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Geothermal Energy Resources and its Potential in India

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Abstract

Geothermal Energy is the vast reservoir of heat energy in the earth's interior, whose surface manifestations are the volcanoes, fumaroles, geysers, steaming grounds and hot springs. About 300 thermal springs are known to occur in India, falling in orogenic (Himalayan) as well as non-orogenic (Peninsular) province. Thirty one areas have been examined in detail and finally, shallow drilling has been done in sixteen areas. The temperatures of these springs range from 35°C to the boiling point of water. On the basis of enthalpy characteristics the geothermal systems in India, are classified into medium(100°C-200°C)-and low enthalpy (<100°C) geothermal energy resources/systems. Medium enthalpy geothermal energy systems are associated with younger intrusive granites (as in Himalayas), major tectonic features/lineaments and rifts and grabens. The Low enthalpy geothermal energy systems are associated with Tertiary tectonism and neo-tectonic activity. The primary and most important aspect of geothermal system is to understand the heat source and its capacity for exploitation. Studies carried out, so far, have clearly pointed that adequate geothermal potential in respect of direct heat utilization and power generation does exist at several geothermal sites. Reservoir simulation studies have suggested the possibility of generating over 3 MW electric power in Puga (J&K) field, if deeper levels are probed at least up to the depth of 500 m. The paper provides an overview on various geothermal fields of India and the status of exploration for future studies.

Introduction

The 'energy crisis' in the seventies and onward changed the approach and priorities in the field of discovery of new non-conventional energy resources. It enhanced the efforts by various countries to look for alternate indigenous and renewable energy resources. In the process wind energy, solar energy, geo-thermal energy and sea wave energies were tried and developed as non-conventional energy resources in various countries depending upon their requirements.

Thermal springs have been known to occur in India since centuries. At places, like Badrinath and Gangotri in Uttar Pradesh; Sohna in Haryana; Rajgir in Bihar; Bakreshwar in West Bengal and Ganeshpuri in West Coast, Maharashtra, temples have been built on thermal springs and thermal water was utilized by locals. Thermal springs have drawn attention, being the surface manifestation of the vast resources of geothermal energy at depth in the form of geothermal reservoirs. Italy, being the pioneer country produced electrical power from geothermal fluids, way back in 1904. At present the total estimated electric power production from geothermal energy is in the range of 8771 MWe all over the globe (Lund, 2004) , which includes U.S.A., Philippines, Mexico, Italy, Japan, Indonesia, New Zealand, El Salvador, China and Costa Rica. In the non-electrical sector, the thermal water is used in greenhouse cultivation, space heating, paper and pulp industry, agriculture industry, fish farming, tourism *viz.* bathing and swimming etc.

In India, almost all the three hundred thermally anomalous areas have been examined and assessed for geothermal potential. Major and representative Indian geothermal provinces are shown in the Fig.1. The temperatures of these springs range from 35^{o} C to the boiling point of water at that height. Thirty one areas have been examined in detail and finally, shallow drilling has been done in sixteen areas. Systematic efforts to explore the geothermal energy resources commenced in 1973 with the launch of Puga geothermal project and gradually the exploration work was extended to cover Chhumathang, Ladakh, J&K; Parbati valley, HP; Sohna, Haryana; West Coast, Maharashtra and Tattapani, Sarguja, Chhatisgarh. Six areas, four in Himalayas and two in Peninsul, hold promise for utilization for either electrical power generation or direct heat applications on industrial scale. The deepest exploratory bore holes have been drilled up to a depth of 385m at Puga, Ladakh, J&K; 220 m at Chhumathang, Ladakh, J&K; 700m at Manikaran, Himachal Pradesh; 728m at Tapoban, Uttar Pradesh and 620m at Tattapani, Sarguja, Madhya Pradesh. As a result, it was deduced that the total thermal discharge from springs and drill holes is 30 liters/sec and 250 tonnes/hr at Puga, Ladakh, J&K; 5 liters/sec and 50 tonnes/hr at Chhumathang, J&K, Ladakh; 15 liters/sec and 100 tonnes/hr at Manikaran, HP; 15 liters/sec and 150 tonnes/hr at Tapoban, Uttarkhand and 1liter/sec and 120 tonnes/hr at Tattapani, Chhatisgarh respectively (Geothermal Energy Resources of India, 2002 and references there in). The exploration endeavor also pointed to the favorable geological-hydrogeological setup in these geothermal fields, which have the possibility of encountering sizeable geothermal reservoirs which could sustain electrical power production on MW scale and non-electrical utilization projects on a commercial scale.

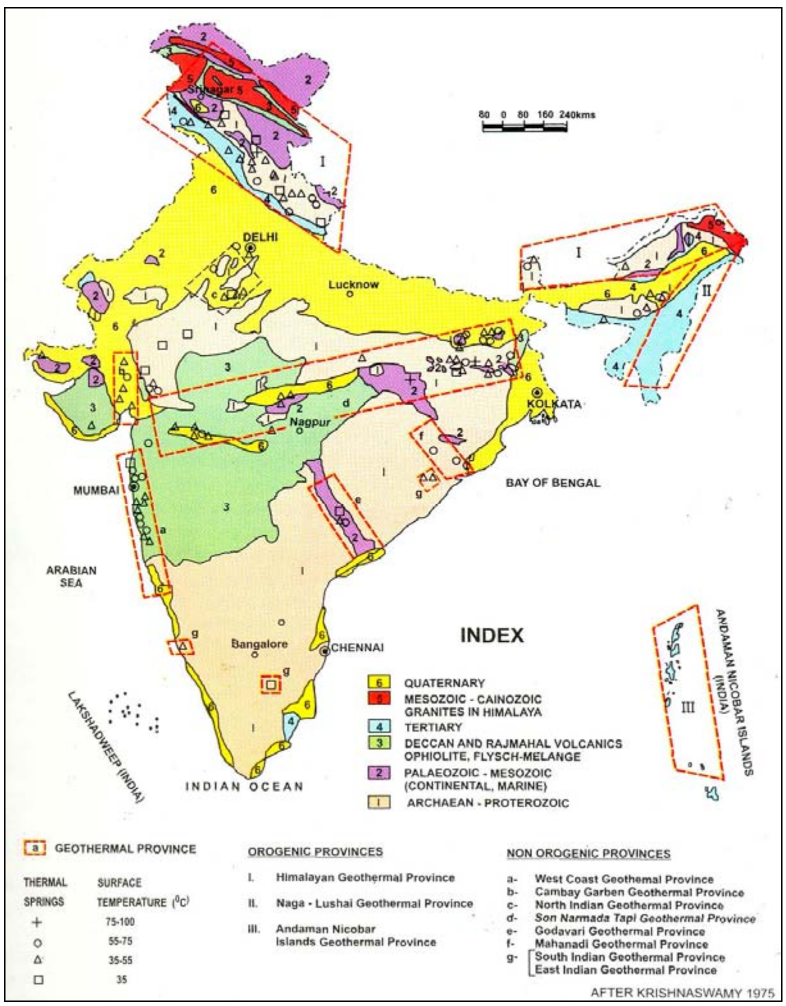

Fig.1: Major and representative Indian geothermal provinces

Geothermal System

On the basis of enthalpy characteristics, the geothermal systems in India, can be classified into medium enthalpy (100°C-200°C) and low enthalpy (<100°C) geothermal systems. These are described as follows:

Medium enthalpy geothermal energy systems:

The medium enthalpy geothermal energy resources are associated with:

1. Younger intrusive granites as in Himalayas, *viz* Puga-Chumathang, Parbati, Beas and Satluj Valley geothermal fields.
2. Major tectonic features/lineaments such as the West Coast areas of Maharashtra; along the Son-Narmada-Tapi lineament zone at Salbardi, Tapi; Satpura areas in Maharashtra; Tattapani in Chhattisgarh and Rajgir-Monghyar in Bihar, Tatta and Jarom in Jharkhand and Eastern Ghat tracts of Orissa.
3. Rift and grabens of Gondwana basins of Damodar, Godavari and Mahanadi Valleys.
4. Quaternary and tertiary sediments occurring in a graban in the Cambay basin of West Coast.

Low enthalpy geothermal energy systems:

The low enthalpy geothermal energy systems are associated with:

1. Tertiary tectonism and neotectonic activity.
2. Shield areas with localized abnormal heat flow, which is normally very low.

Indian Geothermal Resources

Physiographically, India is divisible into three distinct geographical units *viz.* the Extra- Penninsular Region, Indo-Gangetic Plain and the Peninsular Region. A variety of rocks ranging in age from Archaean to Holocene are exposed in these geographical units. The thermal springs have been classified on the basis of their occurrence in specific geotectonic setups and have been grouped under different Geothermal Provinces. The geological and structural criteria that have been used in the identification of the prospective Geothermal Provinces are:

- Occurrence in an orogenic belt, which has undergone Cenozoic folding and upliftment
- Occurrence in structural depressions/grabens, associated with late Tertiary and Quaternary upliftment in non- orogenic belts
- Related to deep fault zones associated with recent seismicity
- Occurrence in the areas of Tertiary or Quaternary volcanic activity

The orogenic and non-orogenic geothermal energy resources of India are grouped as follows:

Orogenic Regions:

The orogenic regions are further divided into different provinces:

1. Himalayan Geothermal province (Northwest and Northeast sub-provinces)
2. Andman-Nicobar Island geothermal province

Northwest Himalayan Geothermal Sub-province:

This sub-province has been divided into three belts on the basis of occurrences of thermal springs. These are the trans-Himalayan belt, the central Himalayan belt and the outer Himalayan belt. This sub-province encompasses the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand. The thermal springs occur at altitudes of 4000m to 4400m in Trans-Himalayan belt, at Chhumathang and Puga, while in central Himalayan belt, the altitude ranges from 1300m to 3000m in Parbati, Beas and Satluj Valleys in Himachal Pradesh and 1000m in outer Himalayan belts. Some of the important thermal fields are described below:

Puga Geothermal Field: The Puga area is located at a distance of about 180km from Leh in Ladakh Region of J&K across the Great Himalayan Range at an altitude of 4400m amsl. Hot spring region is located along the collided junction of two crustal plates, which were involved in the Himalayan Orogeny. Intense basic to ultrabasic, plutonic and sub-marine volcanism of middle to upper Cretaceous age (ophiolites suite of rocks) and several phases of widespread acid igneous activity from upper Cretaceous to upper Tertiary times have been identified.

Thermal manifestations in the form of hot springs (Fig.2), hot pools, sulphur condensates, borax evaporates have an aerial extent of 4 km. Hot springs with temperatures varying from 30^{o}C to 84°C (boiling point at Puga area) and with discharge ranging up to 300 litres/min are present. The hottest thermal spring shows a temperature of 84°C and the maximum discharge from single spring is 5 liters/sec. In addition, hot patches and minor hot water seepages are also noticed in the thermal area. Typical cones of extinct hot spring deposit exist in the eastern part of the area. Borax evaporates occur as loose deposits on the surface while the sulphur condensate fills the joints and cracks (Fig.3).

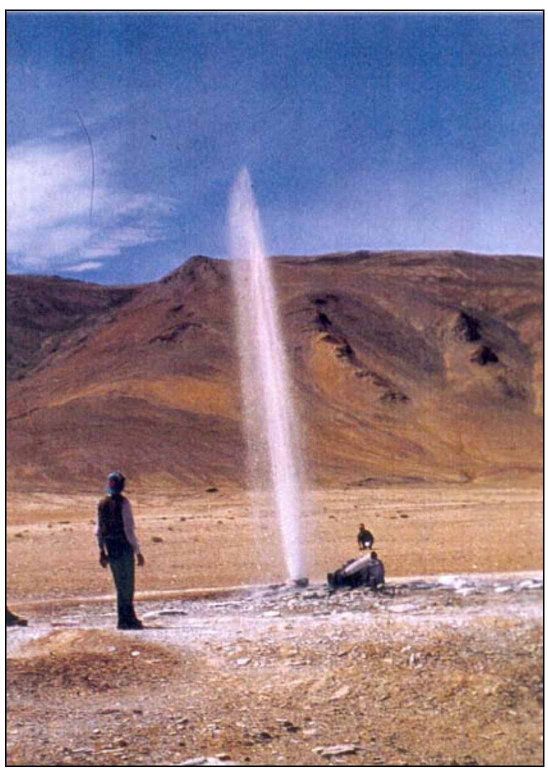

Fig.2: Geyser at Puga

Geophysical surveys have reported a major low resistivity zone (2-10 ohmm) in the southwestern part of the Puga geothermal area, which are indicative of the presence of thermal water in the sub-surface.

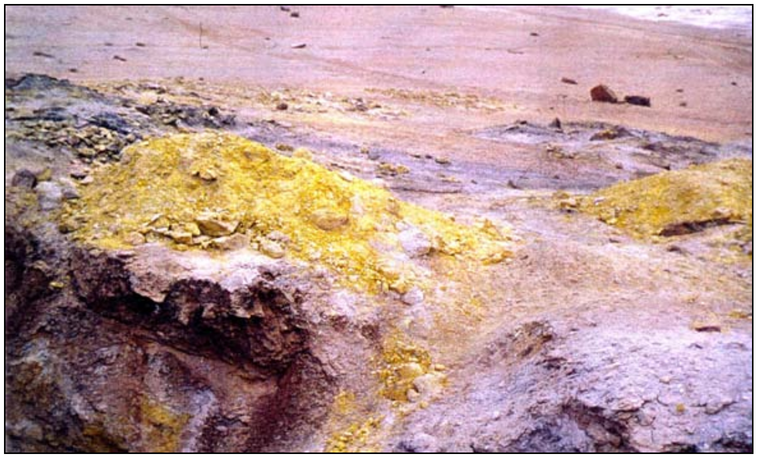

Fig.3: Sulphur deposit at Puga

Thermal waters of Puga field are near neutral to weakly alkaline- pH 6 to 8.3. Major cations and anions, in the order of decreasing concentrations, are Na, K, Cs, Li, Mg, Rb, Fe, and HCO_3, Cl, SiO_2, B, SO_4, As, NH_3 respectively. The water is essentially $NaHCO_3Cl$ type. High concentration of Li, Rb and Cs also suggests indirectly that thermal waters have stayed for longer period underground permitting intensive water-rock interaction. Geochemical thermometers, based on the concentration of Na, K, Ca and Mg, have pointed to the possibility of having thermal fluids of 220°C-260°C temperatures at deeper levels whereas the oxygen isotope thermometry places this estimate at 180°C. Marked Oxygen-shifts depicted by Puga thermal water is a strong indication of presence of high temperature zones at depth. Stable isotope studies on oxygen and hydrogen carried out on thermal water have clearly pointed out that these waters are meteoric in origin.

The thermal logging of the geothermal wells indicates an abnormally high geothermal gradient generally from 0.35 to 2.5°C/m, although higher values up to 6.8°C/m have also been encountered locally. On the basis of the available thermal gradient data and a few thermal conductivity determinations, the minimum heat flow in the Puga valley has been estimated to be over 13 HFU; that is, about eight times the normal heat flow from the earth's crust.

A total of 34 boreholes ranging in depths from 28.5 m to 384.7 m have been drilled in Puga valley. The bore holes that struck steam-water mixture from shallow geothermal reservoir have yielded 10 to 15% of steam at a temperature up to 140°C and a pressure of 2 to 3 kg/cm^2. Of the 17 flowing bore holes, wellhead measurements was carried out on 8 bore holes indicating a total discharge of 190 tonnes/hr of water- steam mixture. The maximum discharge from a single drill hole is 30 tones/hr.

Experimental space heating and refinement of borax and sulphur have been successfully tried utilizing the geothermal fluids at Puga from the shallow wells drilled so far. The extraction plant could handle 1 tone of borax ore per day and the refining plant could handle 500 kg of borax per day. Space heating experiment carried out at Puga has proved quite successful. A prefabricated hut 5m x 5m x 2.5m was heated with thermal fluids and an excess temperature of 20°C over the ambient temperature could be maintained within the hut. Experimental space heating, green house cultivation and poultry farming have also been successfully conducted by the GSI and RRL (Jammu). The thermal waters have been used for hatching poultry and for growth of mushroom in a hut in 500 sq m areas by the RRL, Jammu. Puga fluid has one of the highest Cesium concentration (10 mg/l) in the world. Efforts were applied on to separate this valuable metal from geothermal fluid using the resin developed by BARC (Mumbai).

Puga geothermal field is the only field capable of producing either primary cycle electrical power or binary cycle power at present, though on a very small scale. However, reservoir simulation studies have suggested the possibility of generating over 3 MW electric power, if deeper levels are probed at least up to the depth of 500 m.

Chhumathang Geothermal Field: Chhumathang field is about 40 km north of Puga. It is located at a distance of 150 km from Leh, Ladakh; on Leh-Chushul road at an altitude of 4300 m. Geologically, area exposes a thick sequence of shallow marine to fluvial sediments deposited over granitic basement. These rocks range in age from Cenomanian to Miocene. The Chhumathang geothermal field is located in this belt.

S.P., magnetic, seismic refraction, and resistivity surveys have been carried out. AMT surveys indicated a low resistivity zone of 13-30 ohmm up to a depth of 300m. Geothermal area is characterized by spectacular development of spring deposits. These are in the form of carbonate plateaus up to 100 m diameter and attaining a height of 6-10 m. (Fig.4). Their presence gives clue to much vigorous thermal activity in the past in an area at least twice that of today’s convective flow. Thermally anomalous area stretches for about 700 m along the right bank of Indus River in the form of hot springs, travertine deposits and stained ground. Hot springs with temperatures ranging between 30°C to 87°C (boiling point at Chhumathang) and many H_2S emitting hot spring water pools are the surface manifestations. The maximum temperature of the thermal spring recorded is 87°C with a discharge of 1.5 liters/sec. The cumulative discharge of all the springs is 200 lit/min.

Fig.4: carbonate plateaus at Chhumathang field

Geochemical studies have indicated the existence of thermal fluid in the reservoir of about 150°C temperatures. The possibility, however, cannot be ruled out that thermal discharges are steam-heated re-equilibrated fluids and estimated reservoir temperatures pertain to shallower levels of latest chemical equilibrium. Six boreholes ranging in depth from 20-221 m have been drilled in the Chhumathang area. A temperature of about 109°C was recorded in flowing wells. Cumulative discharge from 4 flowing wells is about 50 tones/hr. The shallow geothermal bore holes drilled at Chhumathang have indicated very high temperature gradient ranging from 0.7°-2.5°C /m.

Chhumathang thermal waters resemble with Puga thermal waters but differ from them in having relatively higher pH and sulphate. Stable isotope studies on oxygen and hydrogen carried out on thermal waters have clearly pointed out their meteoric origin. Chemical thermometry has pointed out deep reservoir temperature of 150°C.

Geothermal energy was utilized at Chhumathang successfully for green house cultivation and space heating. A temperature of 20°C to 25°C could be maintained inside the green house with outside atmospheric temperature as low as -35°C to -40°C in winter. A variety of vegetables were grown.

Manikaran geothermal field: Manikaran geothermal field is located about 50 km east of Kulu, Himachal Pradesh at an altitude of about 1700 m. The field is located to the southwest of the Central Crystalline Axis, which runs along the great Himalayan range and comprises predominantly foliated gneiss intruded by younger granite, where profuse igneous activity has taken place during Tertiary period. The hot springs at Manikaran are located in the Manikaran quartzite (Devonian) beneath the Main Central Thrust. The granites intruding the Manikaran quartzite are possibly the source of heat of the hot-spring waters. The Manikaran quartzite is highly jointed, and these joints hold great significance as far as the movement of hot waters is concerned.

Geothermal activity at Manikaran occurs in the form of hot springs, over a distance of about 1.25 km on the right bank of Parbati river whereas on the left bank, this activity manifests itself over a distance of about 450 m. Thermal springs located on the right bank are in the temperature range of 34°C-96°C, whereas on the other side temperature ranges 28°C-37°C.

The geophysical surveys have indicated a zone of positive S.P. associated with low resistivity. Geothermally anamolous zone is characterized by apparent resistivity in the range of 30-100 ohmm. Thermal water is feebly alkaline with pH value ranging from 7.5 to 8.1. On the basis of dominant cations and anions, the Manikaran thermal water is $NaHCO_3Cl$ type and $NaCaHCO_3Cl$ type. A comparison of relative chloride, bicarbonate and sulfate contents shows that Manikaran water to be very similar to the thermal water discharging at Puga, a definitely higher temperature system, but without any obvious relationship. Geochemistry indicated a thermal water of about 120°±10°C in the sub-surface.

Nine boreholes have been drilled at Manikaran and the deepest being 707 m. Maximum discharge from a single spring is about 7 lit/sec. The cumulative thermal discharge from 8 bore holes is 100 tones/hr with temperature ranges from 45°C to 96°C. Distribution of major high temperature (96°C) thermal springs and bore holes are on the right bank as compared to lower temperatures (45°C) hot spring and drill hole on the left bank point to the inflow of thermal water from northern side.

As far as the utilization aspects are concerned, a 7.5 ton capacity cold storage plant based NH_4-absoption system was set up. A 5 KW pilot power plant based on binary cycle (ISO-Butane) principle was also made test run. In addition, the tourist complex could be developed in the region utilizing the geothermal fluids for hot water baths, spas etc. The thermal waters are seen to be free in respect of large scale corrosion and scaling.

Tapoban geothermal Field: Tapoban Geothermal area is located in Dhauli river valley, a major tributary to Alaknanda River. It is approachable by an all weather 15 km long road from Joshimath, in Chamoli district, Uttrakhand at an altitude of about 1800 m. The surface manifestation is in the form of five hot springs spread over a distance of one km along the hill slopes on the left bank of Dhauli river. The highest temperature recorded is 65°C. The discharge from these springs varies between 0.83-9.22 lit/sec. No secondary deposition is observed. Only one spring has gaseous emanations. The thermal springs emerge through Tapoban quartzite belonging to the Helang Formation (Fig.5).

The rocks exposed in the area comprise quartzite with occasional schistose bands, a thick sequence of gneiss, schist, migmatites, phyllite, limestone and quartzite of the Tethyan sequence. Geophysical Surveys have indicated low resistivity (100 ohmm) zones extending down to 165 m depth.

Geochemical studies indicate that the thermal water is neutral with pH ranging from 6.9-7.2 .The cations in decreasing order of concentration are Ca, Mg, Na, K and HCO_3, SiO_2, SO_4, Cl, B and F. The water is of Ca-Mg-HCO_3 type. Only one spring has gaseous emanations. The gas sample collected comprises 78.6% CO_2, 18.96% N_2 and 2.4% O_2.

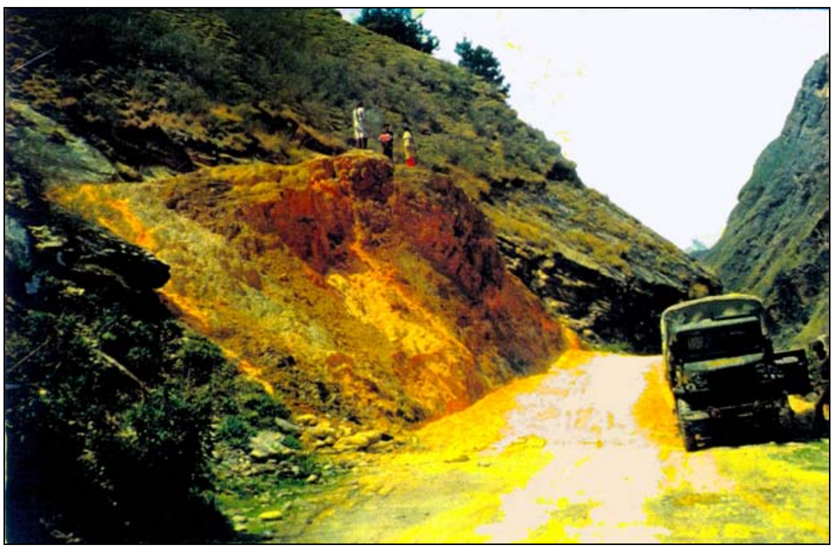

Fig.5: Tapoban geothermal Field, Chamoli district, Uttrakhand

Secondary deposits were precipitated around the collar of the bore hole at Tapoban. The major mineral is aragonite, while quartz, alkali feldspar and mica are present in trace amount. The temperature of water was around 80°C.

The geothermal system provides an example of 'Normal Gradient Heating Model'. Chemically the thermal fluid at 92°C is indistinguishable from local cold springs, except for higher SiO_2 concentration in the former. The fluid descending from higher altitudes (at least 2 km above the discharge level) has attained heat under normal thermal gradient conditions. Lower temperatures and chemical inertness of quartzite have resulted in lack of water-rock interaction reflected in no significant change in fluid chemistry.

Four boreholes of the depth ranging from 291 to 728 m have been drilled in the area. All the boreholes struck artesian conditions. Cumulative discharge from four boreholes is about150 tons/hour. Highest measured temperature in the borehole discharge is 92°C.

Base temperature calculated by Na-K-Ca geochemical thermometry is 65°C. As indicated earlier, with the drop in temperature by 34°C, within a distance of 1.5 m from the bore hole, the chemistry has undergone a very significant change. Silica has precipitated so fast that the base temperature of around 150°C calculated on silica thermometry for the water samples has come down to around 90°C. Similarly ratios of Ca, Na and K have also changed drastically with the drop in temperature (causing quick precipitation).

Northeast Himalayan geothermal sub-province:

Thermal springs located in Sikkim are an integral part of "Himalayan Geothermal Province". Five thermal springs located at Yumthang, Yumesamdong, Borong, Polot and Rishi are distributed in the North, South and West districts of Sikkim. The springs range in surface temperature from 38° to 59°C with moderate discharge and can only be applicable for direct utilization to promote non-conventional energy resources. The spring discharges have medicinal values due the presence of sulphur and boron contents. The discharges presently are used locally for drinking and bathing purposes.

Non-orogenic Regions:

The different non-orogenic are given below:

1. Cambay graben geothermal province
2. Son-Narmada-Tapi graben geothermal province
3. West Coast geothermal province
4. Damodar valley geothermal province
5. Mahanadi valley geothermal province
6. Godavari valley geothermal province
7. North Indian Peninsular geothermal province
8. East Indian geothermal province
9. South Indian geothermal province

Some of the important non-orogenic geothermal fields are described below:

Tattapani Geothermal Field: The Tattapani geothermal field is located 100 km northeast of Ambikapur, Sarguja district, Chattisgarh. Tattapani is most promising geothermal field in the Peninsular India. Geothermal activity is seen in the east at Tattapani and in the west at Jhor, which are located 50 km apart. Thermal manifestation at Tattapani is very intense in an area of 0.05 sq. km with several hot spouts, hot water pools and a marshy land (Fig. 6). The surface manifestations show occurrence of white to dirty white deposit (identified as silica) and moderate to low gas activity. The temperature of the hot water varies from 50°C to 98°C. Surface flow of the individual springs is very low while the cumulative discharge is around 60 litres/minutes. Indications of palaeo-geothermal activity are seen in the form of altered clay and hydrothermal deposits at a place 500m west of the thermal activity.

Tattapani geothermal field has two distinct lithological sequences belonging to Proterozoic and Gondwana Supergroup. Proterozoic rocks are widespread while Gondwana rocks are exposed at Tattapani and further west. Proterozoic rocks comprise grey and pink gneiss, augen gneiss, granulite, kyanite schist, sillimanite schist and hornblende gneiss. Phyllite, carbonaceous phyllite also forms part of the sequence. Gondwana Supergroup comprises green splintery shale; sandstone and shale alternations with coal streaks and plant fossils, reddish brown sandstone and grit bands.

Fig. 6: Geyser at Tattapani geothermal field, Sarguja district, Chattisgarh

Gravity, electrical, magnetic, resistivity, self potential and AMT surveys were conducted in area. The AMT surveys indicated a conductive zone in the sub-surface close to the hot spring area, which may correspond to the hot water bearing formation.

Two distinct types of waters have been identified, on the basis of proportion of cations and anions in Tattapani area *i.e.* Ca-Mg-HCO_3 and Na-HCO_3-Cl-SO_4 types. The thermal water from springs and bore holes show high fluoride content and low TDS. Higher concentration of fluoride is attributed to leaching of fluoride from hornblende of the hornblende granite. Sub-surface temperature using different thermometries is at variance with each other being 120° C to 150°C.

Hydrothermal alterations due to geothermal activity occur as encrustations around the hot springs, in hot water marsh, along joints, cracks and vug fillings in the country rock and breccia. Quartz, chalcedony, cryptocrystalline silica, stilbite, montmorillonite, traces of calcite and pyrite are present as the main alteration minerals. The hydrothermal mineral assemblage is in equilibrium within a temperature range of 100°± 10°C. Occurrence of low temperature alteration minerals in the high temperature zones suggests low water- rock ratio.

Twenty six boreholes have been drilled to depths ranging from 100 m to 620 m. Blow out conditions occurred in five wells. Bore hole GW-6 is the deepest well drilled to a depth of 500m. The shut-in temperature of the thermal fluids is around 112° C. The cumulative discharge from wells is 1600 liters/min. About 4 kg/cm^2 pressure has been measured by ONGC in all the five bore holes.

Based on the cumulative discharge of 1600 lit/min of thermal water (100° C) from five drill holes at Tattapani a joint project of ONGC-GSI-MPUVN (Madhya Pradesh Urja Vikas Nigam) to install a 300 kWe binary cycle power plant is under consideration. Keeping in view the remoteness of the area it is essential to utilize the thermal fluids for non- electrical purposes. Thermal waters can be used for Coccon boiling for extraction of silk thread, mushroom culture, cold storage, food processing, spa and tourist development, drying and canning of fish, rice bran oil and space heating during winter season.

West Coast Hot Spring Belt: Sixty thermal water springs occur at eighteen localities in the West Coast hot spring belt. This belt extends along the West Coast for a distance of about 350km from Koknere, north of Mumbai, to Rajapur in the south, with an average width of 20 km, (maximum width 50 km in the northern part and minimum of 10-15 km in the southern part). This belt falls in Thane, Raigad and Ratnagiri districts of Maharashtra. The NNW-SSE trending belt is hilly and covers basinal areas of seven westerly flowing rivers. The eastern boundary is marked by mighty scraps of Sahyadri Mountain commonly known as Western Ghats while its western margin is marked by coastline of the Indian Ocean. The thermal spring localities have been divided into three distinct clusters in the West Coast *viz.*

- Northern sector consists of six hot springs located at Koknere, Paduspada, Haloli, Sativli, Ganeshpuri and Akloli.
- Central sector consists of four hot springs located at Sov, Vadavli, Pali and Unahvre (Tamhane).
- Southern sector consisting of eight hot springs located at Khed, Unhavre (Khed), Aravli, Tural, Rajawadi, Sangameshwar, Math and Rajapur.
  Geochemistry of all the hot spring waters except Rajapur, are Alkali chloride type.

Rajapur hot spring water is bicarbonate type. Thermal waters have relatively high chloride content. The distinctly different range of chloride content of hot water suggests that occurrence and movement of thermal water is not connected with hydrologic cycle of surrounding cold water. Boron content except Unhavre (Khed), Khed (both 1 ppm), Rajapur, Math (both 0.5 ppm) hot springs is <0.5 ppm. Similarity of Cl/B ratio indicates that Math and Rajapur hot springs probably draw thermal water from reservoirs of similar hydrological condition. Cl/B value of Khed and Unhavre (Khed) hot springs suggest hydraulic continuity and their association with same geothermal system. Similar chloride and boron values form Tural-Rajwadi indicate their source in same geothermal system. Other hot springs having relatively high Cl/B ratio represent independent geothermal systems. Flourine values in thermal water of west coast are 1 to 3 ppm. It is similar to well known geothermal fields at Ice Land, USSR, and New Zealand. Lithium in thermal water at Unhavre (Tamhane), Vadavli, Pali, Ganeshpuri is <0.5 ppm. Lithium is more similar to thermal water in Basaltic province of Iceland. In other geothermal fields of the world, the lithium content is higher. Majority of geothermal systems in West Coast have minimum reservoir temperature of the order of 120 ± 10°C.

Twelve exploratory bore holes were drilled with depth ranging from 50 m to 500 m in West Coast areas. These included four bore holes at Ganeshpuri-Akloli, six at Unhavre (Khed), and two at Tural Rajwadi. Studies carried out, so far, have shown that adequate supplies of hot water can become available by drilling shallow production wells at Unhavre khed, Tural-Rajwari and Ganeshpuri-Akloli and Sativli thermal spring areas.

Ganeshpuri hot springs are already attracting large numbers of tourists for hot water bath. Development of "Sauna baths", animal husbandry, poultry farming, fresh water fish farming and greenhouse on a large scale for increase in the production of vegetables mushrooms under controlled conditions through multiple cropping can be thought of, which not only save the sizeable amount of fossil fuels but raise the economy of the Nation.

Conclusion

Almost all the 300 thermally anomalous areas have been examined. 31 areas have been studied in details, out of which, shallow drilling has been done only in 16 areas. Surface studies on Geology, Hydrogeology and Geochemistry (including isotope geochemistry) have been accomplished in all the areas. Sub-surface studies based on geophysical exploration and shallow to intermediate drilling have been accomplished in all the areas. The deepest exploratory boreholes drilled are in Puga (385m), Chhumathang (220m), Manikaran (700m), Tapoban (728m), Tattapani (620m) and West Coast (500m). Thermal discharges are at temperatures of 90°C to 140°C in the promising areas. Thermal fluids issuing from the boreholes have limited output. Electrical power production of KWe level only is possible from the thermal discharges from the exploratory boreholes drilled so far. However, reservoir simulation studies have suggested the possibility of generating over 3 MWe electric power in Puga geothermal field if deeper levels are probed at least up to the depth of 500m. Direct heat application on a moderate scale only, is possible from the thermal discharges available from the boreholes. Monitoring of some of the selected geothermal manifestations in northern part of India has been taken up systematically for geochemical studies since 2005. This will add to in synthesizing the enormous geothermal data generated during the last three decades and will also help in deciding the future course of action for the development of geothermal prospects in the country.

GSI has also synthesized most of the geothermal data, so far, carried out in the last three decades in the form of publications *i.e.* “Geothermal Atlas of India” in 1989 and subsequently “Geothermal energy resources of India” in 2002.

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