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Evaluation of the Economic Feasibility of Geothermal Resources Along the Western Continental Margin of India

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ABSTRACT

Extensive work has been carried out in the past on the major ion and isotope chemistry of the thermal waters along the west coast of Maharashtra. However trace element and rare earth element (REE) study was never attempted. This is for the first time such a project has been taken up with the aim of understanding the evolution and circulation pattern of these thermal springs. The concentration of trace elements viz., Al, Ag, B, Ba, Cd, Co, Cr, Cs, Cu, F, Fe, Li, Ga, Mn, Ni, Pb, Rb, Zn, Si, Sr and Tl and REE's in the thermal springs, ground-waters and surface waters have been determined. The thermal waters had temperatures ranging from 42 to 71 °C, pH from 7.1 to 8.8 and total dissolved solids between 337and 8698 ppm. Most of the thermal waters were Na-Ca-Cl type except one which is of Na-Ca-HCO_3 type. The thermal waters contained low concentration of some elements such as < 0.1 ppb of Ag and Cd, 1-3 ppb of Cr, Zn, Co, Cu, Pb and Ni, whereas elements like Li (18-340 ppb), B (34 – 1073 ppb), Sr (20-13560 ppb), Rb (24-220 ppb), Cs (0.75-34 ppb) and Ba (3- 2077 ppb) were much higher in concentration. Owing to the shallow depth of bore-wells, pumping through the lateritic terrain, the ground-water samples showed high concentrations of Fe (13-3448 ppb), Mn (15-806 ppb) and Zn (0.3 – 538 ppb) as compared to the thermal waters. In the light of the present study, it appears that there could be different sources of rocks playing there part in the evolution of these thermal springs in contrast to the earlier belief that all the springs are issuing through a similar geological set-up of the Deccan Flood Basalts. A detailed estimation of chemical and isotopic composition of the thermal springs, estimated a reservoir temperature of 135-140oC. From a Geothermal direct perspective, west coast geothermal provinces serves as a ready platform for developing Natural green houses, dehydration units for perishable food products, Aqua culture centers and Natural health spas, thus promoting the growth of secondary and tertiary industries. Power generation may not be the ideal use in this region

1. INTRODUCTION

The west coast of Maharashtra which is a part of the Deccan trap territory hosts an array of thermal springs along the west coast fault line with temperatures ranging from 42 to 71 °C. Sixty thermal springs occur at at eighteen localities in the West Coast hot spring belt. The springs fall in straight line along the coast which an average distance of about 50 km from the shore and are flanked by the western Ghats on the east. The northernmost Koknere hot spring and the southern-most Rajapur hot spring are approximately 350 km apart.

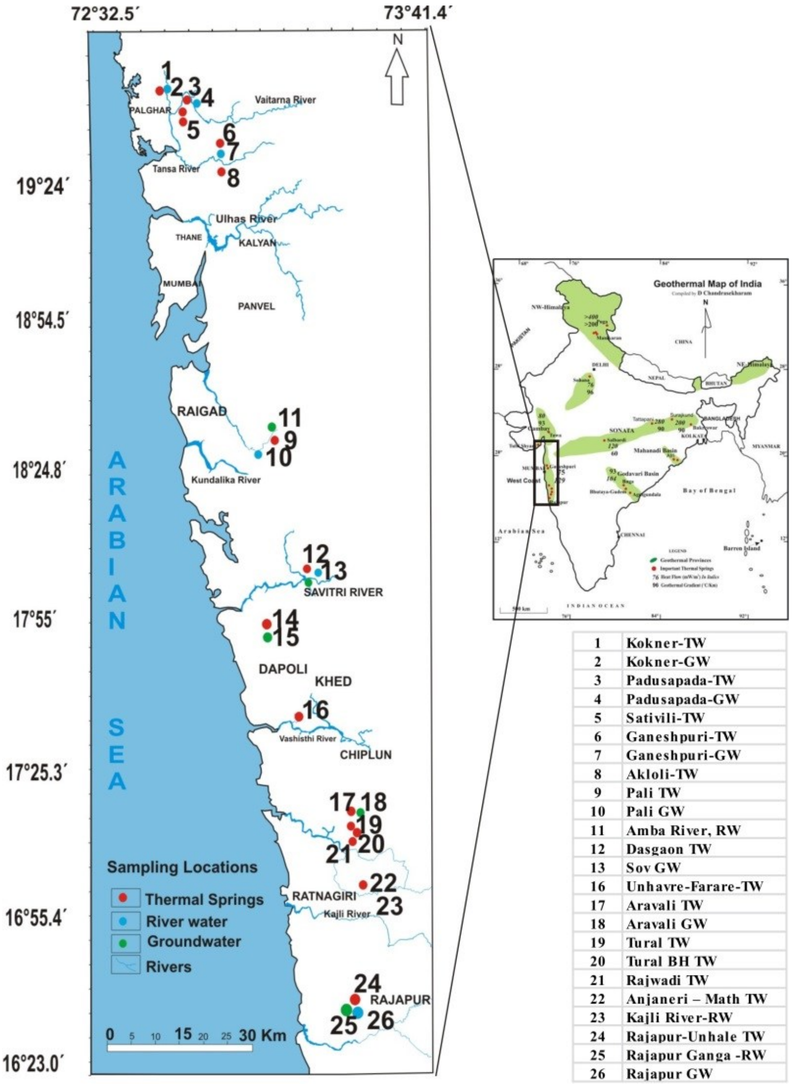
The circulation of these springs is through several faults and graben structures which were formed during the attenuation and foundering of the continental crust prior to the outpouring of the large volume of lavas along the coast (Chandrasekharam and Parthasarathy, 1978; Chandrasekharam et al., 1985). All the tectonic structures in the Konkan coastal tract are oriented in the NS and NNW-SSE directions developed during the break-up of the Gondwanaland and all thermal springs discharge along such structures (Minnisale et al, 2000). The hot springs also show a linear N-S trend. About 1% saline component has been estimated in these thermal discharges.

Though extensive work has been done on the major ion and isotope chemistry of the thermal waters of the study area (Ramanathan, A. and Chandrasekharam, D., 1997, Minnisale et al, 2000 & Sarolkar, 2005); trace element and REE study has not been attempted on any of the hot springs either in the present study area or any other thermal springs in India. Recently many studies have been taken up to study the dissolved trace and REE concentrations in geothermal waters (Möller, 2000; Wood, S.A., 2006; Taran, et. al., 2008; H. Kaasalainen and A. Stefánsson, 2012) in an attempt to understand the origin of fluids, nature of water-rock interaction, their circulation pattern and as a potential aid in exploration for and exploitation of geothermal fields of economic importance.

In view of the same, the present investigation has been taken up to establish baseline concentrations of trace elements and REE's in the thermal springs, Ground water and surface waters along the west coast of Maharashtra. An attempt has been made to understand the reservoir characteristics based on their concentrations and inter-elemental relationships and if it was better suited for power generation or applied direct and indirect used.

2. SAMPLING AND ANALYTICAL METHOD

Samples for trace and REE elements were collected in one liter High Density Polyethylene (HDPE) bottles which were cleaned by soaking overnight in 5% nitric acid followed by soaking in deionized (DI) water. Two sets of samples (1 liter each) were collected at each location. One set of unfiltered sample was acidified in the field to estimate the REE's associated with particulate matter (van Middlesworth and Wood, 1998). The second set of sample was filtered using 0.45µ Polysulfone filter membrane and then acidified with high purity HNO_3. Samples for anion estimation were collected separately (500 ml). Temperature, pH and conductivity were measured in the field. Alkalinity and other anions (F^-, Cl^-, Br^- and SO_4^{2-}) were measured in the laboratory within a week of sample collection.



1	Kokner-TW
2	Kokner-GW
3	Padusapada-TW
4	Padusapada-GW
5	Sativili-TW
6	Ganeshpuri-TW
7	Ganeshpuri-GW
8	Akloli-TW
9	Pali TW
10	Pali GW
11	Amba River, RW
12	Dasgaon TW
13	Sov GW
16	Unhavre-Farare-TW
17	Aravali TW
18	Aravali GW
19	Tural TW
20	Tural BH TW
21	Rajwadi TW
22	Anjaneri – Math TW
23	Kajli River-RW
24	Rajapur-Unhale TW
25	Rajapur Ganga -RW
26	Rajapur GW

Figure 1: Sampling locations along the west coast of Maharashtra; Inset: Geothermal provinces of India (modified after Chandrasekharam, 2000) TW-Thermal springs/water; GW- Groundwater; RW- River water

Trace elements (Al, Ag, As, B, Ba, Cd, Co, Cr, Cs, Cu, F, Fe, Li, Ga, Mn, Mo, Ni, Pb, Rb, Zn, Sb, Si, Sr, Tl, W and Zr were estimated using ICP-MS facility at PRL Ahmedabad after appropriate dilution. For the ICP-MS analysis standards were prepared using commercial mixed, NIST-traceable standards available, which were diluted appropriately as instrument calibration standards using ultrapure grade acids. The $Fe(OH)_3$ co-precipitation technique (Shannon and Wood, 2005) was used as a pre-concentration step for determination of REE's. Dummy samples with known amount of REE's were prepared and the Fe-hydroxide pre-concentration method was tested for recovery of REE which was >95%. Ru and Rh were used as internal standards to compensate for changes in analytical signals during the operation.

3. RESULT AND DISCUSSION

3.1 Major ion chemistry

The water from these hot springs are near neutral to alkaline in nature with pH varying from 7.1 to 8.8 from Koknere (#1) to Rajapur (#24). The temperatures of the thermal springs range from 40 to 71 °C with Unhavre–Farare (#16) recording the highest temperature and Anjaneri the lowest. The groundwater and surface water temperature was between 29-31 °C. The conductivity of the thermal samples varied from 539 µS/cm to 13590 µS/cm with exceptional high value shown by Koknere thermal springs. The springs show very high value of calcium (25 ppm-2000 ppm) but negligible magnesium content which can be attributed to the dilute sea-water basalt interactions at elevated temperatures (Muthuraman and Mathur, 1981).

The chloride concentration in the thermal waters is high with highest concentration of 5500 ppm recorded by Koknere thermal springs. Rajapur TW recorded the lowest concentration with 6 ppm chloride. A general trend of increase in Cl with respect to sodium can be seen in Figure 2. It is apparent from figure 2 that the salinity in thermal waters is controlled by the sea water.

Bromine is linearly correlated to chloride suggesting similar source probably marine in origin. Two Thermal springs Sov and Anjaneri (Table) recorded higher concentration of sulphates of about 275 ppm. Other samples had comparatively lower sulphates (7-175 ppm). Tural (# 19) and Rajwadi (#21) show highest silica content (95 ppm, Table) compared to other springs where average SiO_2 is around 60 ppm. Rajapur has the lowest value at 26 ppm.

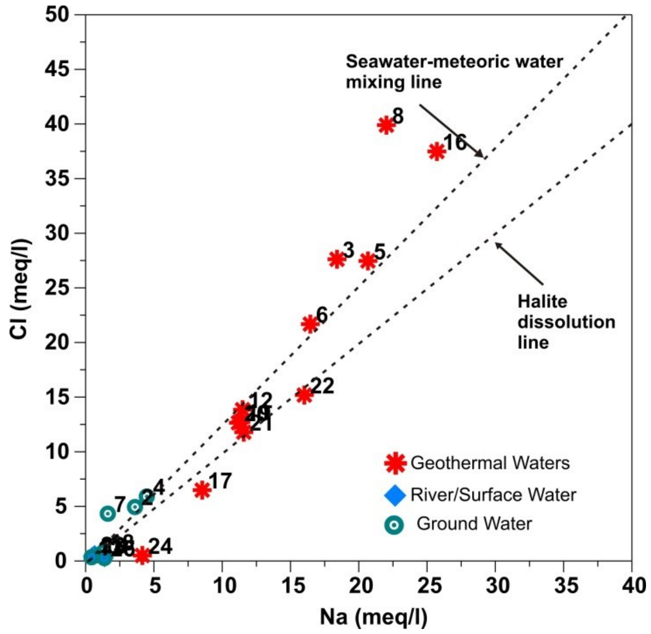


Figure 2: Na-Cl diagram of the West coast thermal and surface waters. The diagram indicates seawater mixing and halite dissolution lines.

The classification of waters using Piper diagram (Piper, 1944; Fig. 2) indicates that most of the thermal springs are either Na-Cl-SO_4 type except the Rajapur thermal spring which is Na-HCO_3 type. The groundwater and surface waters belong to Ca-HCO_3 type and fall close to each other indicating meteoric origin. As seen from the chemistry Rajapur thermal springs (#24) have entirely different chemistry compared to other springs indicating that it belongs to an entirely different reservoir presumably interacting with the Puttur granites or the Precambrian granites underlying the Deccan Basalts (Ramanathan et al, 1987 and Singh et al. 2014). The current data very well matches with the earlier studies conducted by Ramanathan et al, 1987 and Minissale et. al, 2000 indicating a well-organized geothermal system operating in the west coast geothermal province.

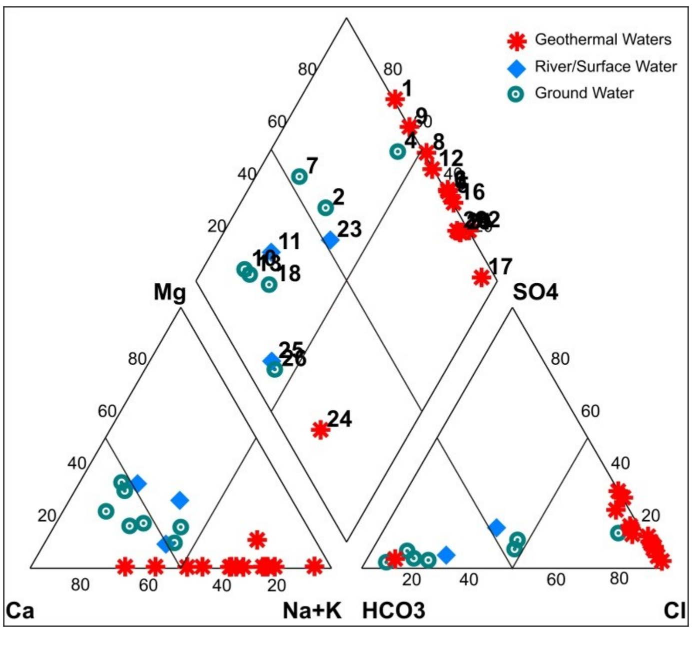


Figure 3: Piper diagram indication classification of water samples

3.2 Trace Element Compositions

Except for a few trace elements (Minissale e al., 2000) , investigation on the trace elements concentration in the thermal waters of west Coast of India is lashing. a systematic study has been undertaken to analyze concentration of trace elements in the west coast thermal waters in order to understand the evolution of the thermal waters and reservoir characteristics. The data is presented in Table 2.

A few elements like Ag, Cd, In, Tl, Th and U were analyzed but were found below the detection limit of the instrument and hence not reported in the Table 2. Trace elements like Li, B, Co, Ni, Ga, Rb, Cs, Sr and Ba remain unaffected in the thermal waters due to secondary processes (Giggenbach, 1988) and hence play a significant role in understating the evolution of the thermal waters.

The alkali metals Li, Rb and Cs that are useful in understanding the deep processes (Giggenbach, 1988) are plotted in the trilinear diagram (Fig. 4). It is interesting to note that sample # 16, 17, 19 and 21 may be belonging to similar reservoir, though Anjaneri thermal spring (# 22) which is much closer to the sample 21 plots in away from it as it has very high lithium and boron values. This can also be seen in the chemistry of major ions where sample 22 has the high SO_4 (Table 2) content whereas all other have slightly lesser..

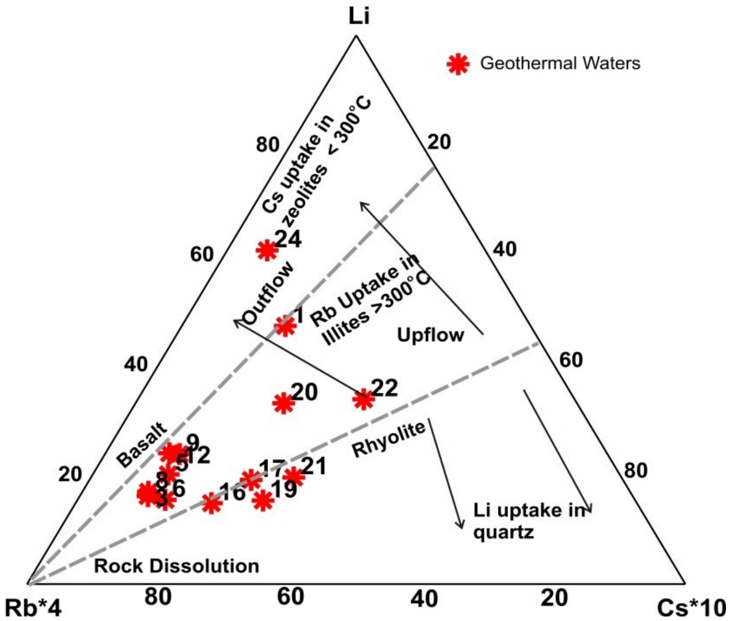


Figure 4: Li-Rb-Cs ternary diagram

Boron concentration in the water samples varied from 34 -1073 ppm for thermal waters and 4-63 ppm for groundwaters. Like Li and Cs, B concentration was also highest in the Anjaneri Thermal spring (#22). It is to be noted that this spring emerges at 42°C very close to the river indicating significant river water mixing. Still these elements are higher than the river water (#23) pointing towards significant water-rock interactions at elevated temperatures. The enrichment of B over Li, Rb and Cs may be due to preferential release of B and also due to incorporation of the alkali elements into secondary minerals as discussed in Figure 3.

The Ba concentrations in the thermal springs range from 2 to 2000 ppb, although the average concentration was approximately 35 ppb. The Rajapur (24, Table 2) thermal springs recorded the highest Ba content of 2000 ppb. Barium and Sr are known to form sulfate and carbonate minerals as well as being incorporated into carbonates, sulphates and aluminium silicates where they substitute for Ca (Nemee, 1975). The Ca-Ba and Ca-Sr relationship is shown in Figure 4. The positive correlation of Ca and Sr points towards additional source of Sr other than water-rock interactions at elevated temperatures. The Rajapur thermal springs are $NaHCO_3$ type and are depleted in Ca as against other springs at the west coast, which may have resulted in such high dissolved Ba in the samples. Also as discussed in the previous sections, the major ions composition of the Rajapur springs depicts a circulation through Precambrian granites high in Ba concentrations. This supports our earlier observation that Rajapur thermal waters are circulating through granite basement rocks even though the springs are issuing through Deccan basalt flows (Ramanathan an Chandrasekharam.....there are two papers by Ramanathan..include bothe here and also the recent publication on Gugi granite),

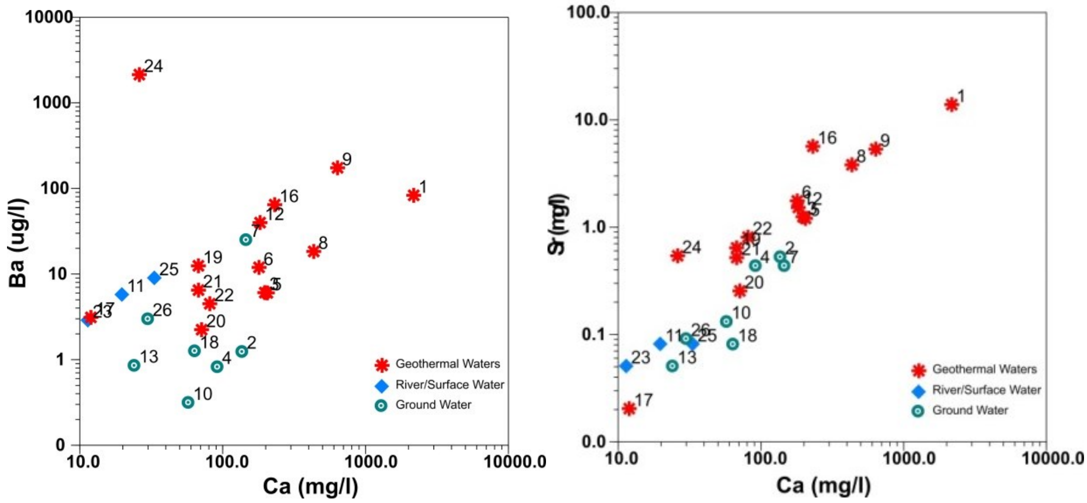


Figure 5: Ca/Ba and Ca/Sr relationship in the geothermal and surface waters of west coast.

3.3 Rare Earth Elements

The studies on REE composition in geothermal waters has gained momentum in a past few years owing to its probable application in tracing the origin of fluids, which is fundamental in understanding any fluid-rock system. The suite of REE's enables to study the source of fluids, the state of equilibrium in water-rock interaction, and changes of fluid composition by both precipitation of scale formation during ascent. Most of these studies are limited to high enthalpy resource's with acidic brines as they contain considerable amount of REE as compared to alkaline waters.

In the present study, REE content of low enthalpy alkaline waters is attempted. The ∑REE content in the unfiltered thermal waters was very low ranging from 11-700 ppt (ng/L) and ranges from~10^{-6} to 10^{-5} times chondrite. The chondrite normalized patterns exhibit an overall negative slope indicating LREE enrichment.

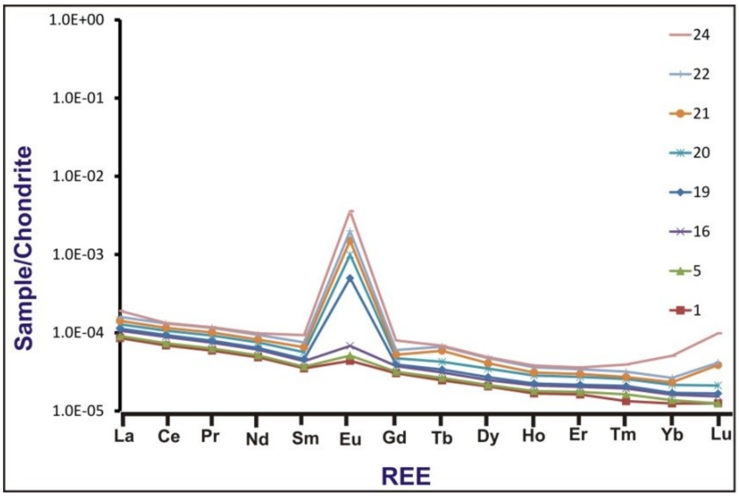


Figure 6: Chondrite normalized REE pattern in unfiltered samples of thermal waters from west coast .

A pronounced positive Eu anomaly can be seen in all the chondrite normalized water samples. Strongly positive Eu anomaly occurs at temperatures above 250°C (Moller, 2000). At higher temperatures Eu occurs as Eu (II) as there are reducing conditions, but in alteration reactions and at low temperatures, Eu is in Eu (III) state and this process rejects Eu (II) which gets sorbed on to mineral surfaces. This can give rise to an inherited Eu anomaly. This can particularly happen in alteration of feldspar particularly plagioclase. Thus alteration of feldspar seems to be a source of such prominent positive Eu anomaly as most of the thermal springs in the west coast circulate through the Deccan Basalts.

4. CONCLUSION

The West coast of Maharashtra in India hosts several thermal springs which are aligned along a major tectonic feature, the West Coast Fault. The temperatures of these springs varied from 42 to 71°C while groundwater temperatures were around 30°C. The chemistry of thermal waters deciphered using Piper diagram indicates that the thermal waters are mostly Na-Ca-Cl or Ca-Na-Cl type with exception of Rajapur which is of $NaHCO_3$ type. Thus showing a high level of Seawater intrusion or a mixing of seawater at a certain depth. The Intrusion will me it difficult for power generation as it shall have a high corrosive effect on the turbines and power generation equipment.

In addition Trace elements namely; Al, Ag, As, B, Ba, Cd, Co, Cr, Cs, Cu, F, Fe, Li, Ga, Mn, Mo, Ni, Pb, Rb, Zn, Sb, Si, Sr, Tl, W and Zr were estimated in Thermal Springs, Ground waters and surface waters for filtered and unfiltered samples. Elements like Fe, Zn and Mn showed large differences in concentrations in filtered and unfiltered water due to their association with particulate matter. In the Li, Rb and Cs plot, samples from the northern part #3, 5, 6, 8 and 9 and samples # 16, 17, 19 cluster together indicating two separate reservoirs or processes controlling these springs. Incorporation into Feldspars and clays at temperature less than 250 °C was seen in Rajapur thermal spring (#24), while sample # 22 would seems to have reached a temperature of > 300 °C for the Rb to be taken up by illites. Sample number # 22 and #24, the most southern sampling points, seem to be controlled by a complete different geological set-up. From the geothermometry in the above figure and gradients of 57 °C it seams clear that expect Rajapur where tempeurates might be in the visinity 250 to 300 °C the average reservoir temperatures might be in the range of 135-140 °C

From a Geothermal direct use perspective, west coast geothermal provinces serves as a ready platform for developing Natural green houses, dehydration units for perishable food products, Aqua culture centers and Natural health spas, thus promoting the growth of secondary and tertiary industries along with its associated direct and indirect job. Geothermal development in Maharashtra should be divided into present, mid and long term developmental plans. With present development plans centered around direct uses which shall promote the concept of geothermal energy to the masses as well as create sustainable small to medium enterprise businesses. Mid and long term development plan should be centered around use of geothermal energy for generating cheap, clean and base power generation systems, beginning with drilling of ten to fifteen deep exploration along the identified locations. A detailed progress, market process study and economic outlay has been submitted to the government, the results of which shall be showcased in the presentation over the next 12 months.

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Table 1. Major ions in the water samples (All values in ppm unless specified)

S. No	Water type	Temp (°C)	pH	Cond (µS/cm)	TDS	Na	K	Ca	Mg	Cl	HCO_3	SO_4	F^-	Br^-	SiO_2
1	TW	44	7.31	13590	8698	1061	14.64	2104	2.93	5500	15	179	0.41	9.78	53.22
2	GW	31	6.86	1199	767	81.2	0.572	134	25.15	172	280	52.9	0.16	0.00	53.65
3	TW	42.5	8.82	3000	1920	419	7.56	191	0.00	975	15	143	1.72	2.37	52.47
4	GW	29	7.06	1064	681	101	0.587	90	19.62	206	40	46.6	0.54	0.00	55.97
5	TW	57	8.78	2941	1882	471	7.99	199	0.00	970	15	129	1.84	2.56	61.07
6	TW	60	8.75	2377	1521	374	6.49	174	0.00	765	10	138	2.57	1.84	66.63
7	GW	29	6.93	916	586	35.4	1.13	143	28.69	150	255	30.1	0.21	0.59	47.43
8	TW	48	8.53	3960	2534	502	8.6	420	0.00	1410	10	160	2.50	3.52	60.34
9	TW	44	7.08	4870	3117	482	8.59	617	1.09	1980	25	117	1.47	3.56	44.81
10	GW	29	7.24	422	270	15.7	1.42	56.4	20.64	15.5	190	11.4	0.14	0.45	46.01
11	RW	30	7.83	171.5	110	8.10	0.75	19.2	7.59	12.4	60	3.08	0.15	0.11	23.46
12	TW	43	8.4	1870	1197	260	3.65	177	0.00	486.5	15	275	3.40	2.48	48.43
13	GW	30	7.04	212.6	136	8.06	0.18	23.6	7.71	9.2	85	2.79	0.18	0.09	58.38
16	TW	71	8.14	3590	2298	587	17.97	224	0.00	1325	15	137	1.29	4.59	66.73
17	TW	44	8.64	875	560	192	4.59	11.6	0.00	226	30	92.3	3.37	0.57	82.92
18	GW	30	7.28	415	266	28.3	2.69	62.5	10.09	26.1	170	4.66	0.20	0.036	19.71
19	TW	63	7.8	1446	925	257	7.94	65.5	0.35	447	40	110	2.31	0.00	94.22
20	TW	53	7.94	1402	897	253	6.39	69.0	0.00	445	45	92.2	2.26	2.31	95.54
21	TW	54	8.19	1480	947	262	7.9	65.6	0.00	414	35	110.3	2.52	0.21	98.76
22	TW	40	8.74	2052	1313	364	8.63	78.7	0.00	535	10	266	7.06	0.62	52.57
23	RW	30	7.25	160.4	103	11.8	0.46	11.1	4.49	17.5	40	9.79	0.20	0.00	26.25
24	TW	42	7.7	526	337	91.4	13.11	25.3	7.91	14.6	255	7.19	0.91	0.00	26.71
25	RW	33	7.98	280	179	28.5	0.88	32.4	3.36	6.61	135	1.48	0.16	0.00	87.86
26	GW	32	7.79	277	177	29.7	0.89	29.4	3.47	6.06	140	2.29	0.14	0.00	85.26

TW – Thermal Springs; GW- Groundwater, RW- River/Surface water