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Physicochemical Evolution of the Thermal Springs over the Siwana Ring Complex, Western Rajasthan

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Abstract: The chemical composition of thermal springs from Siwana Ring Complex (SRC) of Barmer district, Rajasthan, India has been investigated for the first time. These springs are near neutral to mildly alkaline (pH = 6.8 to 7.8) in nature with surface temperatures varying between 31 to 39 °C. Piper diagram suggests that these thermal springs are dominated by Ca-HCO_3 type. Experimental results of water-rock interaction at 100 °C indicate that the thermal springs are circulating through tuff and a sedimentary formation extensively controlled by ring dykes of granites, felsic volcanics and mafic dyke and the fault systems associated with the host rock. Groundwater and thermal springs show similar characteristics. Estimated reservoir temperature suggests that Siwana area geothermal system is a low enthalpy system. Heat flow values of the area range from 83 to 205 mWm^{-2}, promise a viable potential for Enhanced Geothermal System (EGS).

Keywords: Siwana thermal springs, Siwana Ring Complex, Water-rock interaction, Rajasthan.

INTRODUCTION

Geothermal energy is the clean as well as environmental friendly energy stored in the earth which can be used in different ways, out of which most important use is power generation. Contribution to geothermal energy of earth originates from mantle (20%) and from the radioactive decay of the minerals (80%) (Turcotte and Schubert, 2002). The study area, Siwana Ring Complex (SRC) of Malani Igneous Suite is one of the most promising geothermal sites in India.

A group of thermal springs are located in the Siwana Ring Complex (SRC) of Barmer district of Rajasthan, India with surface temperatures varying between 30° and 40°C. These thermal springs discharge through the Neoproterozoic crystalline granites as well as felsic volcanics of Malani Igneous Suite that are covered by blown sand and alluvium. The SRC is surrounded by intrusion of peralkaline granite ring dykes (Bhusan and Mohanty, 1988) and may be connected with roots of volcano (Pascoe, 1960). The volcanic area is exposed from periphery towards the center in the northern part of the SRC, and the amount of inclination gradually decreases from 30° at the fringe to near horizontal in the core. Horizontal lava flow is dominant in the center part of the subsidence structure and is overlain by three conglomerate beds presumably of aqueous origin interbedded with coarse to fine grade tuffs. Presence of stishovite in the SRC supports the formation of ring structure due to the meteorite impact (Tripathi et al., 2010).

This study is aimed at (i) understanding the evolution of Siwana thermal springs; (ii) estimation of the reservoir temperature using geochemical thermometers and (iii) estimation of heat production and surface heat flow value from the U, Th and K content in the granites.

REGIONAL GEOLOGY AND GEOLOGICAL SETTINGS

The Malani Igneous Suite (MIS) is spread over an area of about 55000 km^2 in the western India (Kochhar, 1989; Bhushan, 1991, 2000). It is the largest A-type felsic magmatism in the western India (Bhushan, 2000; Kochhar, 2000) and third largest acid volcanism in the world, occurred in the trans-Aravalli mountain region (Kochhar, 2000). The MIS is controlled by a number of NE – SW trending tectonic lineaments related to “Hot Spot” magmatism and tectonics (Kochhar, 1984, 2000; Pareek, 1981; Eby and Kochhar, 1990; Bhushan, 1991; Bhushan and Chittora, 1999; Roy and Jakhar, 2002; Vallinayagam, 2004; Singh and Vallinayagam, 2002; Singh et al., 2006). Age of the alkaline granite of Siwana, by Rb/Sr dating, is slightly younger than the Malani rhyolite (Crowford and Compston, 1970).

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Siwana Granites

Siwana granites occur as ring dykes in SRC. They are closely associated with acid volcanic rocks and form the most characteristic feature of the area. These rocks rise up to 975 m above ground level and extend about 8 km wide. The granites are medium to coarse grained in nature with hypidiomorphic as well as granophyric micro textures. Presence of high temperature minerals such as sanidine, bipyramidal quartz and orthoclase indicate high temperature granites. The four main localities, where they are predominant are Siwana, Jasai, Mungeria and Bisala. Anhydrous granite is the main source for the evolution of Siwana granites (Eby and Kochhar, 1990).

METHODOLOGIES AND RESULT

Sample Collection and Water Analysis

Two sets of water samples and representative rock samples were collected from the Siwana area (Fig. 1). One set was acidified with HNO_3 onsite (to prevent the adsorption or precipitation of elements, Appelo and Postma, 2005) and

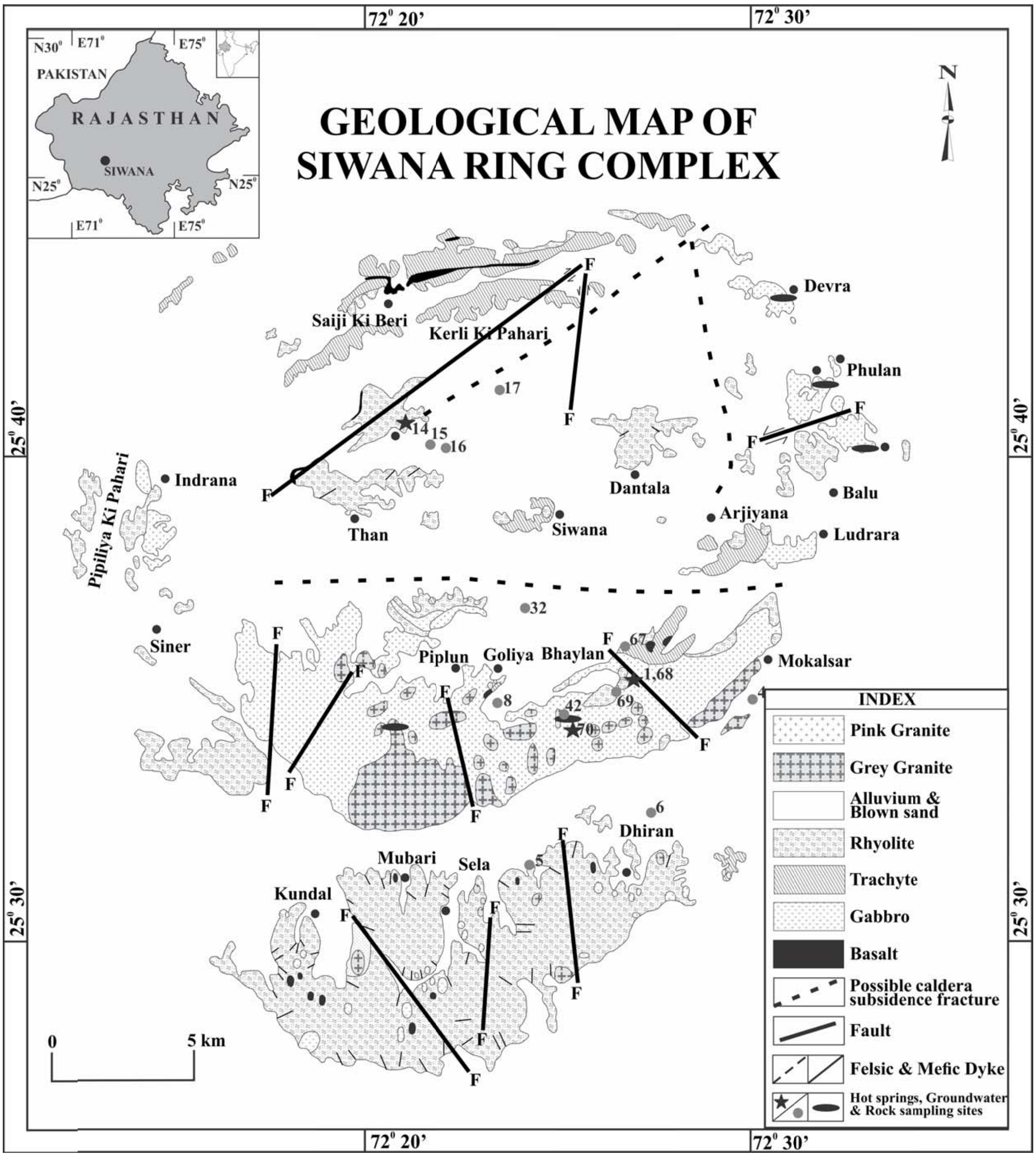

Fig.1. Geological setting in parts of the Siwana Ring Complex including water and rock sample collection sites modified after Bhushan and Mohannty, 1988; Singh and Vallinayagam, 20012.

Table 1. Physical and chemical parameters of water samples from the study area, concentration of major ions, silica in mg/L

Sa. No.*	pH	Temp (°C)	Na	K	Ca	Mg	Cl	HCO_3	SO_4	SiO_2
1	7.1	39	28.9	1.0	88.2	29.0	59.9	330.0	29.3	22.7
14	7.6	35	91.6	3.6	29.5	10.9	101.0	180.0	20.9	18.7
68	6.9	31	33.3	1.2	35.0	11.2	27.0	200.0	16.5	35.8
70	7.2	32	32.3	1.6	40.0	19.3	35.0	230.0	18.6	40.6
67	7.0	26	59.8	1.1	32.0	15.3	48.0	225.0	19.9	36.5
69	6.8	25	38.9	1.0	31.3	19.8	45.0	210.0	23.5	38.2
4	7.2	27	34.8	1.7	88.2	4.8	32.5	285.0	21.0	51.9
5	7.8	28	59.6	1.4	85.2	24.3	63.2	380.0	26.7	45.6
6	7.7	26	60.4	1.5	134.3	14.5	85.3	445.0	17.8	42.2
8	7.8	28	70.3	2.4	102.2	15.4	55.6	440.0	18.0	65.8
32	7.8	27	32.5	1.9	37.0	8.6	39.8	145.0	16.7	35.8
42	7.7	28	38.3	1.6	43.3	16.3	66.2	150.0	55.0	117.8

*where Sa. Nos. 1, 14, 68, 70 are hot springs and 67, 69 are cold springs, and other are groundwater samples.

other set were stored at lower temperature for future analysis (Arnorsson, 2000; Marini, 2000). The pH and temperature of the water were measured in the field itself using ORION pH meter. Cations and silica were analyzed by ICP-AES. Sulfate was measured by UV-spectrophotometer, alkalinity measured by titration and chloride by ion selective electrode (Table 1). These analyses were done as per the standard procedures (APHA, 2005).

To understand the circulation of the water through the Neoproterozoic crystalline rocks, water-rock interaction experiment for selected granite samples was conducted. The granite samples were crushed to <1mm. The water-rock interaction experiment was carried out in a glass chamber with fluid/solid ratio of 10:1 at 100 p C. Rain water was utilized in the experiment as the interacting fluid. The experiments were conducted over a period of six months. Water samples were collected at an interval of one, three and six months. Chemical data of the interacted water is given in Table 2.

Table 2. Chemical analysis of interacted water from representative rock samples (in mg/L)

Sample Name	pH	Na	K	Ca	Mg	Cl	HCO_3	SO_4
A	6.1	0.7	0.2	3	0.9	3.2	9.8	3.4
32 _01m	8.3	43.4	5.8	7.8	0.19	17.6	65.0	39.1
32 _03m	8.2	102.7	10.0	23.0	0.44	14.7	196.0	95.6
32 _06m	8.4	176.6	14.7	48.7	0.99	12.4	413.0	153.3
45 _01m	8.2	24.3	1.4	1.1	0.04	10.5	40.0	11.8
45 _03m	8.1	34.6	2.2	2.5	0.10	9.0	71.0	15.9
45 _06m	8.3	43.9	2.7	7.2	0.32	6.3	104.2	20.8
56 _01m	8.4	32.5	1.4	0.3	0.01	9.7	45.0	22.3
56 _03m	8.6	39.5	2.7	1.0	0.20	9.6	71.0	24.8
56 _06m	8.5	55.6	5.1	3.4	0.14	6.6	110.2	40.7

A: Rainwater; 32, 45, 56: representative rock samples and interacted water after the 1, 3, and 6 month (m) interval

Estimation of Radioactive Heat Production (RHP)

The radioactive heat production (RHP in μWm^{-3}) of granite can be 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)

$$RHP = \rho(9.52C_U + 2.56C_{Th} + 3.48C_K) \times 10^{-5} \quad (1)$$

where ρ is the density of rock in kg/m^3; C_U is concentration of U in mg/kg, C_{Th} is concentration of Th in mg/kg and C_K is concentration of K in weight percent

For the determination of U and Th in rock, samples were crushed to size less than 200 mesh and mixed with cellulose in a 4:1 ratio (Bertin, 1978). Then pellets were analyzed by XRF for U and Th concentration. For K, powder of rock sample was diffused with lithium meta-borate and tetra-borate to make rock solution and analysed by ICP-AES. U, Th, and K value of selected rock samples of SRC and heat production value (RHP) is given in Table 3.

The surface heat flow values were estimated by the following equation (Lachenbruch, 1968).

$$Q = Q_0 + D \times A \quad (2)$$

where Q is the heat flow at the surface, Q_0 is an initial value for heat flow unrelated to the specify decay of radioactive element at the current time, D is the thickness (10,000 m taken given by Arora et al., 2011) of crust over which the distribution of radioactive elements is more or less homogeneous, A is the heat production. Assuming that the background heat flow (Q_0) is approximately 40 mWm^{-2} then heat flow of the Siwana area is given in Table 3.

Table 3. Radioactive elements (U, Th, and K) for selected rock samples, heat production and heat flow value from the SRC.

Sa No.	CKP_45	BLR_41	DMM_02	SUKL_65	PHU_53
U (mg/kg)	17.8	19.6	11.8	6.88	7.9
Th (mg/kg)	165	102	44.7	31.3	28.2
K (wt %)	5.32	4.98	4.77	4.86	3.47
RHP (μWm^{-3})	16.5	12.6	6.6	4.4	4.3
Heat Flow (mWm^{-2})	204.8	165.6	105.7	83.9	83.1

DISCUSSION

Hydrogeochemistry

The major ion composition of the Siwana water samples (Table 1) and water-rock interaction data (Table 2) were plotted in Piper diagram (Fig. 2). The water samples are nearly neutral to mildly alkaline with pH ranging from 6.8 to 7.8. The groundwater is $Ca-HCO_3$ type and thermal waters

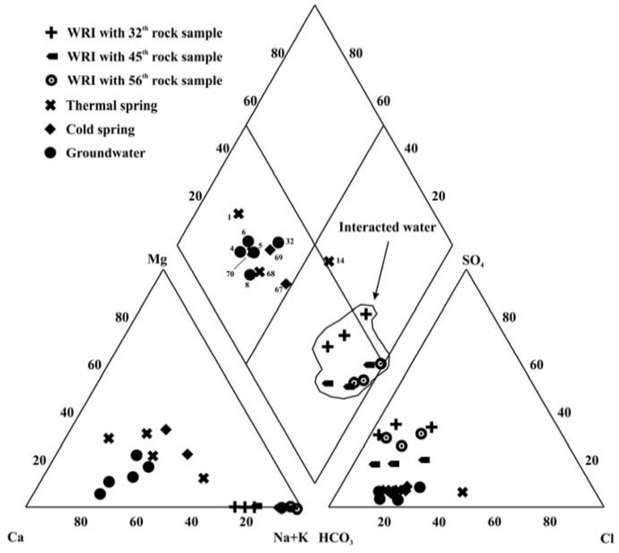

Fig.2. Piper diagram (1944) showing geochemical variation in different water types from Siwana area.

are Ca-HCO_3 and Na-Cl-HCO_3 type. Similar Na/K, Na/Ca and Cl/HCO_3 ratio suggests that, the two thermal springs (samples 68 and 70) are fed by the same reservoir (Fournier, and Truesdell, 1970). One of the thermal spring samples (14) falls close to the field of experimental water-rock data field in Fig. 2, suggesting circulation of the thermal waters within the granite aquifer. Thus, the original Na-HCO_3 thermal waters from the granites flowing through the tuff and other sedimentary material (shallow aquifer) are transforming into Ca-HCO_3 waters due to Ca-Na exchange reactions before emerging to the surface. Our experimental data and the chemical similarity between the thermal spring and experimental water suggest granites as the main thermal reservoir in this area.

Geothermometry

There are several geothermometers available but here we use only few of them. Estimated reservoir temperature based on silica geothermometers (Fournier, 1973) ranges between 68 to 102 °C, whereas it ranges between 76 to 220 °C by cation geothermo-meters (Table 4).

Gravity Anomaly

Gravity anomaly contour map was prepared based on the terrain corrected Bouguer Gravity Anomaly map of India (GSI, 2006). The study area (Fig. 3) is covered by thick sediment and alluvium sand. Negative gravity anomaly

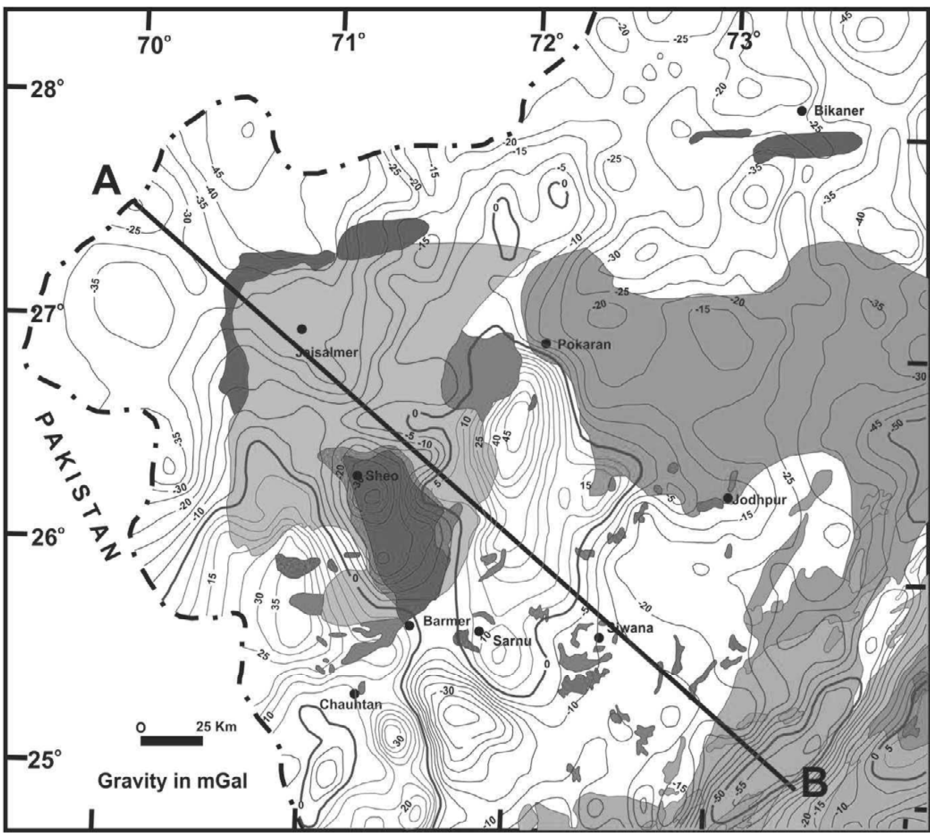

Fig.3. Bouguer Gravity anomaly (Terrain corrected) map of Western Rajasthan (after ONGC, GSI, Survey of India, Oil India and Reliance, 2006)

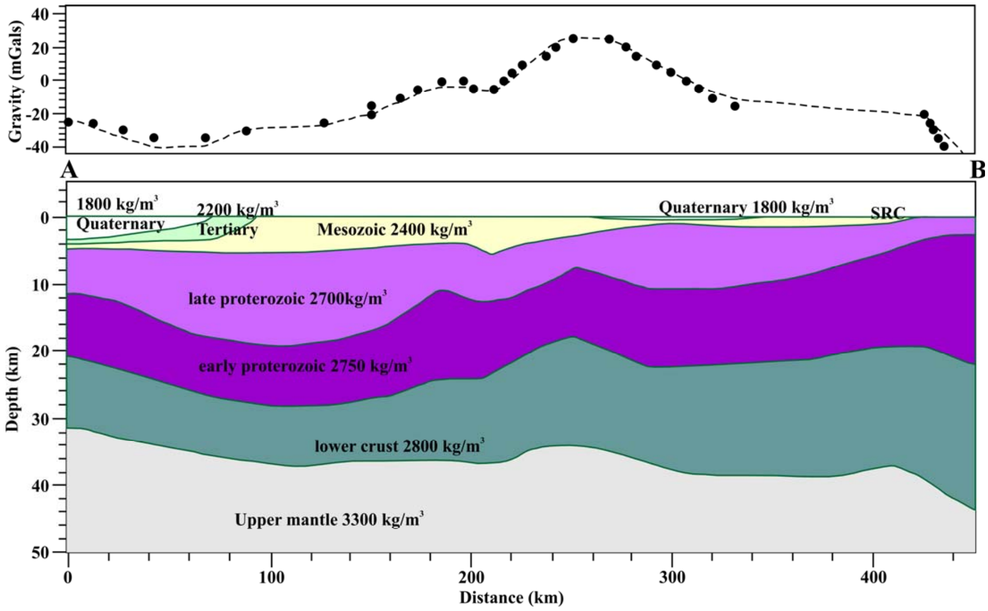

Fig.4. Bouguer gravity along A-B profile and preliminary model of the crustal structure e.g. (after Arora et al., 2011).

depressed area is bounded by uplifted area of gravity high, marked as the graben structure and inferred lithological boundary. The Barmer basin is interpreted as a narrow N-S trending graben, and a northern extension of Cambay rift.

Gravity anomaly profile along A–B in western Rajasthan (Fig. 4) prepared by Arora et al., 2011 shows a thick radiogenic layer of Neoproterozoic MIS at shallow depth. This radiogenic layer is covered by blown sand and alluvial sediments. The gravity high and high heat producing granitic area of western Rajasthan are probable source of high heat flow indicating potential sites of renewable geothermal energy resource for India.

A Conceptual Model

In order to understand the evolution of the geothermal system of Siwana, a conceptual schematic model was developed with the available data (Awasthi, 2002; Satyavani et al., 2004) and field observations as shown in Fig. 5. According to this model, thermal water circulating (gray arrow in Fig. 5) through tuff and high heat producing fractured granite, transforms into Ca-HCO_3 type due to exchange between Ca-Na. The water flows along the fractures and comes in contact with the high heat producing granites of Siwana area and evolve as hot springs. Thus, the geothermal region of this area appears to constitute a low enthalpy geothermal system.

Table 4. Estimated reservoir temperature of Siwana area, based on chemical geothermometers

	Silica Geothermometry		Cation geothermometers			
Sa. No.	Max steam loss	No steam loss	Na-K (Fournier and Truesdell, 1973)	Na-K (Truesdell, 1975)	Na-K (Giggenbach et al., 1983)	Na-K-Ca (Fournier and Truesdell, 1973)
1	80.1	68.3	85.0	94.0	158.6	135.3
14	73.4	60.9	95.9	104.3	167.4	223.4
68	96.7	86.8	90.1	98.8	162.7	172.7
70	101.6	92.3	113.3	120.8	181.0	182.8

CONCLUSIONS

The thermal spring water samples are near neutral to mildly alkaline with range from 6.8 to 7.8. Surface temperature of Siwana thermal springs range 30 to 40 °C. The groundwater is Ca-HCO_3 type and thermal water is Ca-HCO_3 and Na-Cl-HCO_3 type, which indicates mixing of thermal water with near surface groundwater. Water-rock interaction suggests the circulation of the thermal water within the granite. The heat flow values of the Siwana area given in Table 3, indicates that the thermal springs are heated by the high heat generating Siwana granites. With the help of the silica geothermometers reservoir temperature is estimated and it ranges from 75 to 105 °C. Present investigation suggests that these granites appear to be potential candidates for hot dry rock geothermal project.

Siwana granites have high heat production up to 16.48 μWm^{-3}, closely similar to that of the Jhunjhunu granite (16.47 μWm^{-3}). These values are higher than those of Tosham and Jalor anomaly which is 9.83 and 4.93 μWm^{-3} respectively. The production value of Siwana and Jhunjhunu

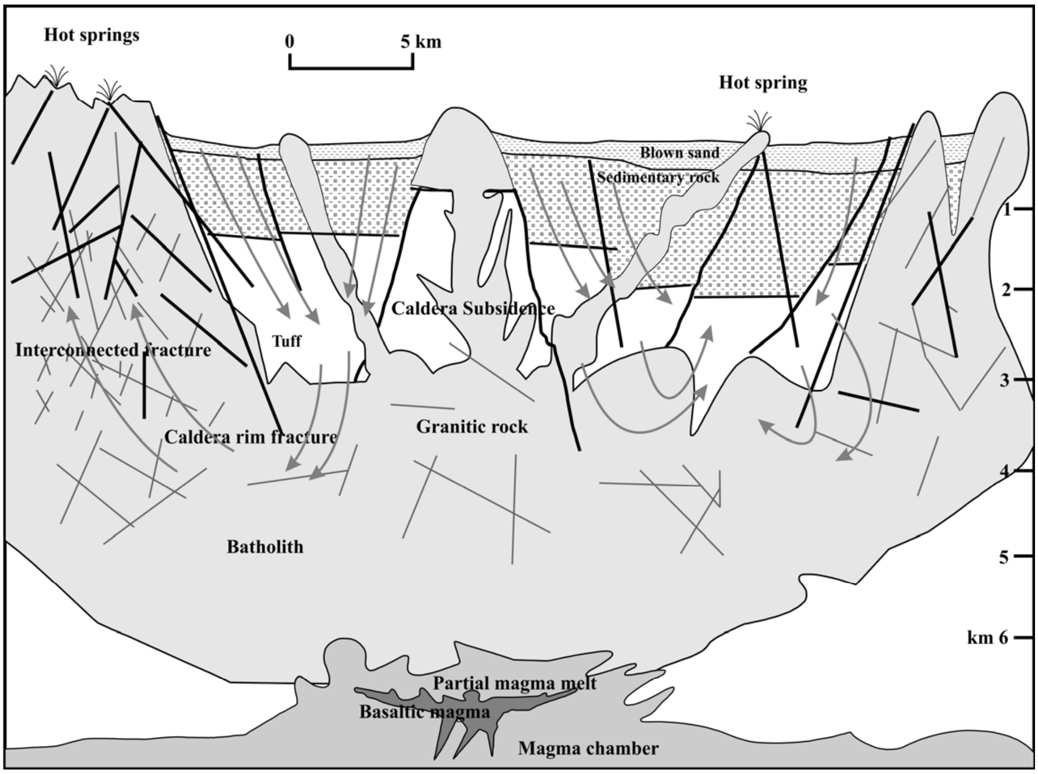

Fig.5. schematic model of high heat producing granite of Siwana Caldera and circulation of hot springs fluid (present study).

granite are thus the highest in Indian shield. Further, 96 mWm^{-2} average heat flow obtained from Tosham granite area of Malani Igneous Suite, is highest heat flow value obtained for Indian shields. Concentration of uranium, thorium and potassium in Siwana granites is up to 37.03 ppm, 165 ppm and 5.32 wt% respectively. The high concentration of uranium and thorium may also be one of the possible heat sources for the hot springs of the Siwana area. The radioactive heat production data of volcanic and plutonic rocks of the area suggest a possible linear relationship between the surface heat flow and crustal heat generation in Malani igneous suite.

Western Rajasthan is characterized by patches of gravity high due to presence of high density material of lower crust or upper mantle at shallow depth in the crust which might be the cause of high heat flow in gravity high areas. The exposed Malani Igneous Suite of rhyolites and granites in western Rajasthan is well within the regional gravity high, but is within zones of relatively lower gravity (due to the intrusion of Malani granite). The gravity map shows thick layer of radiogenic granites of Malani Igneous Suite present at very shallow depth. High heat producing granites of Malani Igneous Suite are excellent hot dry rock sites for renewable geothermal energy resources. The granites of Malani Igneous Suite thus constitute a high heat producing variable new geothermal province of India

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