley (Chamba District, HP). Here, the Awas thermal spring (58°C) discharges at the rate of 40 l/min. Further, a number of thermal springs are also located in the Bhagirath, Darmo and Madhya Maheshwari valleys of Uttar Pradesh.

Bhagirathi valley (Uttar Pradesh) contains six of them.冈ganga thermal spring (30° 54', 80° 41') shows a temperature of 62°C and discharge of 450 l/min. This region experienced a disastrous earthquake in 1991, which significantly affected the thermal activity. Post earthquake geothermal study indicates rise in temperature from 35°C to 45°C at Bhukki thermal spring (30° 52', 80° 48') while drop from 55°C to 27°C at Sonegath thermal spring (Sharma, 1993, 1994). The highest temperature spring (80°C) in the Darmo valley (Pithoragarh district) is at Dhar (50° 04', 80° 19') with discharges at the rate of 700 l/min. Geothermal manifestation in this valley extend for over 5 km. The base temperature is 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 Anhar, 1991).

4.2. Son-Narmada-Teotli lineament and occurrences

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 known thermal, 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 km² around the Tatapani hot spring. Here, temperature gradients are 81 ± 38°C/km (Figure 3a) while heat flow is 210 ± 87 mW/m². The areas of thermal anomaly is likely to extend much beyond the known zone. Telluric field anomalies (Harinarayana et al., 1998), carried out in a 190 sq km area, indicate the presence of an anomalous zone extending in a east-west direction near the hot springs. EM Modelling of the area indicates the possible presence of a conductor (50 ohm m) (or hot water fracture zone) at a depth of about 400 m. A number of bore holes have been drilled here. GFAZ-25 and 26 reveal latest holes yield 200-300 l/min of water at about 100°C (Caroikaran, 1994). Bore hole Tat-26 has a geothermal discharge. Well testing operations suggest that pressure at the bottom may be about 32-45 kg/cm². A deep reservoir is likely to occur at a depth range of 1 and 2 km. 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 210 ± 40°C at 3 km.  

Salbardi region

This region includes parts of the Satpuli district of Madhya Pradesh and the Amarkantak 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 60 ± 8°C/km. Reported base temperature is 110°C.

Anhon - Samoni area

This region is located along the southern part of the lineament situated in the district of Chhindwara and Hoshangabad (M.P.). Anhon 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 depth. Infiltrable gases (80% methane) were encountered in borehole Ah-2 (drilled to a depth of 262 m) (Pitale, 1993). The borehole encountered inter-layered basic sills and volcanic tuffs within the Talchir shales and muddstones, underlain by basic intrusive rocks. No significant hydrothermal circulation has been 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. Basaltic intrusion is at 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 55.5°C. The temperature gradient is reported to be 88°C/km in this well.

Unkeshwar

Unkeshwar thermal field is situated 1 km south of the Penganga river. In the Nanded and Yeotmal 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 140°C.

4.3. West Coast geothermal province

This is a large anomalous, rifted, continental margin of low relief Peninsula is associated with one of the world’s largest flood volcanic eruption. The region encompasses a broad, high heat flow area termed as the west coast thermal anomaly (Nerl et al., 1992). The region covers parts of the Cambay graben, the Bombay offshore and the Konkan coast (Figure 4). A large astropolitical impact appears to have taken place in this region near Bombay offshore, just before Deccan volcanism (Nerl et al., 1993) and 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 Graben in the region lies at an extremely shallow depth of 21 ± 3 km (Singh et al., 1991) beneath which the asthenosphere (250°C in upper) has crossed to a depth as shallow as 40 km. Heat flow is high (average 83 mW/m²) in the northern part of the graben where temperature gradients reach more than 70°C/km (Figure 3b) in certain zones.
with a lovey temperature of 63°C and pressure of 7 kg/cm². The estimated reservoir temperature is 180 ± 20°C. Young acid magmatic intrusions are expected here. No reversal of temperature curve in depth is noted here up to about 50°C. Chemically, the thermal water is of CaMgKCO₃ type, with tritium values ranging from 1 to 27.4. The gaseous emanations are predominantly composed of CO₂ (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° 30') with temperature of 65°C to 76°C, appears to be most promising. Its cumulative discharge is 600 litre/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 litre/minute. Further, a number of thermal springs are also located in the Bhagrathit, Darma and Madhya Maheshwari valleys of Uttar Pradesh.

Bhagirathi valley (Uttar Pradesh) contains six of them. Gangnami thermal spring (30° 54'). 15° 41') shows a temperature of 62°C and discharge of 450 litre/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', 76° 39'), while drop from 50°C to 27°C at Sonpahar thermal spring (Sharma, 1993-1994).

The highest temperature spring (80°C) in the Darma valley (Pithauragadh district) at bar (30° 06', 80° 30') which discharges at the rate of 700 litre/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 Abar, 1991).

4.2. Sone-Karimdo-Tapti lineament and surroundings

This is one of the most important lineament/riifted Structure of the sub-continent. It runs across the coast 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 Controls the thermal spring areas, and is 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 around the Tatapani hot spring. Here, temperature gradients are 81 ± 30°C/km (Figure 2a) while heat flow is 212 ± 87 mW/m². The area of thermal anomaly is likely to extend much beyond the known zone. Telluric field studies (Harinarayana et al., 1988), carried out in this 50 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 conductive body (500 ohm m) at the 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 litre/minute for at about 1900 m. Bore hole Tat-26 has a geyseric discharge. Well testing operations suggest that pressure at the bottom may be about 32-45 kg/cm². A deep reservoir is likely to occur at a depth range of 1 and 3 km. 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 Amarkantak region in Maharashtra. It is structurally located at the faulted junction of the Satpura horst and part of the Tapti-Purna graben. Thermal spring temperatures are much lower here (<30°C) despite temperature gradient of the order of 65 ± 8°C/km. Reported base temperature is 110°C.

Anhon - Samoni area

This region is located along the southern part of the lineament situated in the district of Chhindwara and Hoshangabad (M.P.). Anhon 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 251.2m) (Pitale, 1993). The borehole encountered inter-layered basic sills and volcanic tuffs within the Talchir shales and mudstones, underlain by basic intrusive rock. A thick diorite dike is contempated to be present in 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 51.5°C. Another borehole 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 Pengangar river, in the Mandeli and Yeotkul district of Maharashtra (Karve, 1994). Geothermal activity is in the form of hot springs spread over an area of 10 ha, 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 type. In the western parts of the state, the graben is crossed by several deep-seated faults, appears to have originated due to extensional forces. In connect with this, oil basin has been studied extensively with the number of deep wells re-drilled to evaluate and extract hydrocarbons. The Emu in the region lies at an extremely shallow depth of 21 ± 3 km (Singh et al., 1991) beneath the asthenosphere (145-150 km) (Sarokar, 1950). The heat flow to a depth as shallow as 40 km. Heat flow is high (average 83 mW/m²) in the northern part of the graben where temperature gradient, reach more than 70°C/km (Figure 3b) in certain zones.
PANDEY and NGRI

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 steam 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/m² (Negi et al., 1992) and 36 to 78°C/km (Pande et al., 1984) 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 ghat and the west coast of India. About 60 thermal springs with temperatures ranging from 24°C to 71°C cluster in 38 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 (Yed), 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 (Harihara and Sarna, 1991) indicate a prominent telluric current low in a N-S direction. Modelling results indicate 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 100 m 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/m² (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 *matric* temperature recorded in these bore holes is 35°C. Shallow geothermal surveys indicate large variations 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 (Ferl et al., 1989) suggests that most of the hot springs of the Bihar and West Bengal area are located at the intersections or convergences of four or more lineaments. The hottest temperature (85°C) is found at Surajkund (Hesaribagh, Bihar). Estimated base temperatures in the different thermal spring areas range from 90°C to 150°C. Similarly, the NE region (Assam, Meghalaya, Arunachal Pradesh, Nagaland, Manipur, Manipur and Tripura) also contains a number of thermal areas, with temperatures varying 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, Agignundam and Irade (Purur). Agignundam 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. Maximal reported heat flow from the graben is 5.4 mW/m². 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. Cauvery valley basins

These coal bearing Gondwana basins are situated in the northeastern part of India and contain number of hot springs. Jharia and Raniganj are the most prominent basins. Thick coal seams are found here. The area is crossed by numerous faults, sills and basic intrusions. Hot springs temperatures are up to 80°C while reservoir temperature is estimated at 100 ± 20°C (Gupta, 1990). The measured average heat flow in this basin is 74 mW/m² while the gradient at Jharia is about 45°C/km. The 1250°C isotherm is expected at a depth of 55 km (Nigl et al., 1987). Recent uplift and crustal upwarping and fracture reported from these coal fields. The source of the thermal anomaly is definitely deep. Underground mine fires are common in various parts of the coal fields. It is this 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 island. 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 eruption of 1991. Furnas discharge has found to have a temperature of 100°C to more than 500°C. Some gas samples from this discharge show high concentration of N2, Ag, Cs, Li, Rb and Zn (Sharma, 1992). 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 (Asaer 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. ENERGY 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 100 X 10^7 kcal, 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), which could lead to even 10,000 MW (Ravishanker et al., 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 tested run to its optimum capacity in September, 1992 at the Manipur geothermal area. It utilised the discharge from boreholes NGW-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 NGW-6 drillhole (700 lit/minute at 85.5°C) at Tapoban for green house forming (Sharma, 1994). An attempt has also been made to find gold in geothermal discharges of Badrinath, Tapoban and Gangnani thermal springs, but the concentration was found to be less than 100 ppm (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 major 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 successful 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 bore holes drilled in hydrocarbon bearing sedimentary basins. Not all of them are productive. 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 km. Furnas discharges, if any, may appear suitable 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 Haria 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 definitely be used for power generation, specially those occurring at Puga-Chhumathang, Parbat 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 based on chemical data only.

The occurrence of deep reservoirs has not yet been proven 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 geological 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. Vasudeo potential exists at many 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.

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