High heat production of granites from Southern Khetri Belt, Rajasthan, India

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The Mesoproterozoic A-type granites from Chapoli–Chowkri area, South Khetri Belt (SKB) of Aravalli craton are characterized by high content of thorium and uranium with variable Th/U ratio. Average radiogenic heat production of Udaipurwati granite, Chapoli granite and albitite are 6.67 μWm^{-3}, 6.90 μWm^{-3} and 6.92 μWm^{-3} respectively, which are much higher than the average RHP values for continental crust and the granites of North Khetri Belt (NKB). Average contribution of RHP due to thorium (56.86%) is higher than uranium (40.84%) and potassium (2.28%). Based on the heat production and their geochemical behaviour, these granites from South Khetri Belt are classified as moderate to high heat producing granites. Study on heat flow suggested that the high levels of radiogenic heat production in the uppermost crust could be the reason for high heat flow in the area.

Keywords: Albitites, Chapoli–Chowkri area, Chapoli granite, RHP, Southern Khetri Belt, Udaipurwati granite.

CONCENTRATION of radiogenic heat producing elements (^{238}U, ^{235}U, ^{232}Th and ^{40}K) is high in earth's crust and therefore serves as an important heat source in continental crust. Granite, a prominent constituent of continental crust, typically contains higher concentration of radioactive elements than any other rocks. Distribution of these elements and combined determinations of radiogenic heat production (RHP) and surface heat flow provide basic information about the thermal field and the structure of the Earth's crust[1–8]. While reviewing the radiogenic element contents and heat production of granites from various parts of the globe, Artemieva *et al.*[5] suggested that bulk heat production in granitic rocks of all ages is ca. 2.0 μWm^{-3} and there is a remarkable peak in heat production in Middle Proterozoic granites (presently 4.36 ± 2.17 μWm^{-3}). The A-type (anorogenic) granites contain higher radioactive elements concentration and RHP[5].

Several studies on heat flow and RHP of rocks from different parts of India including Aravalli–Delhi fold belts have been published during the past few decades[6–20]. However, RHP data for the major rock types, in particular the felsic igneous rocks, are inadequate to characterize the thermal structure of the different geological province/regions. Some of the Proterozoic age granites, exposed in the Aravalli craton (NW India), have been studied for their RHP. High radioelement (K, Th and U) concentration for many of the granites from Middle to late Proterozoic Erinpura–Malani Igneous Suit (EMIS) with high heat production values has been reported in the literature[9–16]. Similar studies on RHP from the granitic rocks of Khetri Belt, which is divided as Northern Khetri Belt (NKB) and Southern Khetri Belt (SKB) (Figure 1), from NE part of Aravalli Delhi Fold belts, are also available[12,17,18]. Most of these granites are studied for their RHP, fall in the NKB. RHP data from SKB granites is lacking.

To bridge the gap, the present paper reports new data on the radioelement enrichment and heat production from the granites which are also associated with fluorite mineralization of Chapoli–Chowkri area in SKB. Attempt is also made to compare it with other granites from the province and relate with the heat flow values.

Geology and petrography

Basic geological structure for the Precambrian terrain of Rajasthan is the basement Banded Gneissic Complex overlain by cover sequences of Proterozoic supracrustal rocks of Aravalli and Delhi fold belts[21,22]. The NE–SW oriented Khetri Belt, a part of North Delhi Fold Belt, is located in the northeastern most part of the Aravalli–Delhi mountain range extending for about 100 km from Pacheri (Jhunjhunu district) in northeast to Sangarva (Sikar district) in southwest. It is divided into NKB and SKB. NKB is truncated in the south by an E-W trending fault named as the Kantli Fault. The present area of study falls in the southern part of Khetri Belt and particularly restricted to south of Kantli Fault. The rock types exposed in the area belong to Alwar and Ajabgarh Groups of Meso- to Neo-Proterozoic Delhi Supergroup intruded by granites, amphibolites, pegmatites and quartz veins. Udaipurwati granite (UG), Chapoli Granite (CG) and albitites are three prominent and extensive felsic igneous rock exposures present in the SKB. Albitite, which is formed by the metasomatism, appears to play an important role in fluorite mineralization of Chapoli–Chowkri area.

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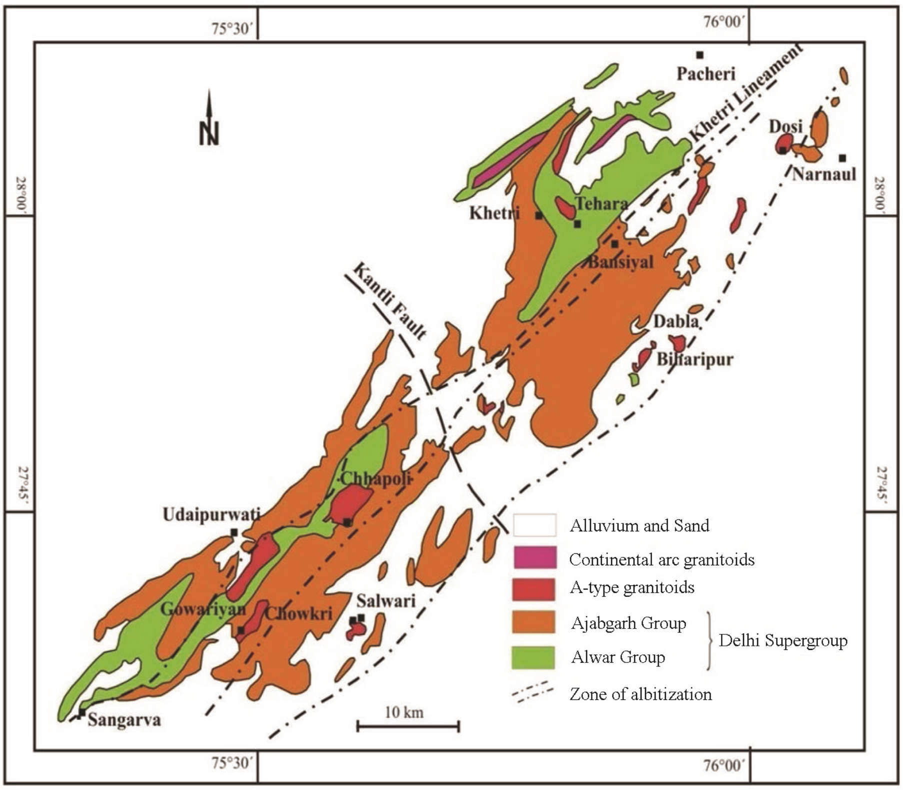

Figure 1. Geological map of Khetri Belt showing zone of albitization (after Kaur *et al.*[48]).

The CG (1680 ± 12 ma; ref. 23) is an oval-shaped intrusive (5 km × 2 km) occurring in the core of an antiform of quartzite. CG is leucocratic and fine to medium-grained rock. It is characterized by hypidiomorphic nature and consists of quartz, microcline, orthoclase, plagioclase with subordinate amounts of biotite and hornblende. Microcline is being replaced by albite giving rise to prominent chess board twinning (Figure 2 *a*). Zircon, titanite and apatite are present as accessory phases.

The UG complex (1678 ± 23 ma, ref. 24) is the largest elliptical massif (7.5 × 1.5 km) of the Khetri Belt. It occupies the axial zone of a major antiform of quartzite and metapelitic schist[25]. UG is pink, medium to coarse-grained rock. It essentially consists of quartz, microcline and plagioclase with minor biotite and hornblende. K-feldspar is present in considerable proportion in the rock with microcline dominating over orthoclase. Titanite, zircon and allanite (Figure 2 *b*) are present as accessory phases. Opaque mineral grains are also present in small amounts.

Albitite is a brick red coloured, medium to coarse-grained rock and is exposed at Salwari. The presence of newly formed minerals due to metasomatism, mainly albite (Figure 2 *c*) and quartz is the characteristic feature. Chief mineral constituents of albitite in order of decreasing abundance are albite (An_0–An_{10}), quartz, hornblende, biotite, allanite and opaque minerals. Titanite, chlorite, rarely K-feldspars, muscovite, zircon, fluorite, apatite and rarely monazite and uranothorite are the minor mineral phase. Prominent feature of albitite is the occurrence of chessboard twining (Figure 2 *d*) which is considered to have formed by the complete replacement of microcline by albite during albitization.

Analytical techniques and major oxide geochemistry

Representative samples of granitic rocks were chosen carefully after petrographic studies for the geochemical analysis. Care has been taken to collect fresh samples from the field. Chips of rock samples were powdered to –200 mesh using TEMA swing mill maintaining the homogeneity and representativeness of samples. Major and selected trace elements were analysed by wavelength dispersive XRF system (Siemens SRS-3000) at Wadia Institute of Himalayan Geology, Dehradun. Analysis was performed at accelerating voltage of 20/40 kV (for major elements) and 55/60 kV (for trace elements) using Rh X-ray tube with no filter path. International Geostandards for granitic rock, including GS-N and MA-N were used as reference standards. The average precision was better than 2.0% (ref. 26).

Major oxides for the rocks of study area are summarized in Table 1. Granites of the area show higher concentration of SiO_2, Al_2O_3, total alkalies and Fe_2O_3 and are

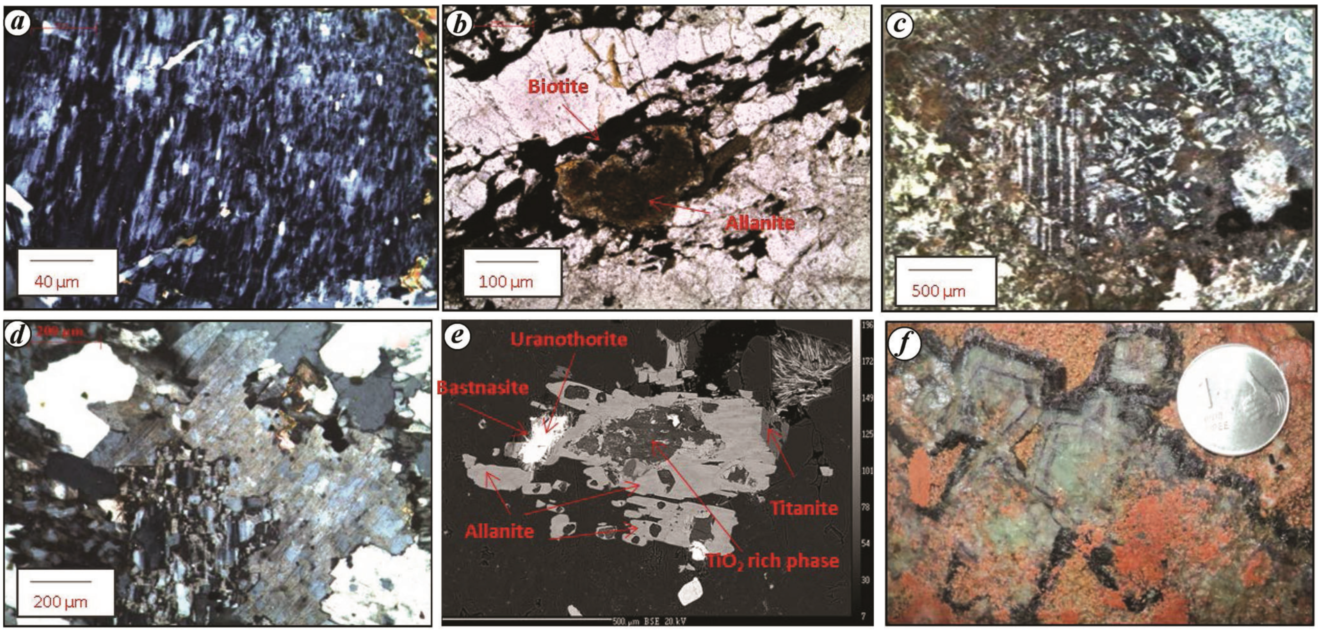

Figure 2. ***a***, Chess board twinning showing replacement of microcline by albite; ***b***, Allanite crystal in plagioclase feldspar; ***c***, New albite is formed at the expense of early albite; ***d***, Chess board twinning seen in albite rock; ***e***, EPMA image of minerals in albitite; ***f***, Pockets of coloured zoned fluorite in albitite (dia of coin is 2.19 cm).

Table 1. Average values of major oxide analysis of the Udaipurwati granite, Chapoli granite and albitite (in wt%)

Oxide	Udaipurwati granite ($n = 4$)	Chapoli granite ($n = 6$)	Albitite ($n = 5$)
SiO_2	72.75 ± 1.66	73.30 ± 2.69	74.39 ± 6.63
Al_2O_3	13.56 ± 0.37	13.54 + 0.57	14.19 ± 2.56
Na_2O	2.78 ± 0.16	7.81 ± 0.28	8.84 ± 2.04
K_2O	5.56 ± 0.49	0.50 ± 0.30	0.21 ± 0.23
Fe_2O_3	3.04 ± 0.38	2.15 ± 0.87	1.63 ± 0.95
CaO	1.01 ± 0.09	0.72 ± 0.27	0.46 ± 0.26
TiO_2	0.33 ± 0.07	0.49 ± 0.18	0.21 ± 0.13
MgO	0.36 ± 0.07	0.53 ± 0.28	0.10 ± 0.09
MnO	0.03 ± 0.01	0.02 ± 0.01	0.01 ± 0.00
P_2O_5	0.06 ± 0.02	0.13 ± 0.05	0.03 ± 0.01
Total	99.46 ± 1.22	99.19 ± 0.87	100.06 ± 1.71

low in CaO and MnO than the average granite. Granites and albitite from the area show high SiO_2 content with an average of 73.30%, 72.75% and 74.39% for CG, UG and albitite respectively.

Albitite show pervasive to semi-pervasive alteration and show wide range for Al_2O_3 with an average of 14.2%. Na_2O content in albitized samples goes high up to 12.07% with an average of 8.84%. The higher concentration of Na_2O in these granites is due to albitization. Average K_2O content in CG is 0.49% which is, in general, lower than the K_2O content of UG (average K_2O = 5.56%). Albitites also show low K_2O ranging with an average of 0.21%. This is also evident by the petrographic studies on the CG and albitites where replacement of microcline by albites is clearly seen (Figure 2 *a*, *d*). When the rocks of study area plot in Ga versus Al_2O_3, all the rocks fall in A-type granite field[27].

Radioelement concentration and heat production

U, Th and K contents of CG, UG and albitite are given in Table 2. Both CG and UG are characterized by high concentration of radioactive elements, U (av. 8.25 ppm and 7.43 ppm respectively) and Th (av. 61 ppm and 67 ppm respectively) with higher content of thorium. Th/U ratio for these granite ranges between 6.35–12.5 and 5.89–10.32 respectively. Albitite, however, shows higher content of uranium (av. 16.92 ppm) than the studied granites which is also supported by the presence of uranothorite in the albitite (Figure 2 *e*). Th/U for albitite is lower than the other granites and ranges between 0.84 and 4.3.

Overall average concentration of all the studied granites from SKB for Th (54.80 ± 23.82) and U (10.92 ± 7.52) is much higher than the trace radioelement concentration of the average A-type granites (Th = 23 ± 11 and U = 5 ± 3)[27]. In granitoid rocks, U and Th tend to concentrate in accessory minerals such as zircon, monazite, apatite, titanite and allanite or as impurity in fluorite and mica[28]. The studied granite contains most of these accessory minerals (zircon, allanite, apatite, titanite) and is highly enriched in their SiO_2 content (>72%). Potash is depleted in some of the granites due to alteration/albitization. The higher values of U and Th of CG, UG and albitites are hence attributed to their mineralogical composition.

Based on the surface abundance of U, Th and K of granites from the area, the heat production by the granites

Table 2. Heat production, radioelement and heat generation data of rocks

Sample	Rock type	U (ppm)	Th (ppm)	K (wt%)	Th/U	Total heat production (μWm^{-3})	Heat production (μWm^{-3}) due to U	Th	K	Contribution due to U, Th and K (in %) U	Th	K
RM1	Udaipurwati granite	9.30	96.00	4.39	10.32	9.60	2.44	6.74	0.43	25.37	70.19	4.44
RM2		6.80	48.00	4.92	7.06	5.63	1.78	3.37	0.48	31.64	59.86	8.50
RM16		7.30	43.00	5.00	5.89	5.42	1.91	3.02	0.49	35.30	55.73	8.97
RM17		6.30	57.00	4.16	9.05	6.06	1.65	4.00	0.40	27.24	66.08	6.68
RM4	Chapoli granite	10.70	68.00	0.38	6.36	7.61	2.80	4.77	0.04	36.81	62.70	0.49
RM5		7.20	90.00	0.32	12.50	8.23	1.89	6.32	0.03	22.90	76.72	0.38
RM6		11.50	81.00	0.07	7.04	8.70	3.01	5.69	0.01	34.60	65.32	0.08
RM12		5.00	43.00	0.52	8.60	4.38	1.31	3.02	0.05	29.91	68.94	1.15
RM14		10.40	69.00	0.35	6.63	7.60	2.72	4.84	0.03	35.83	63.72	0.45
RM15		4.70	51.00	0.81	10.85	4.89	1.23	3.58	0.08	25.17	73.22	1.61
RM7	Albitite	10.00	43.00	0.49	4.30	5.69	2.62	3.02	0.05	46.07	53.09	0.84
RM8		16.90	16.00	0.09	0.95	5.56	4.43	1.12	0.01	79.63	20.21	0.16
RM9		34.30	29.00	0.04	0.85	11.02	8.98	2.04	0.00	81.49	18.47	0.04
RM10		17.40	67.00	0.20	3.85	9.28	4.56	4.70	0.02	49.11	50.68	0.21
RM11		6.00	21.00	0.05	3.50	3.05	1.57	1.47	0.00	51.51	48.33	0.16

is calculated using the method given by Ashwal *et al.*[29]. According to this method, heat production can be calculated by the formula

$$\text{Heat production (A) in } \mu Wm^{-3} = \rho(0.0966\ cU + 0.026\ cTh + 0.036\ cK),$$

where cU and cTh are an abundance of U and Th in ppm respectively and cK is the abundance of K in wt% and ρ = density of rock (in this case 2.7 g/cm^3).

Calculated heat production by UG, CG and albitite is given in Table 2. RHP values for UG, CG and albitite range between 5.42 μWm^{-3} and 9.60 μWm^{-3}, 4.38 μWm^{-3} and 8.70 μWm^{-3}, and 3.05 μWm^{-3} and 11.02 μWm^{-3} respectively. Heat production from different elements is taken as HP U, HP Th, HP K and are calculated using the above mentioned method. The ratios of heat production due to U (HP_U/HP_{Total}), Th (HP_{Th}/HP_{Total}) and K (HP_K/HP_{Total}) are taken as contribution by radioelement for all the studied samples and are listed in Table 2. It shows that the average contribution from the two elements (Th and U) combined is about 97% of the total heat production. Higher heat production of CG, UG and albitites are hence attributed to their higher U and Th content.

Discussion

Upper continental crust plays a major role in the global thermal budget[19], because most of heat producing elements are concentrated in granitic rocks. Therefore, knowledge of radioelement concentration and heat production in granitic rocks is pivotal for understanding thermal structure of any geological province.

Th/U ratios

Th/U ratio of continental crust shows significant variability. Average Th/U ratio of upper part of continental crust is estimated as 4.2 (ref. 30). Globally, there is a significant variation in Th/U ratio in felsic rocks between, less than 1 to 10 with an overall constant Th/U ratio of c ≈ 4 in granites[5,31]. It has been estimated[5] that the global average Th/U value for the Archaean–Early Proterozoic granites is around 3.50 ± 2.18 whereas for Middle–Late Proterozoic granites, it is 3.63 ± 1.95. Studied granite from SK is of Middle Proterozoic age and shows Th/U value ranging from 5.89 to 12.5 with an average value of 6.52 which is much higher than the average Th/U ratio for the granites of Middle to Late Proterozoic age from all over the globe and also from the average value for the upper continental crust.

The present study also reveals that Th/U ratio can be variable within the same area. Albitites which are result of sodic metasomatism in the area shows high variability in the area for Th/U ratio ranging from 0.85 to 4.30 (av. = 2.69). Udaipurwati and CGs vary in similar range from 5.89 to 12.5 with an average of 8.4. This variation in Th/U ratios or Th and U concentrations, particularly in albitite is due to its higher concentration of U, may be because of the source composition as well as later metasomatic processes. When U and Th concentrations of studied granites and albitites from SKB are plotted along with the granites of NKB and granites from EMIS, they show similar trend as of the granites from the NKB and a general positive trend (Figure 3).

Heat production classification and comparison with other granites

Some authors[32,33] have constrained the definition of HHP granites as evolved calc-alkaline granites which have comparatively higher content of Th, U, K and total REE and responsible for nearly half of the crustal heat flow through radiogenic decay of isotopes of Th, U and K. However, there are diverse views on fixing the RHP threshold to qualify any granite as HHP granite. Huston[34] proposed 8 μWm^{-3} for high-heat-producing granites and a range of 4–8 μWm^{-3} for moderate-heat-producing granites while others proposed RHP values greater than 5 μWm^{-3} sufficient to be considered as HHP granites[35].

UG and CG fall in A-type granite category (Figure 4) and have been also found belonging to calc-alkaline granites with higher content of radioelements and total REE[36]. Further, the RHP values for the studied granites (av. for UG = 6.67 μWm^{-3} and avg. for CG = 6.90 μWm^{-3}) and albitite rocks (av. 6.92 μWm^{-3}) classify as moderate to high heat producing granites.

RHP values of granites from SKB are compared with the reported RHP values for granites from NKB and from EMIS of the Aravalli craton for evaluating regional heat production variability (Figure 4). The present study suggests that the granites from SKB shows higher RHP values than the granites from NKB but lower compared to granites of EMIS. In particular, the granites of Jhunjhunu and Kundal show high heat production values among other EMIS rocks, whereas the Jalor granite show fewer values when compared with Khetri granite.

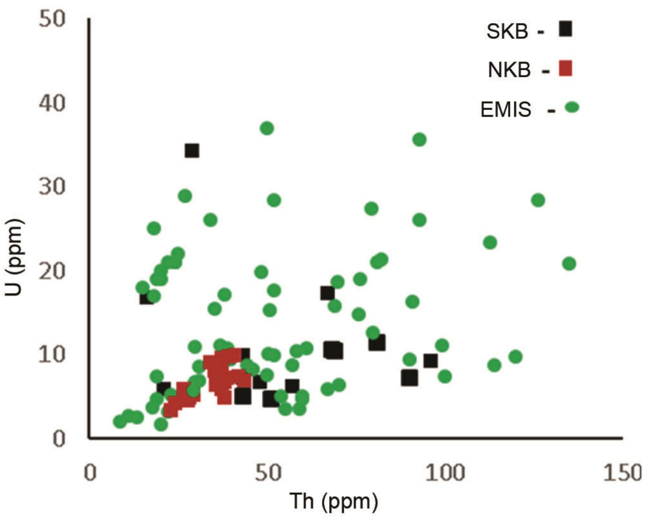

Figure 3. Correlations between uranium and thorium.

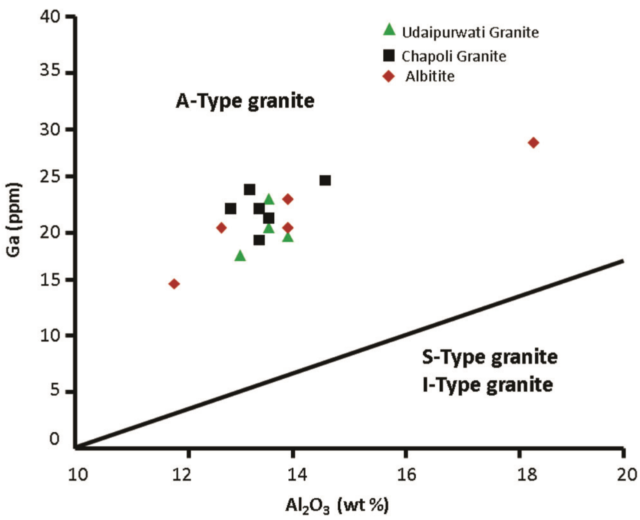

Figure 4. Ga versus Al_2O_3 plot[27].

It has been established that heat production values are controlled basically by U and Th concentrations (85% of the total RHP) and to a lesser extent to the K concentration[3]. In the present study also, the heat generation contributions by various radio elements (Table 2) suggest that the heat production values are primarily controlled by U and Th concentrations and much less by K. When the heat production data from the granites of Aravalli cratons are plotted against their Th and U concentration, a good positive relationship between the heat production and Th and U concentration of granite is observed (Figure 5 *b* and *c*) much like the global data trend[5].

Many researchers have tried to correlate the heat production values of granites with their ages. It has been reported that the heat production values of Archaean samples are always lower than Post-Archaean[3]. A remarkable peak in heat production of Middle Proterozoic granites (4.36 ± 2.17 μW/m^3) was found in comparison with the Archaean-Early Proterozoic granitic rocks (1.67 ± 1.49 and 1.25 ± 0.83 μW/m^3 respectively) followed by a gradual decrease towards Phanerozoic granites (3.09 ± 1.62 μW/m^3)[5]. Present study area belongs to Middle Proterozoic Granites and have a higher RHP value (6.85 μWm^{-3}), confirming the findings of Artemieva *et al.*[5].

Significance of high heat producing granites

Granite contributes significantly in the heat production in continental crust and regionally varies from ca. 30% to 80–90% (ref. 37). Whalen[38] carried out compilation of 148 compositions of A-type granites, suggesting the typical RHP values range between 0.52 and 12.7 μWm^{-3}. In the upper crust, concentration of U is 3–4 ppm and concentration of Th is 10–15 ppm[39]. Average value of RHP is 1.65 μWm^{-3} for upper continental crust[40]. Granitic rocks of the present study show higher concentration of uranium (10.92 ± 7.52) and thorium (54.80 ± 23.82) with much higher average RHP value of 6.85 μWm^{-3} than the average continental crust.

We also examined the correlation between surface heat flow and heat production in granites. Few workers have observed a linear relationship between high heat production and surface heat flow and suggested that the variation of surface heat flow within a given heat flow province is related to variations in the total crustal heat production[1,41,42]. Mantle contribution to surface heat flow ('reduced heatflow' in the concept of 'heat flow provinces'), however, may also be significantly different in different regions. From the Aravalli craton, nine heat flow values are reported[20] which suggest that high and variable

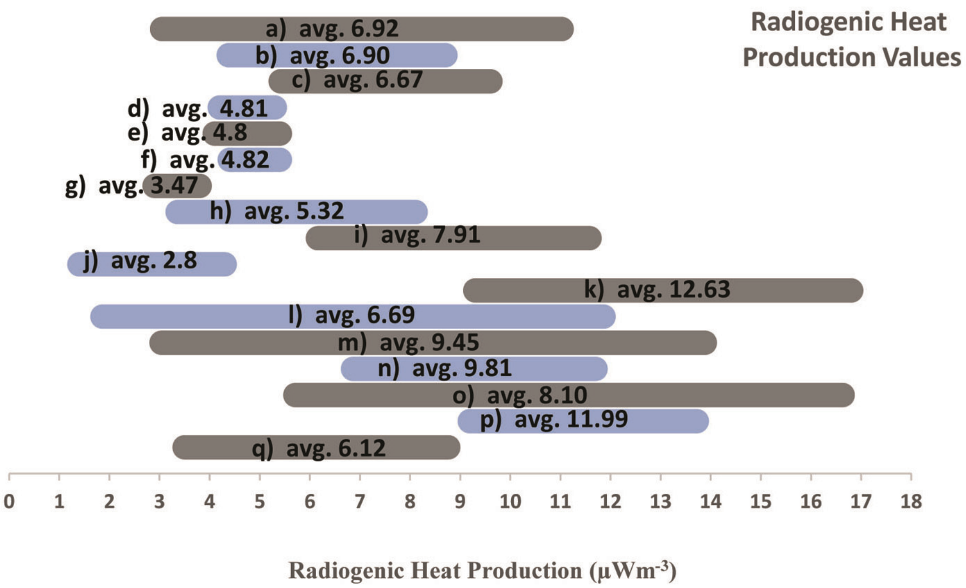

Figure 5. Radiogenic heat production values for the granites from Sothern and Northern Khetri belts and EMIS of Aravalli Craton; a, Albitite (present study); b, Chapoli granite (present study); c, Udaipurwati granite (present study); d, Tehara granite[17]; e, Bansiyal granite[17]; f, Gothara granite[17]; g, Ajitgarh granite[18]; h, Dhanota Granite[12]; i, Degana Granite[11]; j, Jalor Granite[9]; k, Jhunjhunu granitoids[9]; l, NE of Jodhpur[15]; m, Tosham granite[16]; n, Devsar Granite[16]; o, Khanak granite[16]; p, Kundal granite[13]; q, Siwana granite[13].

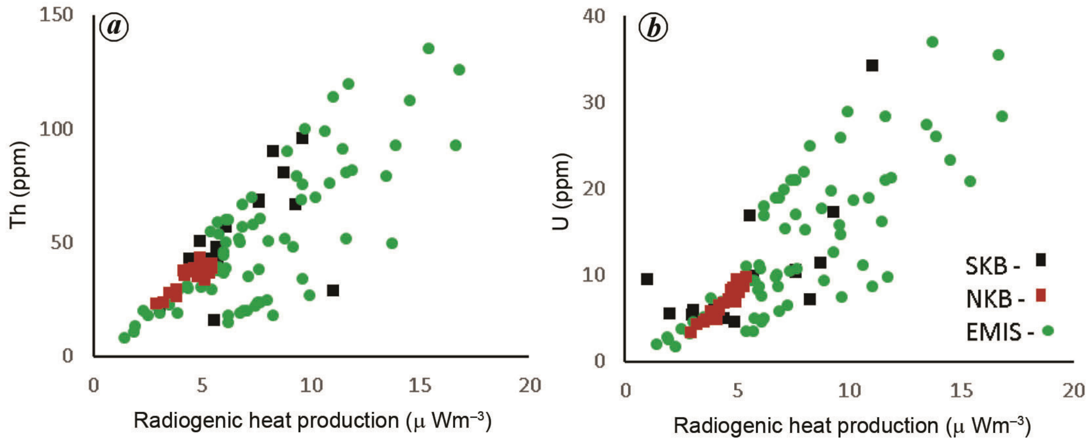

Figure 6. Variation of Th and U with radiogenic heat production values for the granites from Southern and Northern Khetri belts and EMIS of Aravalli craton.

heat flow ranges from 46 to 96 mW/m^2. The highest heat flow value (96 mW/m^2) is recorded in Tusham granitic region, located within the Trans-Aravalli igneous suite[43]. Heat flow at Khetri Belt is estimated as 74 mW/m^2 but all these values were calculated from the NKB[3]. In our study area, in particular, there are no specific heat flow values available. RHP values for Tusham granites (9.45 mWm^{-3}) and Khetri granites (6.85 mWm^{-3}) indicate that the high levels of radiogenic heat production in the uppermost crust could be the reason of high heat flow in the area[6,43,44]. It is also concluded that in recent times there is no evidence of tectonothermal events, so the high heat flow is explained on the basis of high heat production of the crustal rocks[7].

The Khetri Belt is famous for its mineral resources of Cu–Au, Fe-oxides, fluorite and uranium mineralization. The study area is also mineralized with high quality fluorite. Knight *et al.*[45] reported that high-heat producing granites in the Khetri complex host IOCG and uranium mineralization. Also, within the Khetri Belt, uranium mineralization in NKB is less when compared to SKB[46]. HHP granites act as 'heat engine' and prolong the circulation of ore-bearing hydrothermal fluids which ultimately may lead to the formation of a mineral deposit[47]. It is suggested that the widespread occurrence of high heat production and A-type granite bodies in the Khetri Belt might have provided the heat source for driving the fluids responsible for widespread albitization and fluorite mineralization in the area.

Conclusion

Mesoproterozoic A-type granites from Chapoli–Chowkri area, Southern Khetri Belt of Aravalli craton have a high concentration of radiogenic heat producing elements. Th/U ratios for studied granites are much higher than the global average of Th/U ratio for Middle to Late Proterozoic age granites and upper continental crust. Average contribution of RHP due to thorium (56.86%) is higher than uranium (40.84%) and potassium (2.28%). The present study suggests that the granites are classified as moderate to high heat producing granites and show lower RHP values than EMIS but show higher RHP values than the granites from the NKB. It is construed that high levels of radiogenic heat production in the uppermost crust could be the reason for high heat flow in the area.

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