Radiogenic heat production of Late Archaean Bundelkhand granite and some Proterozoic gneisses and granitoids of central India

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Abundances of heat-producing elements, K, U and Th, in some of the granites and gneisses of the Bundelkhand and Bastar terrains have been estimated by *in situ* gamma-ray spectrometry. The Bundelkhand granite is an I-type, calc-alkaline granite complex made up of porphyritic, coarse-to-medium grained and fine-grained granites. It carries macro enclaves of ~ 3.5 Ga-old tonalitic gneisses. These gneisses have a low heat production of 1.4 μWm^{-3}. The mean heat production of the dominant porphyritic and medium-to-coarse grained Bundelkhand granite is 5.5 μWm^{-3}. The heat production of the Proterozoic Jabalpur granite intruding the Mahakhosal greenstone belt is 3.4 μWm^{-3}. The Tirodi gneisses resulting from migmatization of psammopelites of the Sausar Group, are characterized by a mean heat production of 3.8 μWm^{-3}. The cataclastic biotite gneisses of the Tattapani geothermal area are the highest heat-producing rocks encountered in the Bundelkhand terrain with a mean heat production of 7.4 μWm^{-3}. The tonalitic Amgaon gneisses of the Bastar terrain are characterized by a heat production of 0.7 μWm^{-3}, which is about half of the mean heat production of the tonalitic gneisses occurring as inclusions in the Bundelkhand granite. Mean heat production of the Proterozoic Amgaon and Dongargarh granites are 2.5 and 2.9 μWm^{-3}, respectively. Preliminary heat production data presented here show that the gneisses and granitoids of the Bundelkhand and Bastar terrains may have distinct heat production ranges, with the rocks of the Bundelkhand terrain being more heat-producing.

RADIOACTIVE decay of long-lived isotopes of potassium, uranium and thorium contributes to the bulk of the heat-produced in the crust. Variation of abundance of these radioactive elements in rocks constituting the crustal column over a large region is reflected in the lateral variation of surface heat-flow[1–5]. Most of the potassium is present in K-feldspar and micas, while uranium and thorium are largely present in the accessory minerals such as zircon, allanite, sphene, monazite, apatite etc.[6,7]. These minerals are more abundant in granitoid rocks, which therefore, account for bulk of the heat production in the continental crust. The Central Indian shield has been suggested by earlier workers to be a region of high heat-flow, although both heat-flow and heat production data are scanty compared to the data available on the southern Indian shield[8,9]. Heat production of the basement granitoids in this region has largely remained uncharacterized. In this article, we present data on radioelemental abundances and heat production of some major gneissic and homogeneous granitoid rocks in the Central Indian Shield.

Geological setting

Geology of the Central Indian Shield has received greater attention in recent years by the Geological Survey of India under the project CRUMANSONATA[10,11]. These studies have shown that the Precambrian basement rocks of Central India form part of two discrete terrains – the Bundelkhand terrain in the north and the Bastar terrain in the south.

Middle to Late Archaean Bundelkhand granite complex constitutes the Bundelkhand craton. Fringing this craton and probably overlying the basement granitoids are the Proterozoic Mahakhosal, Bijawar and Sausar supracrustal sequences that evolved in epi- to peri-cratonic mobile belts in the southern part of the Bundelkhand terrain. A large part of the mobile belt fringing the Bundelkhand craton lies in the Central Indian Tectonic Zone (CITZ) that includes the well-known Narmada–Son lineament. The supracrustal rocks of the Mahakhosal belt have been invaded by the Jabalpur granites, which are exposed as small plutons around Jabalpur city. Supracrustal rocks of the Sausar sequence have been migmatized and transformed into the Tirodi gneisses. The gneisses of the Tattapani area are cataclasites, with large K-feldspar porphyoclasts in a quartzo-feldspathic matrix rich in biotite. The middle to late Archaean cratonic and the Proterozoic mobile zone rocks of the Bundelkhand terrain are characterized by a strong, nearly E-W tectonic fabric.

In the Bastar terrain, middle to late Archaean granite–gneiss basement constitutes the Bastar craton. This is overlain by Proterozoic Kotri–Dongargarh and Sakoli Group of rocks, which evolved in mobile belts. The

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> 2.3 Ga-old Amgaon gneiss forms a part of the basement of the Sakoli Group, whereas the Amgaon and Dongargarh granites intrude the Sakoli Group. The rock formations of the Bastar terrain are characterized by a nearly N–S to NE–SW tectonic fabric.

The boundary between the Bundelkhand terrain and the Bastar terrain has been intensely reworked in the CITZ and are juxtaposed along the Central Indian suture[12,13]. A number of large-scale E–W to ENE–WSW striking faults such as the Son–Narmada North Fault, Son–Narmada South Fault, Balarampur–Tattapani Fault, Tan Shear, Central Indian Suture, and Sakoli East Shear Zone traverse the CITZ (Figure 1). These faults have got reactivated during the late Precambrian controlling the development of the Vindhyan basin, and during the Phanerozoic times influencing control in the development of Gondwana basins. The region also witnessed Cretaceous

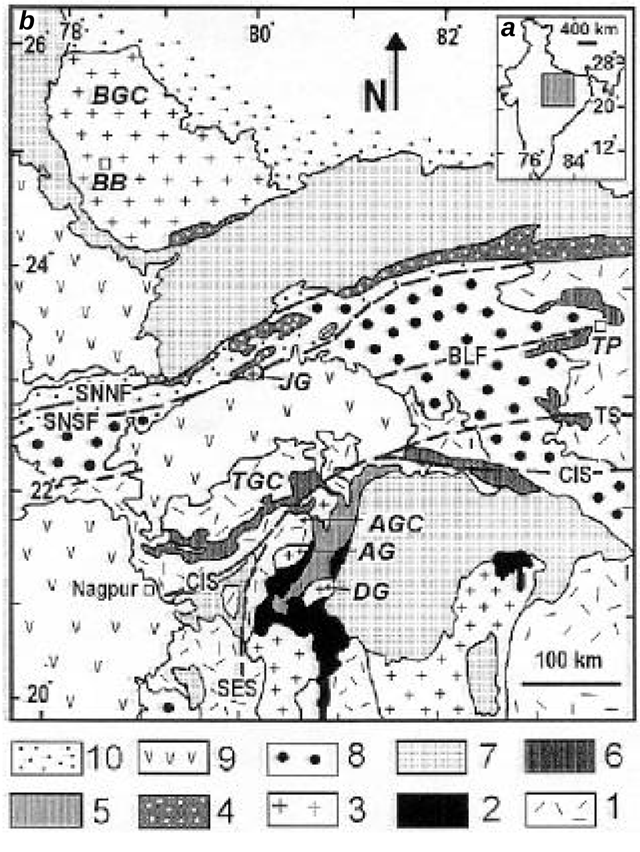

Figure 1. ***a***, Study area in Central India. ***b***, The geological map of the Central India showing locations of granites and gneisses studied in this work (after Acharyya and Roy[14]). 1, Gneisses (undifferentiated); 2, Neoarchaean to Palaeoproterozoic supracrustal belts; 3, Granitoids; 4–7, Palaeo-, Palaeo- to Meso-, Meso-, and Meso- to Neoproterozoic sedimentary rocks, respectively; 8, Gondwana sedimentary rocks; 9, Deccan flood basalts, and 10, Quaternary–Recent sediments. Shear zones: SNNF, Son–Narmada North Fault; SNSF, Son–Narmada South Fault; BLF, Balrampur–Tattapani Fault; TS, Tan Shear; CIS, Central Indian Suture; SES, Sakoli East Shear Zone. Study areas: BGC, Bundelkhand Granite Complex; BB, Babina; TP, Tattapani; JG, Jabalpur Granite; TGC, Tirodi Gneissic Complex; AGC, Amgaon Gneissic Complex; AG, Amgaon Granite and DG, Dongargarh Granite.

Deccan Trap magmatism. However, there is no evidence of Quaternary magmatism in the CITZ. But some of the faults in the CITZ are active at present, as evidenced by the occurrence of earthquakes in this region[14].

The Bundelkhand granite is a complex which consists of macro-enclaves of ~ 3.5 Ga tonalitic gneisses in a host of ~ 2.5 Ga K-feldspar-rich granitoid rocks[15,17]. The gneiss inclusions were observed near Babina. Porphyritic, coarse-to-medium grained, homogeneous and fine-grained, textural variants of granite constitute the Bundelkhand Granite Complex. Rare instances of occurrence of rapakivi textures have been noticed on the Lalitpur/Mehraunipur road and near Khajuraho. Geochemical studies carried out by earlier workers show that the Bundelkhand granite is an I-type, metaluminous to weakly peraluminous, calc-alkaline granite[18,19]. The 1.5 Ga-old Tirodi gneiss has resulted by migmatization of the supracrustal rocks of the Sausar Group[20]. The Tirodi gneiss is dominantly a two-mica gneiss, although in some parts only biotite has been observed. The gneisses are strongly banded with alternating quartzo-feldspathic and mica-rich bands. At places, quartzite beds, which are resistors to migmatization, are preserved. The two-mica composition and relict metasedimentary rocks suggest that the Tirodi gneisses have probably been formed from sedimentary protoliths[20]. However, according to some other workers, they are A-type granitoids[21]. The gneisses exposed to the south of Tattapani whose age is not known, have calc-silicate bands as resistors to migmatization. Both the Tirodi and Tattapani gneisses are mica gneisses, composed of K-feldspar megacrysts; sphene, apatite, tourmaline, and zircon are the principal non-opaque accessories. Unlike the Tirodi and Tattapani gneisses which are strongly foliated, the Proterozoic Jabalpur granites are massive, homogeneous, K-feldspar-rich granites. Their homogeneous fabric suggests that they may be post-tectonic with reference to the Proterozoic deformation that has affected the supracrustal rocks of the > 1.8 Ga Mahakhosal belt[10,11].

The > 2.3 Ga-old Amgaon gneisses of the Bastar terrain[22] carry macro inclusions of > 3.3 Ga tonalitic gneisses[23]. The Amgaon gneiss itself is a hornblende–biotite gneiss, which shows evidence of polyphase deformation. Inclusions of metabasaltic amphibolites and quartzites, probably belonging to the Amgaon Group, occur in the Amgaon gneiss. The Amgaon gneiss forms a part of basement to the Sakoli Group[12]. Mafic microgranular enclaves provide evidence for the igneous origin of the Amgaon granites. These are pinkish-grey in colour due to the predominance of K-feldspar. Intruding the metavolcanic rocks of the Proterozoic Nandgaon Group are the Dongargarh granites[22]. The Dongargarh granites of monzogranite composition exhibit rapakivi texture[24]. Mafic microgranular enclaves in the Dongargarh granite provide evidence for their igneous origin. Amphibole and biotite are the dominant mafic minerals. Sphene, zircon, apatite and allanite are the important accessories.

The Bundelkhand granite, Jabalpur granite, and Tirodi and Tattapani gneisses are the principal granitoid rocks that belong to the Bundelkhand terrain. The Amgaon gneisses, Amgaon granites and Dongargarh granites form a part of the granitoids of the Bastar terrain.

Data acquisition

Abundance of fresh rock outcrops satisfying 2*p* geometry has facilitated estimation of potassium, uranium and thorium by *in situ* gamma-ray spectrometry. *In situ* analyses provide estimates representative of larger mass of rock of the order of 40 kg, in contrast to the laboratory analysis on much smaller samples of 1 kg or less. The method of *in situ* analysis has been described in ref. 25. Precision is estimated at 0.1 ppm for U, 0.5 ppm for Th and 0.1% for K. Heat production is computed using the relation given by Birch[26]. *In situ* gamma-ray spectrometric survey was carried out in some of the gneissic and granitic regions of the Bundelkhand and Bastar terrains along the following traverses.

Bundelkhand terrain

(1) Bundelkhand granite: Babina (25°13′09″N; 78°27′48″E) – Lalitpur (24°34′44″N; 78°37′30″E) – Tikamgrah (24°45′13″N; 78°50′11″E) – Chattarpur (24°53′46″N; 79°36′18″E) – Khajuraho (24°50′00″N; 79°55′03″E).
(2) Tattapani gneisses: Tattapani (23°41′08″N; 83°37′08″E) – Sendur (23°40′14″N; 83°36′19″E) – Balrampur (23°39′12″N; 83°37′14″E).
(3) Jabalpur granite: from SW part of the Jabalpur city (23°09′26″N; 79°54′07″E) to the NE part of the city (23°11′05″N; 79°58′12″E).
(4) Tirodi gneisses: Tumsar–Katangi (21°31′32″N; 79°43′38″E) – Tirodi (21°40′40″N; 79°43′48″E).

Bastar terrain

(1) Tonalitic Amgaon gneiss: Arjuni–Gondia road (21°13′48″N; 80°12′02″E) – Mundipar (21°17′58″N; 80°12′09″E).
(2) Amgaon granite: Gondia–Amgaon road (21°21′38″N; 80°17′34″E) – Soni (21°20′50″N; 80°17′48″E).
(3) Dongargarh granite: Chandi Dongri (21°04′47″N; 80°38′00″E) – Dongargarh (21°10′28″N; 80°44′30″E).

Radioelemental data and heat production estimates

The radioelemental concentrations and heat production values calculated from them for the granitoid rocks of the Bundelkhand terrain are given in Table1 and those of the Bastar terrain in Table 2. These data show the following:

(a) The middle Archaean tonalites, which occur as macro-enclaves in the Bundelkhand granite are distinctly low in K, U and Th abundances that account for low heat production of 1.4 μWm^{-3}.
(b) The porphyritic and the medium-to-coarse grained varieties of the late Archaean Bundelkhand granite show a wide range of U and Th abundances, giving rise to a broad range of heat production. The mean heat production of these textural varieties, which are the most dominant rock types in the Bundelkhand Granite Complex is 5.5 μWm^{-3}. The fine-grained granite, which is a minor phase has a restricted range and lower heat production of 4.4 μWm^{-3}. This may have arisen because of a slightly lower content of U compared to that present in the porphyritic and coarse-to-medium grained variants.
(c) The distinct rise in the heat production of granitoids from Middle to Late Archaean has been observed as evident from (a) and (b). However, such a rise in heat production is not evident between the Late Archaean and the Proterozoic granitoids. The Proterozoic Jabalpur granites have a mean heat production of 3.4 μWm^{-3} and the Tirodi gneisses, 3.8 μWm^{-3}.
(d) Among all the granitic and gneissic rocks studied in the Bundelkhand terrain, the gneisses exposed to the south of Tattapani thermal springs are the most enriched in radioelements, which thereby accounts for the highest heat production of 7.4 μWm^{-3}.
(e) The granitoid rocks of the Bastar terrain examined in this work in general appear to be characterized by a

Table 1. Mean K, U and Th abundances in granites and gneisses of the Bundelkhand terrain

Rock type	N	K (%)	U (ppm)	Th (ppm)	HP (mWm^{-3})
Late Archaean Bundelkhand Granite Complex					
Banded tonalitic gneisses inclusion (> 3.3 Ga)	8	1.4 (0.1)	3.0 (0.3)	6.9 (0.8)	1.4 (0.1)
Porphyritic granite	34	4.3 (0.1)	8.0 (4.1)	42.5 (23.5)	5.5 (2.7)
Medium-to-coarse grained granite	50	4.6 (0.7)	8.8 (5.6)	38.1 (21.6)	5.5 (2.8)
Fine-grained granite	22	4.4 (0.6)	5.9 (1.8)	31.4 (10.3)	4.1 (0.9)
Proterozoic gneisses and granitoids					
Tattapani biotite gneiss	19	5.3 (0.5)	11.3 (3.1)	56.0 (10.7)	7.4 (1.2)
Tirodi gneisses	12	4.2 (0.9)	4.6 (2.4)	32.5 (17.2)	3.8 (1.6)
Jabalpur granite	19	4.6 (0.4)	5.7 (1.4)	21.5 (6.0)	3.4 (0.7)

Standard deviation is given in parentheses.

lower heat production compared to the granitoids and gneisses of the Bundelkhand terrain. Mean heat production of the tonalitic Amgaon gneisses is 0.7 μWm^{-3}, which is about half that of the tonalites of Babina area in the Bundelkhand Granite Complex.

(f) Mean heat production of the Amgaon granite is 2.5 μWm^{-3}, and this value matches with the lower end of heat production values of the Late Archaean and Proterozoic granites of Bundelkhand terrain. Even the Rapakivi granites of Dongargarh are characterized by a mean heat production value of 2.9°μWm^{-3}, which is lower than the lowest mean heat production of 3.4°μWm^{-3} characteristic of the Jabalpur granite of the Bundelkhand terrain.

Discussion

The data presented in the foregoing section bring forth certain salient features about radioelemental distribution and heat production in major rocks comprising the upper crust in some parts of central India.

An increase in the abundance of radioelements with decreasing age has been well documented in the Early to Late Archaean granitoids of the Barberton Mountain Land of South Africa[27]. A similar secular variation has been reported from several other shield areas (refs 28, 29; P. Senthil Kumar, unpublished thesis). This general observation holds good for the middle and late Archaean granitoids of the Bundelkhand craton.

Origin of late Archaean–early Proterozoic K-rich granitoids is an important stage in the evolution of the continental crust during which the upper granodioritic crustal differentiation is accomplished on a worldwide scale[28]. This event marks the time of most significant fractionation of LILE, including radioelements in the upper crust. According to many workers, this large-scale crustal differentiation event was accomplished through a combination of magmatic accretionary processes and partial melting of the older Archaean felsic (tonalitic) crust. Evidence of mixing of melts from these above distinct sources is provided by ubiquitous occurrence of mafic micro-granular enclaves[30] and a wide range of initial strontium isotopic ratios. The widespread occurrence of mafic microgranular enclaves and the Sr_i ranging from 0.7095–0.7125 in the Bundelkhand granite[15] suggest that mixing of melts formed from older Archaean felsic crust, and accretionary melts derived from the mantle may have played an important role in the evolution of the Bundelkhand granite.

Table 2. Mean K, U and Th concentrations of the Proterozoic gneisses and granites of the Bastar terrain

Rock type	N	K (wt%)	U (ppm)	Th (ppm)	HP (mWm^{-3})
Tonalitic Amgaon gneisses (> 2.3 Ga)	10	1.3 (0.2)	1.1 (0.24)	4.3 (1.0)	0.7 (0.1)
Amgaon granite	10	3.6 (0.2)	4.0 (1.4)	16.4 (3.4)	2.5 (0.5)
Dongargarh granite	12	3.9 (0.5)	3.7 (1.5)	22.6 (8.2)	2.9 (0.8)

Similar origin may be valid for the Jabalpur, Amgaon and Dongargarh granites in which ubiquitous occurrence of mafic microgranular enclaves has been observed.

Unlike the Bundelkhand and Jabalpur granites of igneous origin, the 1.5 Ga-old Tirodi gneisses of the Bundelkhand terrain are considered to have been produced from psammo pelitic sedimentary protoliths[20]. One possible explanation for low U content in Tirodi gneisses is as follows. The detrital sedimentary protoliths are considered to be of Mesoproterozoic age. During their sedimentation, in the presence of oxygenic atmosphere, U might have been lost in uranyl form in solution leaving the detritus depleted in U (ref. 28). Gneisses formed from such protoliths depleted in U may have given rise to comparatively U-poor Tirodi gneisses.

The Tattapani gneisses underlying the Gondwana sedimentary rocks[31] form a part of the Proterozoic Chotanagpur gneiss terrain. They have the highest radioelemental abundance among the granitoid rocks of central India studied in this work. Previous studies have shown that the Chotanagpur gneiss terrain hosts widely-distributed zones of U-mineralization[32,33]. It is possible that the source rocks for U-mineralization are fertile granitoids and gneisses that are rich in heat-producing elements[34]. The Tattapani fault along which the high temperature thermal springs are observed, traverses these high heat-producing rocks. Widely distributed high heat-producing basement granitoid rocks persisting to depths of a few kilometres, as evident from geological studies in this region, may elevate the heat-flow in this region. Deep circulating meteoric waters in fault zones, in such elevated heat-flow terrains, can attain high temperatures at shallow depths (~ 3–5 km), provided, these waters remain in contact with them over an extended period of time. Tritium ages of Tattapani thermal spring waters show that they are 30 to 40 years old[35] and their nitrogen content, O– and He-isotopic compositions show that they are meteoric waters[36]. There is no evidence in their isotopic composition for mixing of primary magmatic waters. Therefore, the high temperature of the Tattapani thermal spring waters can be attributed to the high radioactive heat production of the Tattapani gneisses. No Quaternary volcanism/magmatism has been reported in this region. Therefore, models supporting heat-contribution from subjacent magmatic reservoirs do not appear to be tenable. Though the present study has brought out the presence of high heat-producing rocks in this area, further study is essential to assess the contribution of the mantle to the surface heat-flow.

The Bundelkhand and Bastar terrains have been suggested to be discrete terrains based on geological and geophysical evidences[11–13]. It has been proposed that the two terrains are juxtaposed along the Central Indian Suture. A comparison of the composition of the tonalitic gneisses of the Bundelkhand and Bastar terrains shows that the tonalitic gneisses of the Bundelkhand terrain are comparatively richer in radioelements relative to those of the Bastar terrain. The radioelemental abundances and the heat production of the Proterozoic granites and gneisses of the two terrains are also distinct. The U as well as Th contents of the granitoids of the Bundelkhand terrain are significantly higher than those in the Bastar terrain. The processes leading to the differences in the radioelemental abundances in the granites and gneisses of the two terrains are engaging our attention.

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