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High-heat-producing granites of East Dharwar Craton around Gugi, Karnataka, and their possible influence on the evolution of Rajapur thermal springs, Deccan Volcanic Province, India

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Abstract

Background: The thermal springs of Rajapur situated along the west coast of Maharashtra and parts of high-heat-generating granites of Gugi in Karnataka (India) seem to be genetically related. The present investigation involves quantification of the heat generated by the Gugi Granites using the U, Th and K contents in the rock samples and probing their possible influence on the evolution of the Rajapur springs, based on the geochemistry of the thermal waters, published Bouguer gravity anomaly data, and the overall geological setup.

Methods: Fourteen water samples from Rajapur including thermal and groundwater samples were analysed for major ions and five rock samples from the gugi area were analysed for U, Th and K.

Results: Rajapur thermal spring is of Na-HCO₃ type, while other thermal springs along the west coast are either Na-Cl type or Na-Cl-CO₃ type. The stable isotope data of the thermal waters signifies mixing with the ground water. The gravity anomaly data supports the extension of the Gugi Granites below the Deccan Volcanics of the study area.

Conclusions: The present investigation suggests that the Gugi Granites could be the main source of heat for these thermal springs, even though the springs issue through the Deccan volcanic flows.

Keywords: Heat source; Rajapur thermal springs; Gugi Granite; Heat generation

Background

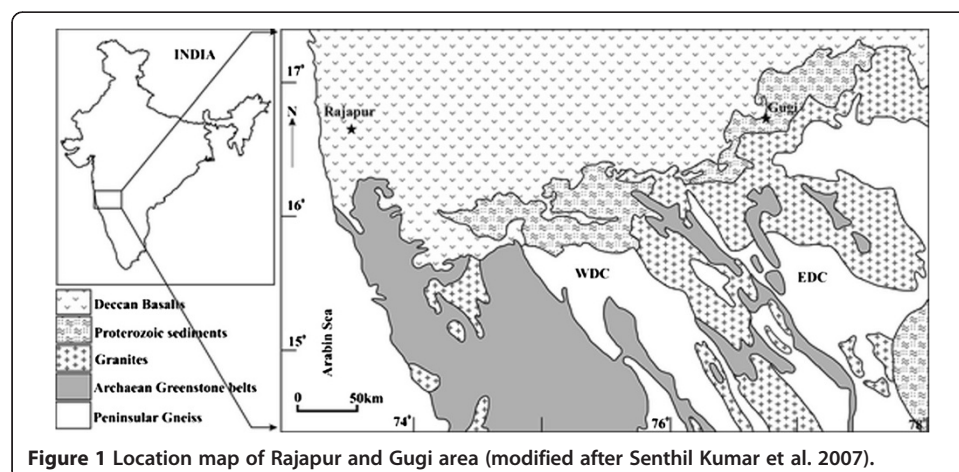
The Rajapur thermal springs belong to a group of thermal springs located along the west coast of India, which emerge through the 65 Ma Deccan Flood Basalt (DFB). The western margin of the Deccan Trap is characterized by these thermal springs, extending for a distance of about 300 km along the Konkan coast in the Thane, Raigad, and Ratnagiri districts of Maharashtra (Chandrasekharam 2005; Kumar et al. 2011). Although these springs discharge through the Deccan Volcanics, some of them show a close relationship to the Precambrian gneissic and granitic basement (Ramanathan and Chandrasekharam 1997). Along the western margin of the Deccan Volcanic Province (DVP), an approximately 1,000-m-thick sequence of near horizontal lava flows is

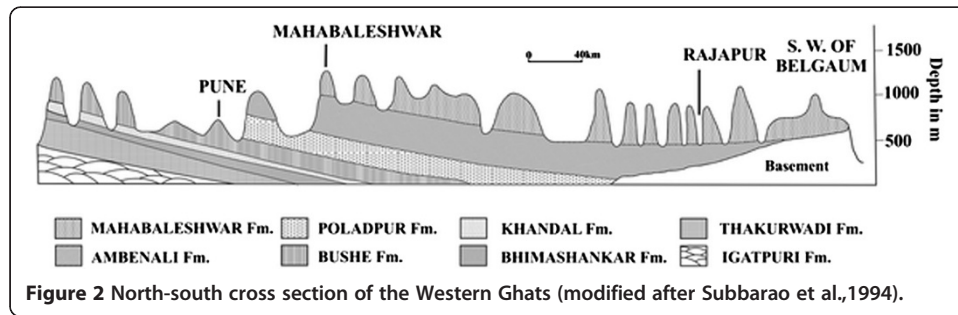
exposed, overlying Precambrian sedimentary and meta-sedimentary (Kaladgi and Dharwar) rocks and Archaean crystallized complex (Kumar et al. 2011). Basaltic lava flows that overlie the older rocks of Dharwar and Kaladgi are both of 'a'a and Pahoe-hoe types (Sahasrabudhe et al.: A geological report on the Koyna earthquake of 11.12.67, unpublished work; Ghodke et al.: West coast geothermal investigation, District Ratnagiri, unpublished work). In the southern portion of DVP, flows are characterized by the 'a'a type, e.g., in the Ratnagiri district, Maharashtra (Kumar et al. 2011). Large outcrops of these granites can be found towards the south and southeast of the DVP. The nearest location (350 km from Rajapur) of such an outcrop is encountered at Gugi in Karnataka (Figure 1), where granites with high U and Th content have been reported (Senthil Kumar and Srinivasan 2002). Further, these granites also host uranium veins (Senthil Kumar and Srinivasan 2002). Such granites also occur as inliers, as encountered south of Rajapur (Ramanathan and Chandrasekharam 1997).

The present investigation deals with the possible influence of high-heat-producing granites of Gugi on the propagation of the Rajapur thermal springs. With the help of gravity anomaly data (GSI in 2006), an attempt has been made to find the extent of these granites below the volcanic flows at the thermal springs site.

Geology of Rajapur thermal spring site

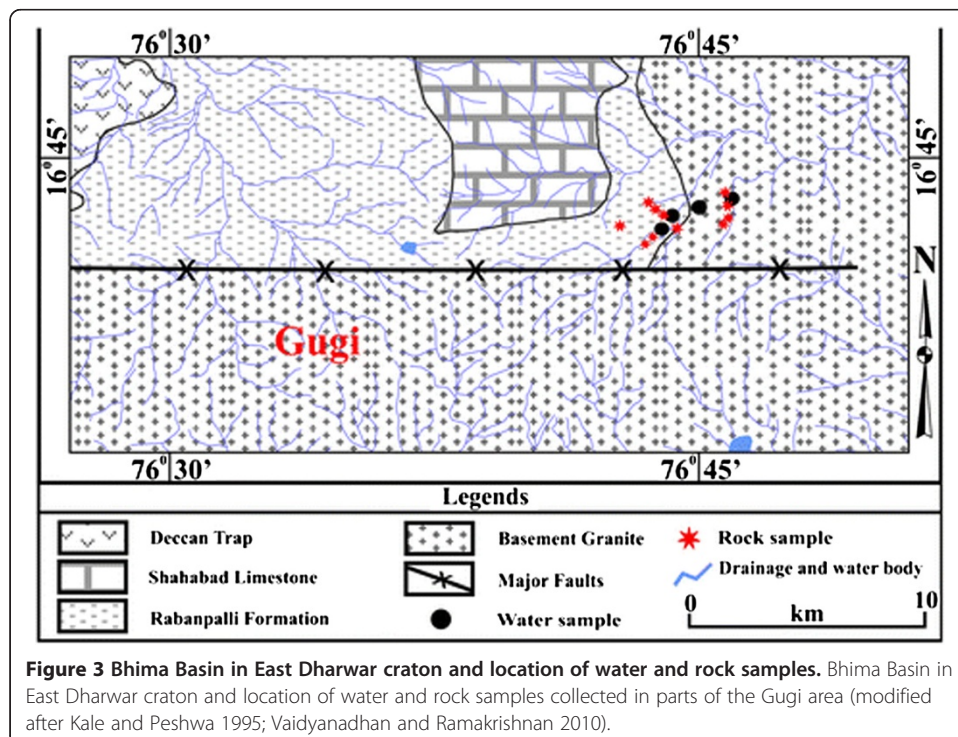
DVP is one of the world's largest continental flood basalts, which are spread out over the north-western, central, and southern Indian Peninsula, with a total exposed area of about 5.0×10^5 km². The total thickness of the basalt lava flows varies from 2,500 to 3,000 m along the west coast, decreasing gradually towards the east. The Deccan Trap flows are traversed by a large number of N-S trending faults and dyke swarms (Hooper 1990). The thermal springs on the west coast are aligned along this major tectonic feature, i.e., the West Coast Fault (Chandrasekharam 1985; Minissale et al. 2000). The geothermal gradient, deciphered from the study of boreholes, is about 57°C/km (Chandrasekharam 2000). In the Rajapur area, the thickness of the basalt flows is approximately 600 m (Figure 2) (Subbarao et al. 1994). The study area is dominated by the highly fractured Deccan Basalt. In some places, scoria and layering in basalt are also present. This is where both cold springs (<27°C) and thermal springs (41°C to 72°C) are present.





Geology of the Gugi Area

The major exposed rock type is Closepet Granite at the western margin of the Eastern Dharwar Craton (Swaminath and Ramakrishnan 1981), where it meets with the Bhima Basin. The basement of Neoproterozoic Bhima Group consists of the Late Archean granitoid, which can be seen exposed along the southern margin of the Bhima Basin (Figure 3). These granitoid rocks are rich in U- and Th-containing minerals such as sphene, apatite, and zircon (Senthil Kumar and Srinivasan 2002; Senthil Kumar and Reddy 2004). Closepet Granite Suite also contains K-rich granitoids in which uranium mineralization is reported (Senthil Kumar and Srinivasan 2002). Most of the uranium mineralization is within the Archean granitoids of Dharwar Craton and Neoproterozoic fault of Bhima Group of rocks (Pandit et al. 1999; Dhana Raju et al. 1999). The available heat flow data in the Dharwar Craton ranges between 25 and 51 mW/m² (Senthil Kumar and Reddy 2004).



A detailed geological map was prepared based on the field observations around Gugi. The Archaean Granite is exposed with Proterozoic sediments, which are mostly carbonates of the Bhima Group. Both are in contact with an E-W trending reverse fault, steeply dipping towards the north, known as 'Gugi-Karalagere fault', extending up to Karalagere in the west with a maximum width of 500 m. This fault, cutting across the carbonate and granitoid rocks and horizontal beds of sedimentary formation of the Neoproterozoic Bhima group, forms steep dips in the fault zone. Lamination, brecciation, and asymmetric folds are clearly observed in the carbonate rocks.

Occasionally, small blocks of granite are exposed around Gugi. Grey and purple shale, limestone, and basement conglomerate of the Bhima Basin are exposed along the fault zone. Dark-colored, coarse-grained blocks of peninsular gneiss are also observed in several places. Grey soil is observed because of the presence of phosphate in the Bhima Basin sediments.

Methods

Sample collection and water analysis

Representative rock and water samples were collected from Gugi area (Figure 3), while only the water samples were collected from the Rajapur area (Figure 4). All the water samples were collected in two sets. One set of water samples was acidified with HNO_3 (with 5 mL 14 M ultrapure HNO_3/L) on site, and the other set was stored at a lower temperature for future analysis (Arnorsson 2000; Marini 2010). The water samples from Rajapur include samples from thermal springs, rivers, bore wells, and ponds. Temperature and pH were measured in the field using an ORION pH meter (Thermo Fisher Scientific, Hudson, NH, USA).

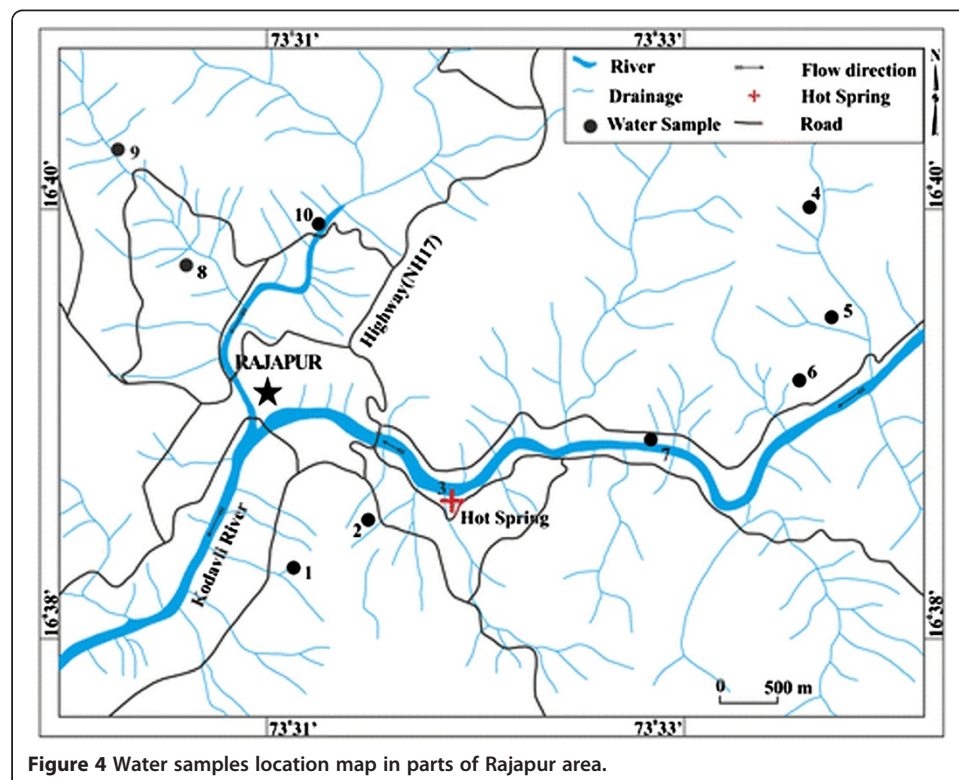


Figure 4 Water samples location map in parts of Rajapur area.

Table 1 Physical and chemical parameters of water samples from the study area

Serial no.	Sample name	Temp (°C)	pH	TDS	Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	SiO ₂
1	RGw	26.5	6.5	54	3.7	0.01	4	2.4	6.5	4.3	16	8.3
2	RGw	24	7	87	3.9	0.1	7	8.7	8.5	5.3	50	8.3
3	RTw	41	8.3	557	74.6	11.8	43.1	11.6	17.6	11.9	340	52.5
4	RGw	26	7	96	3.5	0.1	14	3.9	9.7	8.7	40	13.1
5	RGw	27	6	138	6.9	1.6	12.6	2.4	10.4	4.6	50	24
6	RGw	26	6.7	277	4.2	0.01	31.1	10.6	10.2	9.9	120	56.6
7	RSw	26.4	7.6	156	3.1	0.4	18	7.7	8.4	7.3	75	27.5
8	RGw	26	7	621	13.1	0.45	50.1	6.2	12.9	8.1	180	86.1
9	RSw	27	6.5	104	3.8	0.3	12	7.3	9	8.7	60	8.9
10	RSw	26	7	91	4.2	0.4	12	2.4	7.3	8.9	40	11.8
11	GWs	26.7	7.6	219	65.5	2.7	38.1	22.7	77.5	55.1	185	19.6
12	GWs	27	7.9	358	101.8	3.7	32.1	29.6	99.3	44.1	275	13
13	GWs	26	7.5	497	130.2	3	102.3	11.5	202	47.6	275	1.7
14	GWs	26	7	412	101.1	14.6	111.3	15.5	137	50.3	370	29.4

RTw, Rajapur thermal water; RGw, Rajapur groundwater; RSw Rajapur surface water; GWs, groundwater sample, Gugi.

The water samples were analyzed for major cation and anion concentrations. Cations and silica were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES). The sulphate concentration was measured with the aid of a UV spectrophotometer and alkalinity by a H₂SO₄ titration and chloride using the ion selective electrode method (Table 1). These analyses were conducted as per the standard procedures (APHA 1977).

Estimation of radioactive heat

The radioactive heat production (RHP in μW/m³) of granite was calculated by taking into account the heat generation constant (amount of heat released per gram U, Th, and K per unit time) and the uranium, thorium, and potassium concentration C_U, C_{Th}, C_K present in rock (Rybach 1976; Cermak et al. 1982):

$$RHP = \rho(9.52C_U + 2.56C_{Th} + 3.48C_K) \times 10^{-5}$$

where ρ is the bulk density of rock in kilogram per cubic meter, C_U and C_{Th} are in weight parts per million, and C_K is in weight percent.

To determine the U and Th concentrations in rock samples, powdered samples of less than 200 mesh were mixed with cellulose in a 4:1 ratio (Bertin 1978) to form pellets, which were analyzed by XRF. For potassium, powdered rock samples were diffused with lithium meta-borate and tetra-borate to make a rock solution then analyzed by

Table 2 U, Th (in ppm), and K (%) values in selected rock samples

Sample no.	U (ppm)	Th (ppm)	K (wt.%)	RHP (μW/m ³)	Heat flow (mW/m ²)
L2	1.1	66.8	0.2	4.92	44.9
L3	6.1	4.7	5.8	2.43	42.4
L4	3.2	1.0	1.6	1.04	41.0
L5	4.8	5.7	5.3	2.13	42.1
L16	6.4	1.0	5.9	2.28	42.3

ICP-AES. The RHP from the granites of Gugi is shown in Table 2. In the present investigation, the heat flow value of the area was measured by the relationship between the radioactive decay to the surface heat flow described by the following equation (Birch et al. 1968; Lachenbruch 1968):

$$Q = Q_0 + D \times A$$

where Q is the heat flow at the surface, Q_0 is an initial value for heat flow unrelated to the specific decay of radioactive element at the current time, D is the thickness of crust over which the distribution of radioactive elements is more or less homogeneous, and A is the heat production rate per volume of rock (Glassley 2010). Assuming that the background heat flow is approximately 40 mW/m^2 (Glassley 2010), then heat flows of the location are given in Table 2.

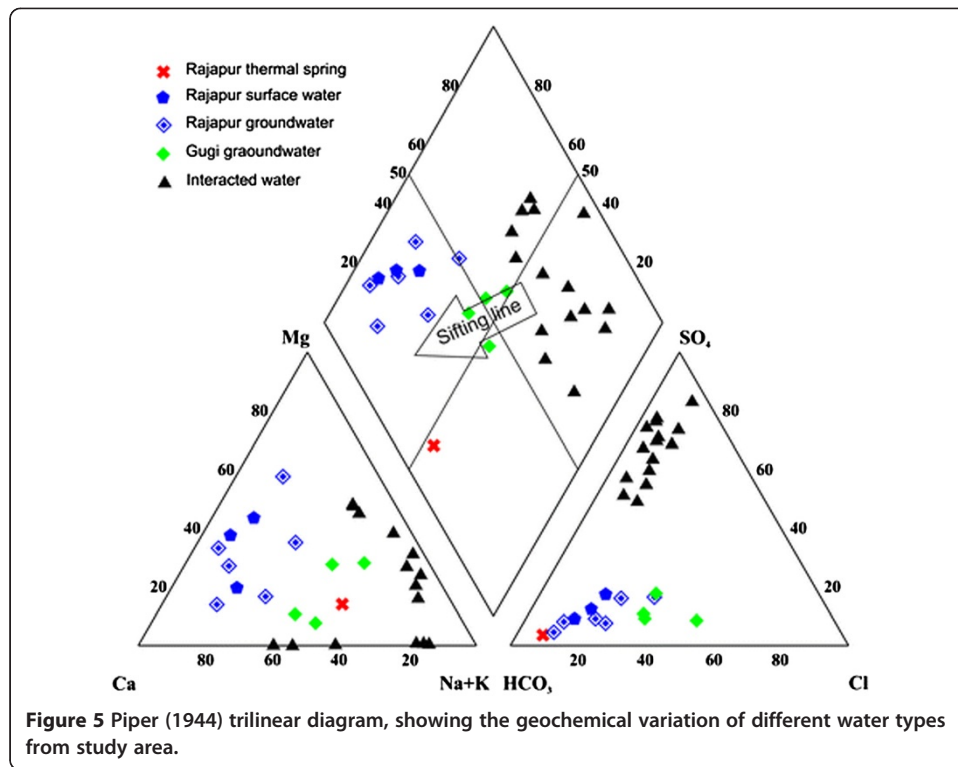
Gugi is located in the Eastern Dharwar Craton (EDC) where the heat flow values range between 25 and 51 mW/m^2 (Senthil Kumar and Reddy 2004), common to the all Archean provinces (Jaupart and Mareschal 1999). In the Gugi granites, the observed concentration of U is at 1.1 to 6.4 ppm, Th at 1.0 to 66.8 ppm, and K at 0.2 to 5.9 ppm, and the average heat flow value is $42.5 \text{ mW/m}^2/\text{m}$ (Table 2). However, in the Deccan basalt province, the average concentration of U is at 0.64 to 1.79 ppm, Th at 0.54 to 1.32 ppm, and K at 0.17 to 0.34% (Paul et al. 1984). These values indicate the RHP value to be in the range of 0.27 to $0.59 \mu\text{W/m}^3$ which is much less than that of the Gugi granites, signifying the role of Gugi granites in the propagation of the Rajapur thermal springs.

Results and discussion

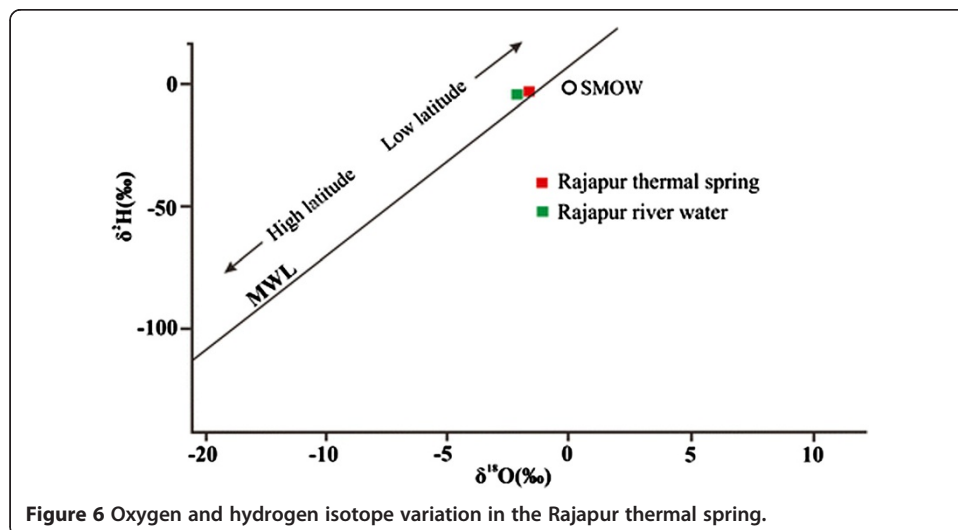
Hydrogeochemistry

Earlier studies carried out on the West Coast thermal springs have shown a high Na content (Ramanathan and Chandrasekharam 1997; Minissale et al. 2000), and most of the thermal springs are of the Na-Ca-Cl and Ca-Na-Cl types, mainly due to the interaction with seawater (Muthuraman 1986). However, the Rajapur thermal spring which is also along the west coast is of Na-HCO₃ type. The thermal spring is slightly alkaline in nature (pH = 8.3 at 25°C) with 557 mg/L total dissolved solids. The SiO₂ concentration in the thermal water is slightly lower than some of the groundwater which can be attributed to the precipitation of SiO₂ during its ascent. The ionic concentrations measured during the present investigation are shown in Table 1 and were plotted with water-rock interaction data from Singh et al. (2012) in Piper trilinear diagram (Piper; Figure 5). The plots clearly indicate that the thermal spring water is Na-HCO₃ type. The data fall in the secondary alkalinity field (Figure 5) dominated by the alkaline earths (Ca²⁺, Mg²⁺) and weak acids (HCO₃⁻). Well, river, and pond water samples are also Ca-HCO₃ type, and their chemistry is compatible with the chemistry of the rocks through which they flow. In the Piper diagram (Figure 5), surface and cold spring waters plot in almost the same field, indicating that they are recharged through meteoric water. The amount of total dissolved solids in the thermal water is found to be about 550 ppm in Rajapur, while in Gugi area it varies from 220 to 500 ppm in the water samples.

To understand the circulation of the water through the Gugi granite, we conducted water-rock interaction experiment for selected granite samples. The granite



samples were crushed to <1 mm. The water-rock interaction experiment was carried out in a glass chamber with fluid/solid ratio of 10:1 at 100°C. Rainwater was utilized in the experiment as the interacting fluid. Water-rock interaction experiment with samples derived from the granites shows wide range of geochemical variation. Most of them fall in the Na-SO₄ field (Singh et al. 2012), while the thermal springs and the surface waters fall in the Ca-HCO₃ field (Figure 5). It indicates circulation of meteoric water within the granites (host of the thermal reservoir) and emerging through the Deccan Basalt flows, after mixing with the near-surface groundwater and thus becoming rich in Ca-HCO₃ component. It further



strengthens our earlier view (Chandrasekharam and Chandrasekhar 2010) that the granites are the main source of heat for the thermal springs in several geothermal provinces of India.

Isotope data

The stable ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) isotope data is taken from an unpublished work (Ramanathan: Geochemistry of the thermal springs located along the West Coast, unpublished work) and plotted in the $\delta^{18}\text{O}$ vs. $\delta^2\text{H}$ diagram (Figure 6). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for thermal water is -1.6‰ and -5‰ and for Rajapur river water is -2.2‰ and -6‰ , respectively. The thermal spring does not show significant 'oxygen shift' indicating that the spring is not of high-temperature type, which does not attain more than 220°C (Nutti 1991), or the residence time may not be sufficient for the exchange to occur.

Geothermometry

Silica geothermometry

In 1973, Fournier gave the silica geothermometry for the estimation of the reservoir temperature as follows (Fournier 1973):

Quartz geothermometer with no steam loss:

$$T(^{\circ}\text{C}) = \frac{1,309}{5.19 - \log S} - 273.15$$

Quartz geothermometer with maximum steam loss:

$$T(^{\circ}\text{C}) = \frac{1,522}{5.75 - \log S} - 273.15$$

where S is the concentration of silica in thermal water. The estimated reservoir temperatures based on quartz is always lower than that of the ion-exchange geothermometry because of the quick re-equilibration of quartz to the surroundings (Fournier 1977). The estimated reservoir temperature of 104°C and 105°C , respectively, is considered as the minimum reservoir temperature.

Cation geothermometry

Cation geothermometers are used to estimate the reservoir temperatures. We have calculated the reservoir temperature using the following formula (Giggenbach 1988):

$$T(C_{\text{kn}}) = \frac{1,390}{1.75 - \log\left(\frac{K}{\text{Na}}\right)}$$

where 'kn' represents 'K and Na' and K and Na are in milligram per liter.

$$T(C_{\text{km}}) = \frac{4,410}{14 - \log\left(\frac{K^2}{\text{Mg}}\right)}$$

where 'km' represents 'K and Mg' K and Mg are in milligram per liter.

The reservoir temperature calculated using the above equations individually gives two different values (281°C and 70°C respectively) since the reaction involved K-Na equilibrates at high temperatures while $K/\sqrt{\text{Mg}}$ equilibrates at low temperatures. Further, the reaction involving K and Mg equilibrates is faster, and their

temperatures estimated from surface geothermal waters give very low reservoir temperatures. Reactions involving K and Na do not adjust quickly to the physical environment at shallow depths. So in this case, cation geothermometry overestimates the reservoir temperature.

Cation composition geothermometer

Nieva and Nieva (1987) developed the cation composition geothermometer; the relationship between cations is as follows:

$$T(K) = \frac{14,990}{7 \log\left(\frac{[Na^+]}{[K^+]}\right) + 2 \log\left(\frac{[Ca^{2+}]}{[Na^+]}\right) + 2 \log\left(\frac{[Mg^{2+}]}{[Na^+]^2}\right) + 29.39}$$

where $[x]$ is the mole concentration of species x (mol kg^{-1}).

He divided this equation into four subgroups, and according to this division our data fall in the first subgroup. In the first subgroup, the equation is modified as follows:

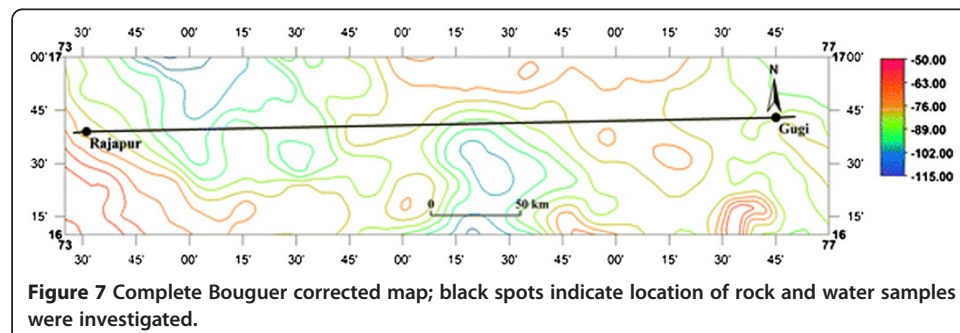
$$T(K) = \frac{11,140}{6 \log\left(\frac{[Na^+]}{[K^+]}\right) + \log\left(\frac{[Mg^{2+}]}{[Na^+]^2}\right) + 18.30}$$

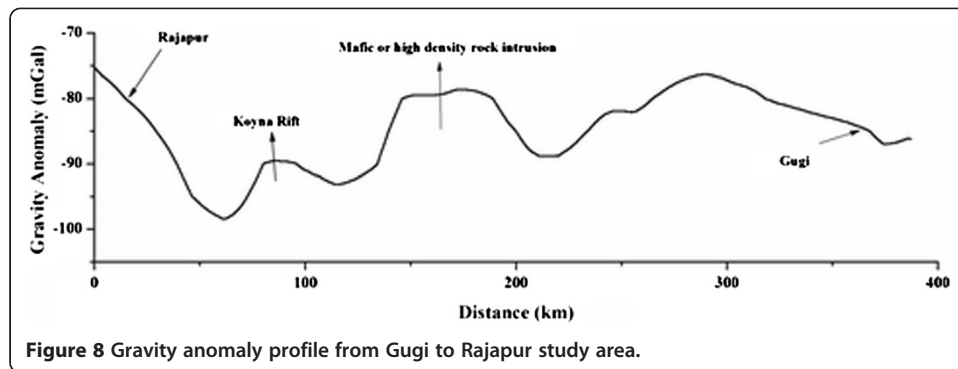
With the cation composition geothermometer (CCG), estimated reservoir temperature is 157°C.

Gravity anomaly

A gravity contour map was prepared based on the terrain-corrected Bouguer gravity anomaly map of India (2006). The study area shown in Figure 7 is characterized by large negative anomalies (-80 mGal). In parts of Gugi and Rajapur areas, low gravity anomaly was observed.

A gravity profile along the line connecting Rajapur and Gugi (Figure 7) is shown in Figure 8. Near Rajapur, a large gravity anomaly is found due to the presence of the Koyna Rift having an average thickness of 50 km (Krishna Brahmam and Negi 1973; Dobrin 1976; Telford et al. 1990). Another gravity anomaly may be due to the presence of dyke or some high-density rock below the Deccan Trap. The exposed granitic rock in parts of Gugi area resulted in negative gravity anomaly. Therefore, a low gravity anomaly near the Rajapur area suggests the presence of granitic terrain below DVP.





Conclusions

The Rajapur thermal waters are of Na-Ca-HCO₃ type, and the stable isotope analysis of thermal and river waters shows a close relationship, which indicates mixing of the geothermal water with the near-surface groundwater. The thermal water is rich in Na⁺, K⁺, Mg⁺⁺, and HCO₃⁻. Water-rock interaction experimental result shows the circulation of the meteoritic water through granites and emerging as the Rajapur thermal springs. Higher total dissolved solids in thermal water can be ascribed to high-temperature water-rock interaction at great depth. Due to the basalt-water interaction at Rajapur, the Na to K and Mg to Na ratio and excessive Ca become less sensitive to temperature variation. The concentration of silica showed a great variation (70 to 400 ppm; Chandrasekharam et al. 1992; Ramanathan: Geochemistry of the thermal springs located along the West Coast, unpublished work). Reservoir temperature estimation based on CCG is here considered as reliable, which gave a reservoir temperature of 157°C. Also, the surface and groundwater from Rajapur show very low concentration of other major ions in comparison to the thermal water in the area (Minissale et al. 2000), whereas the surface and groundwater from Gugi have higher concentrations of major ions with high total dissolved solids. There is no indication of an interaction of seawater with the thermal spring water as is the case of other west coast springs. Thus, the geochemistry of thermal water confirms the location of thermal reservoir to the Precambrian granites underlying the Deccan Basalt.

Radioactive heat production data of granites of Gugi show high values on an average of 42.6 mW/m², which are similar to many other potentially viable areas around the world. This is, hence, considered as the greatest possible heat source of the reservoir of the Rajapur thermal springs.

The gravity profile (Figure 7) from Gugi to Rajapur shows a disparity in gravity anomaly, perhaps due to the variation in thickness of the Deccan Flood Basalt. The gravity anomaly in Rajapur is 10 mGal, which is lower than others observed in the Gugi area. If we apply complete Bouguer correction in the Rajapur area for the 600-m-thick basalt layer, we find a comparatively similar gravity anomaly as in the Gugi area. Also, the existence of low density rock like granite underlying the DFB cannot be ruled out. With the help of the gravity anomaly, it can be predicted that the main heat source for the Rajapur thermal springs is the granitic batholith, which extends from Gugi to the Rajapur. Finally looking at all these aspects, it can be postulated that the thermal waters from Rajapur area, coming from underneath Dharwar Granitic Batholith and underlying the basaltic terrain, interact with the

near-surface groundwater on their way to the surface, to emerge as thermal springs.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

HKS compiled the data, prepared the gravity anomaly map, interpreted the data and drafted the manuscript. YK carried out the experimental work as a part of his M Tech dissertation. TG supervised the experimental work along with participating in drafting the manuscript. Prof DC is our guide/supervisor and guided us throughout the process. BS help to manuscript preparation and data interpretation. All authors read and approved the final manuscript.

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