Episodic crustal growth in the Bundelkhand craton of central India shield: Constraints from petrogenesis of the tonalite–trondhjemite–granodiorite gneisses and K-rich granites of Bundelkhand tectonic zone

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MS received 19 April 2017; revised 6 July 2017; accepted 13 August 2017; published online 12 April 2018

Tonalite–trondhjemite–granodiorite gneisses (TTG) and K-rich granites are extensively exposed in the Mesoarchean to Paleoproterozoic Bundelkhand craton of central India. The TTGs rocks are coarse-grained with biotite, plagioclase feldspar, K-feldspar and amphibole as major constituent phases. The major minerals constituting the K-rich granites are K-feldspar, plagioclase feldspar and biotite. They are also medium to coarse grained. Mineral chemical studies show that the amphiboles of TTG are calcic amphibole hastingsite, plagioclase feldspars are mostly of oligoclase composition, K-feldspars are near pure end members and biotites are solid solutions between annite and siderophyllite components. The K-rich granites have biotites of siderophyllite–annite composition similar to those of TTGs, plagioclase feldspars are oligoclase in composition, potassic feldspars have X_K ranging from 0.97 to 0.99 and are devoid of any amphibole. The tonalite–trondhjemite–granodiorite gneiss samples have high SiO_2 (64.17–74.52 wt%), Na_2O (3.11–5.90 wt%), low $\text{Mg\#}$ (30–47) and HREE contents, with moderate $(\text{La/Yb})_{\text{CN}}$ values (14.7–33.50) and Sr/Y ratios (4.85–98.7). These geochemical characteristics suggest formation of the TTG by partial melting of the hydrous basaltic crust at pressures and depths where garnet and amphibole were stable phases in the Paleo-Mesoarchean. The K-rich granite samples show high SiO_2 (64.72–76.73 wt%), K_2O (4.31–5.42), low Na_2O (2.75–3.31 wt%), $\text{Mg\#}$ (24–40) and HREE contents, with moderate to high $(\text{La/Yb})_{\text{CN}}$ values (9.26–29.75) and Sr/Y ratios (1.52–24). They differ from their TTG in having elevated concentrations of incompatible elements like K, Zr, Th, and REE. These geochemical features indicate formation of the K-granites by anhydrous partial melting of the Paleo-Mesoarchean TTG or mafic crustal materials in an extensional regime. Combined with previous studies it is interpreted that two stages of continental accretion (at 3.59–3.33 and 3.2–3.0 Ga) and reworking (at 2.5–1.9 Ga) occurred in the Bundelkhand craton from Archaean to Paleoproterozoic.

Keywords. Tonalite–trondhjemite–granodiorite gneiss; K-rich granites; Bundelkhand craton; subduction; continental crust; central Indian shield.

1. Introduction

The continental crust holds the key to the record of how processes of crust generation have evolved

through geologic time and preserves evidence of secular variation in crustal composition. One way of deciphering the primitive crustal composition and its evolution through time is to study the

petrological and geochemical attributes of the various rock types preserved in Archaean cratons as the Archaean period is known to represent nearly one-third of the Earth's early history.

Archaean cratons are known to be dominated by four major types of rock associations with distinct chemical signatures namely (a) Tonalite–trondhjemite–granodiorite (TTG) suite are characterized by Na-enrichment ($\text{Na}_2\text{O}/\text{K}_2\text{O} > 1$), $\text{Al}_2\text{O}_3 > 15$ wt%, $\text{Mg\#} = 0.43\text{--}0.51$, $\text{Cr} = 29$ ppm, $\text{Sr} > 400$ ppm, and low HREE ($\text{Y} < 15$ ppm, $\text{Yb} < 1.6$ ppm) which result in high $\text{Sr}/\text{Y} > 40$ and strongly fractionated REE ($\text{La}/\text{Yb}_{\text{CN}} = 15\text{--}100$) (e.g., Martin 1999; Martin and Moyen 2005), (b) Sanukitoids are characterized by $\text{SiO}_2 = 55\text{--}70$ wt%, $\text{Na}_2\text{O}/\text{K}_2\text{O} = 0.5\text{--}3$, $\text{MgO} = 1.5\text{--}9$ wt%, $\text{Mg\#} = 45\text{--}65$, $\text{K}_2\text{O} = 1.5\text{--}5.0$ wt%, $\text{Ba} + \text{Sr} = 1400$ ppm and $(\text{Gd}/\text{Er})_{\text{CN}} = 2\text{--}6$ (e.g., Smithies and Champion 2000; Moyen *et al.* 2003a, b; Kovalenko *et al.* 2005; Lobach-Zhuchenko *et al.* 2008; Halla *et al.* 2009; Heilimo *et al.* 2010; Oliveria *et al.* 2010), (c) the leucocratic, peraluminous granitoids are rich in incompatible elements Rb and Th, $\text{Na}_2\text{O}/\text{K}_2\text{O} < 0.5$, moderately fractionated REE ($\text{La}/\text{Yb}_{\text{CN}} < 30$ with strong Eu anomaly (Moyen *et al.* 2003a, b) and (d) K-rich granites are biotite bearing and are characterized by $\text{Na}_2\text{O}/\text{K}_2\text{O} < 1$, moderately fractionated REE patterns ($\text{La}/\text{Yb}_{\text{CN}} < 30$) (Sylvester 1994; Manya *et al.* 2007).

Of these rock associations, the tonalitic–trondhjemitic–granodioritic rocks and the greenstone belts are considered to be the best proxy to Archaean mantle as they represent 60–80% of the exposed Archaean crust. They occur mainly as basement to the greenstone belts although they may occasionally occur as syn-to post-tectonic plutons (Champion and Smithies 1999). The K-rich granites represent the second abundant Archaean rock type constituting ~20% of the exposed Archaean crust and in many cratons; they appear to have formed later than the TTG in the late Archaean (Sylvester 1994). Indian shield is one of the many significant sites in the world, which preserves the records of the evolution and the growth history of the early Archaean–Palaeoproterozoic crust. The peninsular shield region of India is known to consist of several Archaean cratons which has TTG occurrences, viz., the Bundelkhand craton in the northern India (Mondal *et al.* 2002), the Singbhum craton in the east India (Upadhyay *et al.* 2014), the Bastar craton in the central part of India (Ghosh 2004) and the Dharwar

craton in the southern part (Jayananda *et al.* 2015) (figure 1a).

In the Bundelkhand craton the TTG and K-rich granites are reported from the Bundelkhand Gneissic Complex which is considered to be the oldest litho-unit of this craton (Mondal *et al.* 2002; Singh *et al.* 2007) (figure 1b). The evolutionary history and tectonic processes responsible for cratonisation of the Bundelkhand need to be well constrained for any hypothesized position of India in Precambrian supercontinent reconstruction. In this paper, we present for the first time mineral chemical data and new geochemical data for petrographically well-constrained TTG and K-rich granites from the Bundelkhand Tectonic Zone of the central part of the Bundelkhand craton to infer its petrogenesis for a better understanding of the crustal and tectonic evolution of the peninsular shield region of India during Archaean to Palaeoproterozoic.

2. Geologic setting

Although the Precambrian crustal evolution of the Bundelkhand craton is not robustly constrained, it is broadly agreed that the Precambrian basement of the Bundelkhand craton is a result of amalgamation of many micro-blocks (Sharma 2009; Mohan *et al.* 2012). Naqvi and Rogers (1987) proposed that the Great Boundary Fault divides this proto-continent into two blocks, viz., the Aravalli cratonic block to the east and the Bundelkhand–Gwalior cratonic block to the west.

The Bundelkhand–Gwalior cratonic block is a semi-circular massif spread over an area of about 29,000 km² (Basu 1986) (figure 1b). Sharma and Rahman (2000) proposed three distinct lithostratigraphic units for the block namely, (a) the Archaean enclaves of highly deformed older gneisses–greenstone components (3.59–2.6 Ga) (Sarkar *et al.* 1984; Mondal *et al.* 2002; Kaur *et al.* 2014; Saha *et al.* 2016; Verma *et al.* 2016; Joshi *et al.* 2016), (b) the early Proterozoic undeformed multiphase granitoid plutons (2.5–2.1) (Crawford 1970; Sarkar *et al.* 1984; Mondal *et al.* 2002; Verma *et al.* 2016; Joshi *et al.* 2016; Kaur *et al.* 2016) and (c) lastly the younger mafic dyke swarms (Basu 1986, 2001; Pradhan *et al.* 2012).

Various workers based on geochemical and geochronological study on basalts, komatiites, TTG and younger granitoids have proposed an arc-related subduction setting for generation of various litho-assemblages reported from the Bundelkhand

Figure 1. (a) Map of India showing the relative position of the Bundelkhand craton with respect to various cratons of the Indian shield (modified after [Pradhan et al. 2009](#)). (b) Geological map of the Bundelkhand craton (reproduced after [Basu 1986](#)). Granitoid magmatism ages reported by various authors are displayed on the map ([Mondal et al. 2002](#); [Kaur et al. 2014, 2016](#); [Joshi et al. 2016](#)). (c) Detailed geological map of the Bundelkhand Tectonic Zone showing the various litho units reported from the area. Marked on it are the sample locations of the TTGs and K-rich granites of the present study.

craton ([Mondal et al. 1998, 2002](#); [Singh et al. 2007](#); [Malviya et al. 2006](#); [Kumar et al. 2011](#); [Mohan et al. 2012](#)). Age of the TTG gneisses reported from the Bundelkhand craton range is from 3.59 to 2.66 Ga ([Mondal et al. 2002](#); [Kaur et al. 2014, 2016](#); [Verma et al. 2016](#); [Saha et al. 2016](#); [Joshi et al. 2016](#)). [Crawford \(1970\)](#), [Roy and Kröner \(1996\)](#), [Mondal et al. \(1998, 2002\)](#) and [Meert et al. \(2011\)](#) have proposed that multiphase K-rich granite magmatism (2.55–2.69) marks the cratonization of the Bundelkhand craton. It has been suggested that in subduction derived magmatism granitoids may differentiate into two types: one

bearing high Ca resulting in the TTG formation and the other bearing low Ca resulting K-rich granites. The high Ca granitoids are generally trondhjemites and tonalities derived due to partial melting of a depleted basaltic source and the K-rich granites are mostly derived through partial melting of the felsics associated with older TTGs ([Champion and Sheraton 1997](#)). Hence, the Archaean enclaves of gneisses and greenstones and the younger granitoids intruding the pre-existing greenstone gneiss assemblage of Bundelkhand craton provide the ideal rock types to investigate the Precambrian crustal evolution of the peninsular Indian Shield.

Figure 1. (Continued.)

3. Sampling and petrography

3.1 Sampling

The TTGs are exposed along the E–W striking Bundelkhand Tectonic Zone (a major shear zone) extending along N25°15" (Pati 1999). The tectonic zone extends along the strike of around 200 km from Mahoba through Mauranipur to Babina (figure 1a). This belt consists of metavolcanics and minor sedimentary components in association with the TTG gneisses. The TTG gneisses are exposed along this zone from different areas including Mahoba, Kabrai, Kuraicha and Babina.

K-rich granite occurrences are sporadic and are found associated with this belt. The TTGs show evidence of three generations of folds related to three deformation events and the foliation generally strikes NW–SE with north-easterly or south-westerly dips (60°–70°) (Singh *et al.* 2007). There is a sharp contact between the TTG and granites. The TTG samples are generally medium to coarse-grained and are leucocratic to mesocratic. Well-developed gneissosity of variable thickness of mafic and felsic minerals are prominently observed for TTG samples.

Samples for this study were collected from road sections where fresh rocks are best exposed. A total

Figure 2. Field photographs (a, b) outcrops of tonalite–trondhjemite–granodiorite gneisses with well-developed gneissic foliation, (b, c) K-rich granites; one on the left showing a weak gneissic foliation and other with no visible gneissic foliation.

of 59 samples (36 TTG and 23 K-rich granites) were collected for laboratory analysis. Sample locations are marked in figures 1(c) and 2(a, b) which show field outcrops of TTG and figure 2(c, d) shows K-rich granites.

3.2 Petrography

Representative samples of both TTGs and K-rich granites were made into thin sections and studied under polarizing microscope.

3.3 TTGs

They are composed of plagioclase (21 vol%), quartz (45 vol%), biotite (15 vol%), amphibole (hastingsite) (4 vol%) and K-feldspar (15 vol%). Accessory phases observed include titanite, epidote, apatite, monazite and zircon (1 vol%) (figure 3a–d).

Plagioclases occur as small to large sized grains with anhedral to subhedral form and are identified by low relief, first order grey interference colour and lamellar twinning. Sieved plagioclase texture is also present. Plagioclase is partly altered to sericite due to late hydrothermal alteration. Quartz occurs as medium to large sized grains

showing anhedral to subhedral form. Undulose extinction is common. Biotite shows light brown colour and pleochroism from light brown to dark brown. It occurs as medium to large sized grains with anhedral to subhedral form. Alteration of biotite grains to chlorite is observed in few sections, amphiboles are medium grained and are subhedral in form. In few sections, amphibole is seen altering to biotite which at places is seen replaced by chlorite. Samples also show occurrence of anhedral K-feldspar/microcline. TTGs show typical gneissic fabric with parallel layering and alignment of plagioclase, quartz, amphibole and biotite.

3.4 K-rich granites

They are characterised by K-feldspar and mostly are granitic gneisses according to the field and petrographic characteristics. The mineral assemblage mainly consists of K-feldspar (29 vol%), plagioclase (20 vol%), biotite (7 vol%) and quartz (43 vol%). Zircon, epidote and apatite are the common accessory minerals (1 vol%) (figure 3e, f). These rocks show weak gneissic layering of biotite alternating

Figure 3. Photomicrographs displaying (a–d) assemblage of biotite (Bt), plagioclase feldspar (Fsp), quartz (Qtz) and amphibole (Amph), sericitised feldspars (Ser Fsp) of TTGs from the Bundelkhand suite. Amphiboles and biotites are forming alternate bands with feldspar and quartz rich layers. (e, f) K-rich granites of the Bundelkhand craton with characteristic assemblage of biotite (Bt), K-feldspar (Kfs), and plagioclase feldspar (Fsp). Grain sizes are coarser than that of the TTGs.

with K-feldspar, quartz and plagioclase. The proportion of K-feldspar is more relative to the TTGs.

Plagioclase and K-feldspar occur as subhedral to anhedral grains of varying sizes. Cross-hatch twinning is prominent in the K-feldspars. Plagioclase feldspars commonly show alteration to sericite. Biotite is occurring as lath-shaped grains aligned along the foliation plane alternating with the quartz and feldspar bearing layer. At places they are found surrounding the plagioclase grain

boundary as well. No alteration of biotite to chlorite is observed in the granites. The quartz grains are anhedral and are coarse to medium grained.

4. Mineral chemistry

4.1 Analytical technique

Mineral chemical analyses of various minerals in the TTGs and K-granites were carried out on

polished thin sections using a CAMECA SX 5 electron microprobe with acceleration voltage of 15 kV and beam current of 20 nA at the Electron Microprobe Analyzer Laboratory, Department of Earth Science, Indian Institute of Technology, Bombay. Analyses were carried out with a beam diameter of 0 μm for all phases except Na-rich plagioclase for which it was 5 μm . Standards used include Rhodonite for Mn, TiO_2 for Ti, Albite for Na, Al_2O_3 for Al, Fe_2O_3 for Fe, Diopside for Ca and Mg, Orthoclase for K, Apatite for P and F, CrO_3 for Cr, NaCl for Cl, BaSO_4 for Ba, ZnS for Zn and Th glass for Si. The ZAF correction was applied to the data.

Electron microprobe data of feldspars, biotite and amphibole together with the calculated number of ions per unit cell are given in table 1. Representative back scattered electron images of each rock type are shown with characteristic assemblage in figure 4.

The TTGs and K-granites both have plagioclase and alkali feldspar. Figure 5(a, b) shows a composition plot with feldspar chemistry in terms of Albite–Anorthite–Alkali feldspar for the TTGs and K-granites. Plagioclases in the TTGs are mainly oligoclase with X_{Ab} contents of 0.70–0.80 and X_{An} varying from 0.18 to 0.28. The K-feldspars of TTGs show X_{K} value ranging from 0.96 to 0.97. Plagioclases in the K-granites are mainly oligoclase with X_{Ab} contents of 0.73–0.80 and X_{An} varying from 0.18 to 0.25. We have K–Na feldspar as well with X_{Ab} content of 0.61 and X_{K} content of 0.35. The K-feldspars of potassic granites show X_{K} value ranging from 0.97 to 0.99.

Biotite compositions of the TTGs and K-granites from this area are representative of the siderophyllite–annite end members (figure 6a). The biotites of TTG display high FeO contents (24–25%), TiO_2 contents (0.31–2.15%) and high Fe/(Fe+Mg) ratios (>0.6), whereas the biotites of the K-rich granites display FeO content varying from (25–27%), TiO_2 content displays a range from 1.61 to 2.94% and high Fe/(Fe+Mg) ratios (>0.6). In the plot of Mg vs. total Al plot of Abdel-Rahman (1994) (figure 6b), all biotite data of the K-granites fall in subalkaline field, whereas the TTG biotites range from alkaline to subalkaline type.

The amphiboles are only present in TTGs of the Bundelkhand craton. The amphiboles are generally Al rich (Al total ranges from 1.89 to 2.14) and exhibit Fe/Fe+Mg ratios ranging from 2.14 to 3.90. These minerals belong to the calcic amphibole sub-group. Using the classification of Leake *et al.*

(1997), the amphiboles are classified as hastingsite (figure 7). Crystallization of amphibole affects the composition of the derivative melt during magmatic differentiation. We have applied geobarometers based on Al in Hornblende equilibrated with quartz by Hammerstrom and Zen (1986); Hollister *et al.* (1987) for the TTGs of Bundelkhand. The results show the TTG crystallization pressure to be 4.9–6.8 kbar based on the equation of Hammerstrom and Zen (1986) with an average of 5.94 kbar whereas the Hollister *et al.* (1987) geobarometer gave a pressure range of 5.1–7.4 kbar (average = 6.30 kbar). Calculated temperatures for the TTG gneisses using geothermometer of Blundy and Holland (1990) range from 755 to 777°C (average = 767°C) using the pressures calculated by Hammerstrom and Zen (1986). Temperatures vary slightly 751–770°C (average = 762°C), if pressures calculated by Hollister *et al.* (1987) are used for temperature calculation (table 2).

5. Geochemistry

5.1 Analytical technique

Analysis of major oxides and trace elements for TTG samples and K-rich granites was carried out using the XRF technique (Bruker S8 Tiger Sequential X-ray Spectrometer with Rh excitation source) following the procedure of Saini *et al.* (1998, 2000) and rare earth elements (REE) were analysed using ICP-MS (Perkin Elmer made SCIEX quadrupole type ICP-MS, ELAN DRC-e), at the Wadia Institute of Himalayan Geology, Dehradun (India). For the major oxides the operating conditions were No filter, Vacuum path, 20/40 KV; for trace elements the operating conditions were No filter, Vacuum path, 55/60 KV. The overall accuracy in relative standard deviation percentage is $<5\%$ for major and minor oxides and $<12\%$ for the trace elements. The average precision is better than 2.0% (Purohit *et al.* 2006; Saini *et al.* 2007). Sample solutions were introduced for rare earth element analysis into the argon plasma using a peristaltic pump and a cross flow nebulizer. The procedures adopted for sample digestion and preparation of solutions were that of Balaram *et al.* (1990). USGS (BHVO-1, AGV-1) and JGS (JG-2, RGM-1) samples were used as rock standards to minimize matrix effect. Relative standard deviation (RSD) for most of the samples is better than 10%. Representative major and trace element compositions of 10 TTGs and 10 K-rich

Table 1. (Continued.)

Biotites											
	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
Ba	0.006	0.002	0.004	0.003	0.006	0.004	0.003	0.002	0.001	0.001	0.002
P	0.001	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002
Total	15.712	15.699	15.716	15.686	15.727	15.711	13.693	13.715	13.759	13.722	13.726

Biotites											
	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
SiO ₂	35.951	35.55	35.567	35.695	34.684	34.295	35.338	34.852	35.789	35.958	36.163
TiO ₂	1.879	1.735	1.662	1.705	1.688	1.459	1.617	1.721	1.796	1.915	1.858
Al ₂ O ₃	15.235	15.546	15.706	15.498	15.593	15.604	15.766	15.746	15.461	15.845	15.196
Cr ₂ O ₃	0.005	0.019	0.006	0.01	0.014	0	0.031	0.003	0.005	0.013	0.016
Fe ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0
FeO	25.804	25.487	25.683	25.453	26.58	27.033	25.203	25.934	25.385	25.686	25.725
MnO	0.317	0.347	0.348	0.314	0.416	0.38	0.345	0.382	0.359	0.363	0.368
MgO	6.702	6.515	6.676	6.577	6.437	7.09	6.726	6.451	6.673	6.411	6.718
CaO	0.036	0	0.095	0.018	0.042	0.109	0	0	0	0.032	0.043
Na ₂ O	0.031	0.018	0.025	0.017	0.044	0.093	0.015	0.013	0.051	0.032	0.066
K ₂ O	9.434	9.547	9.215	9.367	9.029	7.779	9.224	9.268	9.324	9.284	9.305
Cl	0.16	0.172	0.174	0.151	0.146	0.173	0.136	0.162	0.146	0.146	0.17
F	0	0	0	0	0	0	0	0	0	0	0
ZnO	0.065	0	0	0.105	0	0.046	0.017	0.046	0.046	0.015	0
BaO	0.033	0.165	0.029	0.067	0.052	0.035	0.083	0.018	0.019	0.071	0.108
P ₂ O ₅	0	0.019	0	0	0.025	0	0	0.03	0.013	0	0
Total	95.652	95.12	95.185	94.978	94.75	94.097	94.501	94.627	95.067	95.771	96.699
Si	5.652	5.625	5.611	5.646	5.536	5.492	5.610	5.553	5.648	5.633	5.674
Ti	0.222	0.207	0.197	0.203	0.203	0.176	0.193	0.206	0.213	0.226	0.219
Al	2.823	2.899	2.920	2.889	2.933	2.945	2.950	2.957	2.875	2.925	2.810
Al _{iv}	2.348	2.375	2.389	2.354	2.464	2.508	2.390	2.447	2.352	2.367	2.326
Al _{vi}	0.475	0.524	0.532	0.535	0.469	0.437	0.559	0.510	0.523	0.558	0.484
Cr	0.001	0.002	0.001	0.001	0.002	0.000	0.004	0.000	0.001	0.002	0.000
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	3.393	3.373	3.389	3.367	3.548	3.620	3.346	3.456	3.350	3.365	3.376
Mn	0.042	0.047	0.047	0.042	0.056	0.052	0.046	0.052	0.048	0.048	0.049
Mg	1.571	1.537	1.570	1.551	1.532	1.693	1.592	1.532	1.570	1.497	1.571
Ca	0.006	0.000	0.016	0.003	0.007	0.019	0.000	0.000	0.000	0.005	0.007
Na	0.009	0.006	0.008	0.005	0.014	0.029	0.005	0.004	0.016	0.010	0.020

Table 1. (Continued.)

Biotites											
	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites	K-granites
K	1.892	1.927	1.855	1.890	1.838	1.589	1.868	1.884	1.877	1.855	1.863
Cl	0.043	0.046	0.047	0.040	0.039	0.047	0.037	0.044	0.039	0.039	0.045
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.002	0.010	0.002	0.004	0.003	0.002	0.005	0.001	0.001	0.004	0.006
P	0.000	0.003	0.000	0.000	0.003	0.000	0.000	0.004	0.002	0.000	0.000
Total	15.657	15.680	15.662	15.642	15.715	15.663	15.655	15.694	15.639	15.609	15.642
K-feldspar											
	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	K-Granite	K-Granite	K-Granite
SiO ₂	64.048	63.608	64.433	64.854	64.979	64.935	64.075	64.584	64.075	64.075	64.584
TiO ₂	0	0	0	0.005	0	0	0	0	0	0	0
Al ₂ O ₃	18.289	18.188	18.283	18.303	18.2	18.256	17.962	18.345	17.962	17.962	18.345
Cr ₂ O ₃	0	0	0	0	0	0.003	0	0.056	0	0	0.056
Fe ₂ O ₃	0.029	0.04	0.125	0.135	0.045	0.137	0.087	0.024	0.087	0.087	0.024
FeO	0	0.027	0	0	0	0	0	0	0	0	0
MnO	0	0.015	0.015	0	0	0.006	0.021	0	0.021	0.021	0
CaO	0	0	0	0	0	0	0	0	0	0	0
Na ₂ O	0.503	0.358	0.349	0.334	0.349	0.236	0.232	0.225	0.232	0.232	0.225
K ₂ O	15.35	15.584	15.918	15.668	15.845	16.15	16.353	16.098	16.353	16.353	16.098
Cl	0.021	0.006	0	0.003	0.004	0.068	0	0.007	0	0	0.007
F	0	0	0	0	0	0	0	0.069	0	0	0.069
ZnO	0.027	0	0	0	0	0	0	0	0	0	0
BaO	0.626	0.617	0.615	0.244	0.328	0.205	0.264	0.101	0.264	0.264	0.101
P ₂ O ₅	0.023	0	0	0.018	0	0.017	0.027	0	0.027	0.027	0
Total	98.917	98.443	99.738	99.564	99.751	100.013	99.022	99.508	99.022	99.022	99.508
Si	2.995	2.994	2.996	3.005	3.009	3.002	3.001	2.996	3.001	3.001	2.996
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.008	1.009	1.002	1.000	0.993	0.995	0.991	1.003	0.991	0.991	1.003
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.002
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	0.001	0.002	0.005	0.005	0.002	0.005	0.003	0.001	0.003	0.003	0.001
Mn	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.046	0.033	0.031	0.030	0.031	0.021	0.021	0.020	0.021	0.021	0.020

Table 1. (Continued.)

	K-feldspar									
	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
K	0.916	0.936	0.944	0.926	0.936	0.936	0.936	0.936	0.977	0.953
Cl	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.001
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.011	0.011	0.011	0.004	0.006	0.006	0.006	0.004	0.005	0.002
P	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.000
Total	4.979	4.986	4.991	4.972	4.978	4.978	4.978	4.986	5.001	4.988
Ca + Na + K	0.961	0.968	0.976	0.956	0.967	0.967	0.967	0.974	0.998	0.973
Ab (Na)	4.744	3.374	3.225	3.138	3.239	3.239	3.239	2.173	2.111	2.080
An (Ca)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Or (K)	95.256	96.626	96.775	96.862	96.761	96.761	96.761	97.827	97.889	97.920
Plagioclase feldspar										
	TTG	TTG	TG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
SiO ₂	61.868	62.236	61.893	61.63	60.7	61.212	61.118	63.135	62.873	62.873
TiO ₂	0	0	0	0.031	0	0	0	0	0	0
Al ₂ O ₃	23.551	23.35	23.69	23.992	24.281	23.798	24.245	22.497	22.758	22.758
Cr ₂ O ₃	0	0.004	0	0	0.033	0	0.006	0.016	0.025	0.025
Fe ₂ O ₃	0.187	0.027	0.111	0.107	0.012	0.111	0	0.111	0.076	0.076
FeO	0	0	0.012	0.007	0.015	0.024	0.003	0.058	0.016	0.016
MnO	0	0	0.003	0	0	0.008	0.016	0.008	0.013	0.013
MgO	0	0	0.003	0	0	0.008	0.016	0.008	0.013	0.013
CaO	5.189	4.977	5.158	5.477	5.906	5.465	5.999	4.014	4.061	4.061
Na ₂ O	8.497	8.868	8.614	8.529	8.174	8.597	8.203	9.342	9.307	9.307
K ₂ O	0.092	0.087	0.088	0.117	0.147	0.129	0.089	0.229	0.096	0.096
Cl	0	0.008	0.004	0.004	0.008	0	0	0	0.006	0.006
F	0	0	0	0	0	0	0	0	0	0
ZnO	0	0	0	0	0	0.005	0	0.039	0	0
BaO	0.005	0.005	0	0.021	0	0	0	0	0	0
P ₂ O ₄	0.012	0	0	0.012	0	0	0.001	0	0	0
Total	99.401	99.562	99.573	99.928	99.276	99.348	99.681	99.448	99.232	99.232
Si	2.759	2.769	2.755	2.738	2.717	2.737	2.723	2.810	2.801	2.801
Ti	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.238	1.225	1.243	1.256	1.281	1.254	1.273	1.180	1.195	1.195
Cr	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.001
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	0.007	0.001	0.004	0.004	0.000	0.004	0.000	0.004	0.003	0.003

Table 1. (Continued.)

	Plagioclase feldspar									
	TTG	TTG	TG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
Mn	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.002	0.001
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001
Ca	0.248	0.237	0.246	0.261	0.283	0.283	0.262	0.286	0.191	0.194
Na	0.735	0.765	0.743	0.735	0.709	0.709	0.745	0.709	0.806	0.804
K	0.005	0.005	0.005	0.007	0.008	0.008	0.007	0.005	0.013	0.005
Cl	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	4.992	5.003	4.998	5.003	5.001	5.001	5.012	4.997	5.008	5.005
Ca+Na+K	0.988	1.007	0.994	1.002	1.001	1.001	1.015	1.000	1.011	1.003
Ab (Na)	74.371	75.953	74.759	73.319	70.866	70.866	73.466	70.858	79.772	80.133
An (Ca)	25.099	23.557	24.738	26.019	28.296	28.296	25.808	28.637	18.942	19.323
Or (K)	0.530	0.490	0.503	0.662	0.839	0.839	0.725	0.506	1.287	0.544

	Plagioclase feldspar									
	K-granite	K-granite	K-granite	K-granite	K-granite	K-granite	K-granite	K-granite	K-granite	K-granite
SiO ₂	63.747	62.576	63.003	62.962	62.653	63.959	63.13	62.75	63.346	61.727
TiO ₂	0	0	0	0	0.01	0.005	0.031	0	0.012	0.024
Al ₂ O ₃	22.36	22.997	22.621	23.001	23.548	22.856	23.206	23.034	23.216	23.024
Cr ₂ O ₃	0.011	0	0	0.026	0	0	0	0.008	0	0.021
Fe ₂ O ₃	0.03	0.127	0.112	0.081	0.326	0	0.048	0.03	0	0
FeO	0	0	0	0	0.017	0	0.034	0.001	0	0
MnO	0.001	0.004	0.004	0.002	0.002	0	0	0	0	0.005
MgO	3.948	4.566	4.262	4.651	4.773	4.467	4.731	4.56	4.664	5.337
CaO	9.524	8.983	9.346	9.071	8.921	9.126	9.093	9.027	8.884	8.608
Na ₂ O	0.085	0.151	0.166	0.104	0.233	0.167	0.113	0.115	0.125	0.174
K ₂ O	0	0.004	0	0	0	0.006	0	0.015	0.003	0.014
Cl	0	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0	0
ZnO	0	0	0	0	0	0.098	0	0	0.024	0
BaO	0	0	0	0.009	0.002	0	0.026	0.007	0	0
P ₂ O ₄	0.002	0.026	0.007	0	0	0.01	0.015	0.015	0	0.012
Total	99.708	99.434	99.52	99.907	100.484	100.695	100.428	99.563	100.275	99.744
Si	2.824	2.786	2.803	2.790	2.767	2.809	2.784	2.788	2.793	2.750

Al	1.167	1.207	1.186	1.201	1.496	1.226	1.183	1.206	1.194	1.206	1.236	1.205
Cr	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Fe ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	0.001	0.005	0.004	0.003	0.011	0.012	0.000	0.002	0.005	0.000	0.012	0.000
Mn	0.000	0.000	0.000	0.000	0.008	0.001	0.000	0.001	0.000	0.000	0.000	0.000
Mg	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ca	0.187	0.218	0.203	0.221	0.030	0.226	0.210	0.224	0.211	0.220	0.255	0.221
Na	0.818	0.775	0.806	0.779	0.533	0.764	0.777	0.778	0.781	0.759	0.743	0.768
K	0.005	0.009	0.009	0.006	0.306	0.013	0.009	0.006	0.010	0.007	0.010	0.006
Cl	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
P	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Total	5.003	5.001	5.012	5.002	5.028	5.008	4.989	5.003	5.000	4.986	5.008	4.992
Ca+Na+K	1.010	1.002	1.019	1.006	0.869	1.003	0.997	1.007	1.002	0.987	1.008	0.995
Ab (Na)	80.975	77.402	79.133	77.466	61.353	76.170	77.970	77.178	77.918	76.960	73.750	77.206
An (Ca)	18.550	21.742	19.942	21.950	3.416	22.521	21.091	22.191	21.040	22.328	25.269	22.218
Or (K)	0.476	0.856	0.925	0.584	35.231	1.309	0.939	0.631	1.042	0.712	0.981	0.575
	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000

Amphibole

	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG	TTG
SiO ₂	41.395	40.498	40.155	40.762	41.809	40.744	40.106	39.322	39.159	38.635	38.982	38.982
TiO ₂	0.766	0.74	0.665	0.698	0.748	0.781	0.506	0.558	0.747	0.496	0.629	0.629
Al ₂ O ₃	9.808	10.442	10.923	10.233	9.6	10.283	11.289	11.417	10.478	11.309	11.026	11.026
Cr ₂ O ₃	0.101	0.027	0.081	0.024	0.05	0.023	0.004	0.081	0	0.002	0.009	0.009
FeO	24.04	24.335	24.636	24.239	23.848	23.778	24.409	24.982	26.757	26.823	26.772	26.772
MnO	0.501	0.554	0.537	0.599	0.57	0.472	0.507	0.545	0.573	0.555	0.501	0.501
MgO	6.3	6.027	5.627	5.99	6.614	6.099	5.563	5.286	4.333	3.854	3.973	3.973
CaO	11.282	11.547	11.291	11.478	11.412	11.465	11.467	11.242	11.112	11.228	11.219	11.219
Na ₂ O	1.203	1.162	1.121	1.07	1.29	1.094	1.181	1.19	1.432	1.327	1.19	1.19
K ₂ O	1.246	1.281	1.339	1.323	1.168	1.338	1.411	1.414	1.596	1.679	1.679	1.679
Cl	0.157	0.184	0.192	0.208	0.163	0.174	0.208	0.215	0.228	0.275	0.28	0.28
P ₂ O ₃	0.019	0	0.034	0	0.026	0.006	0.007	0	0.004	0.002	0	0
ZnO	0	0	0	0.181	0	0.045	0.062	0	0.042	0.154	0.063	0.063
BaO	0.001	0.024	0.01	0.025	0	0	0.05	0	0	0	0.023	0.023
F	0	0	0	0	0	0	0	0	0	0	0	0
Total	96.82	96.823	96.61	96.831	97.298	96.304	96.77	96.252	96.461	96.339	96.345	96.345

Figure 4. Back-scattered electron images of a representative sample of (a) TTG and (b) K-rich granite showing the characteristic mineral assemblage. Abbreviations are Ab: albite, Chl: chlorite, Ap: apatite, Kfs: potash feldspar, Qtz: quartz, Fsp: feldspar, Hast: hastingsite, and Pl: plagioclase.

Figure 5. Triangular plots showing the composition of the feldspars of (a) TTGs and (b) K-rich granites of the Bundelkhand craton after [Deer et al. \(1992\)](#).

granites of the Bundelkhand craton are presented in table 3.

5.2 TTGs

The samples of this group contain SiO_2 from 64.17 to 74.52 wt%, whereas the total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vary from 5.61 to 7.76 wt% with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios from 1.28 to 3.89. These compositions exhibit variable contents of MgO (0.55 to 1.29 wt%) and Fe_2O_3 (2.27 to 6.22 and their $\text{Mg\#}$ calculated as $[100 \text{ Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+} \text{ total})]$, $\text{Fe} = 0.8998\text{Fe}^{\text{T}}$ vary from 30 to 47 suggesting slightly primitive to evolved composition. Al_2O_3 contents of the rocks are 13.49–17.04 wt%. In the Ab–Or–An diagram, all the samples are plotted in the tonalite, trondhjemite and granodiorite field

(figure 8). The samples were also plotted on the $\text{CaO}–\text{K}_2\text{O}–\text{Na}_2\text{O}$ diagram of [Moyen et al. \(2003a, b\)](#), which is used to distinguish various types of Archaean granites (figure 9), in which samples plot in the TTG and enriched TTG field with a single outlier. These rocks have a calc alkaline affinity and show weakly peraluminous character with A/CNK ratios ranging from 1.00 to 1.11 (figure 10a, b). The rocks have Sr contents 175–666 ppm and Y contents 5–42 ppm.

On the primitive mantle normalized ([Sun and McDonough 1989](#)) trace element spidergram (figure 11a), the rocks show elevated concentrations of Nd, Ba, Th, Pb and Rb and depletions in Nb, Ti, P, Ba with Sr/Y ratio of 4.9–98.7. On the chondrite normalized REE patterns, the Bundelk-

Figure 6. (a) Classification of biotites observed in the TTGs and K-rich granites of the Bundelkhand craton based on the nomenclature of Speer (1984). (b) Plot of Mg vs. Al total of biotites from the Bundelkhand TTGs and K-rich granites after Abdel-Rahman (1994) showing its alkaline affinity.

Figure 7. Nomenclature of calcic-amphiboles present exclusively in the TTG gneisses of the Bundelkhand craton. Classification after Leake *et al.* (1997).

hand craton TTG samples exhibit LREE-enriched and HREE-depleted patterns with moderate $(La/Yb)_{CN}$ = where CN represents chondrite normalized values after McDonough and Sun (1995) (figure 11b). The samples show weakly negative Eu anomalies ($Eu/Eu^* = 1.3 - 2.7$). The rocks have high La (27–151 ppm) and low Yb (90.67–3.67 ppm) with low $(Gd/Yb)_{CN}$ ratios ranging from 2.2 to 4.6.

5.3 K-rich granites

The rocks of this type have SiO_2 ranging from 64.72 to 76.73 wt%, low Na_2O from 2.75 to 3.31 wt%, Al_2O_3 from 12.43 to 15.65 wt%, Fe_2O_3 from 2.92 to 4.86 wt% and MgO from 0.46 to 1.16 wt%. They show Na_2O/K_2O ratios ranging from 0.58 to 0.79 and high K_2O from 4.21 to 5.44 wt%. The $Mg\#$ of these rocks range from 24 to 40. Their total alkalis ($Na_2O + K_2O$) vary from 7.06 to 8.63 wt% and are slightly higher than those of their TTG counterparts of this study. In the $CaO-K_2O-Na_2O$ diagram of Moyen *et al.* (2003a, b), they plot in the biotite granite field due to their higher K_2O contents than those of studied TTGs (figure 9). On the feldspar normative An-Ab-Or diagram of O'Connor (1965) with fields from Barker (1979) the samples plot in the granite field (figure 8). The rocks have Sr contents of 175–648 ppm and Y concentrations of 27–50 leading to Sr/Y ratios of 2–24. All the rocks show a shoshonitic property (figure 12) and weakly peraluminous feature with A/CNK ratios ranging from 0.96 to 1.17 (figure 10b).

On the primitive mantle-normalized spidergram (figure 13a), the rocks show negative Nb, Ti, P anomalies, negative to positive Sr anomalies and positive K anomalies. These patterns are similar to those of the studied TTGs. All the samples of this group also exhibit a LREE-enriched and HREE-depleted patterns. All the samples show negative Eu anomalies ($Eu/Eu^* = 1.97 - 3.38$) with $(La/Yb)_{CN}$ values of 10–27 (figure 13b).

Table 2. Pressure calculations based on Al-in- Hornblende (using methods of [Hammerstrom and Zen 1986](#); [Hollister et al. 1987](#)) and temperature calculations based on the amphibole-plagioclase thermometer of [Blundy and Holland \(1990\)](#) for the TTG suite of Bundelkhand craton.

Sample no.	Al (T)	Si	Pressure (Kbar) (Hammerstrom and Zen 1986)	Pressure (Kbar) (Hollister et al. 1987)	X _{Ab} .	Temp (°C)
HC 7	1.81	6.47	5.16	5.43	0.744	755
HC 7	1.93	6.34	5.78	6.11	0.760	767
HC 7	2.02	6.31	6.25	6.65	0.748	769
HC 7	1.89	6.40	5.60	5.91	0.733	767
HC 7	1.76	6.49	4.92	5.15	0.709	763
HC 7	1.91	6.41	5.67	5.99	0.735	762
HC 7	2.09	6.30	6.60	7.03	0.709	777
HC 9	1.98	6.28	6.03	6.40	0.801	767
HC 9	2.14	6.22	6.87	7.33	0.779	771
HC 9	2.09	6.26	6.57	7.00	0.758	773
Avg.			5.94	6.30		767

6. Discussion

6.1 Petrogenesis

6.1.1 TTGs

The Bundelkhand craton TTGs exhibit similar geochemical characteristics with other known TTG intrusive bodies in Archaean cratons of the world (e.g., [Martin and Moyen 2005](#); [Manya et al. 2007](#)). Such characteristics include high concentrations of Al₂O₃ (13.49–17.04 wt%, average = 15.46 wt%), high ratios of Na₂O/K₂O (1.00–54.2) and low concentration of heavy REEs with Y contents of 5–42 ppm and Yb = 0.3–0.5 ppm. The TTG samples cover the entire range of tonalite, trondhjemitic and granodiorite in the normalized plot of Ab–An–Or with moderate ratios of Sr/Y ratios (4.9–98) and (La/Yb)_N = 15–30 showing characteristics of TTG and adakites ([Condie 2005](#); [Martin and Moyen 2005](#)). The higher La/Yb and Sr/Y ratios in the Bundelkhand TTG are a result of low HREE contents in the rocks. Since HREE can strongly partition themselves in garnet and amphibole during mantle melting, the low contents of HREE as well as the higher La/Yb and Sr/Y ratios in these TTGs can be attributed to the presence of residual garnet and/or hornblende in the source during partial melting ([Smithies 2000](#); [Martin and Moyen 2005](#); [Condie 2005](#)).

Debate still persists as to the tectonic setting for the generation of TTG assemblage ([Martin 1999](#); [Smithies and Champion 2000](#); [Foley et al. 2002](#);

[Condie 2005](#); [Foley 2008](#); [Moyen 2009](#)), but many workers (e.g., [Drummond and Defant 1990](#); [Kay and Kay 1993](#); [Martin 1999](#); [Rapp et al. 1999](#); [Smithies and Champion 2000](#); [Martin and Moyen 2005](#); [Manya et al. 2007](#); [Moyen 2009](#)) have shown that Archaean TTGs and adakites are all interpreted to be the product of partial melting of hydrous basaltic crust in the subduction zones under eclogite facies condition with a characteristic high Mg# values and low Cr and Ni concentrations due to interaction of the ascending partial melt with the mantle peridotite. Another formation mechanism considered is the partial melting of amphibolite/eclogite at the base of thickened arc crust and partial melting of wet mafic roots of an oceanic plateaus have also been considered, which would produce melts with low Mg# values and low Cr and Ni concentrations ([Atherton and Petford 1993](#); [Rapp et al. 1999](#); [Smithies 2000, 2002](#); [Condie 2005](#); [Huang et al. 2014](#)). The Bundelkhand TTG samples of this study have high SiO₂ concentrations, low Mg# values and low Cr and Ni concentrations, implying that the trondhjemitic samples are probably derived from a hydrous thickened, basaltic lower crust.

When the Bundelkhand TTG rock data are plotted on the major oxide ratios of experimental melts obtained from the partial melting of common crustal rocks such as amphibolites, tonalitic gneisses, metagreywackes and metapelites under variable melting conditions (e.g., [Patiño-Douce 1996, 1999](#)), it plots in the field of amphibolites (figure 14a, b). The plotting of the Bundelkhand

Table 3. Representative major oxide and trace element analyses of the TTGs and K-rich granites from the Bundelkhand craton.

Type	TTG									
Sample	HC 5	HC 7	HC 9	HC 14	HC 18	HC 29	HC 38	BK 12	BK 16	BK 18
North	N25°13'20.7"	N25°13'20.7"	N25°27'9.4"	N25°27'16.6"	N25°11'5.5"	N25°23'24.4"	N25°02'5.4"	N25°23'15.4"	N25°11'5.5"	N25°11'5.5"
East	E78°28'04.1"	E78°28'04.1"	E78°12'49.3"	E78°7'30.1"	E79°6'24.4"	E80°00'15.5"	E79°50'18.0"	E79°45'16.0"	E79°6'24.4"	E79°6'24.4"
SiO ₂	74.52	62.99	73.47	68.18	67.66	67.35	64.17	69.94	70.82	67.14
Al ₂ O ₃	13.49	15.53	14.53	16.8	15.46	16.1	17.04	15.33	15.11	15.26
Fe ₂ O ₃	2.57	6.22	3.01	2.89	3.05	2.27	4.24	2.61	3.12	4.4
MnO	0.05	0.1	0.04	0.08	0.04	0.05	0.07	0.03	0.04	0.06
MgO	0.55	2	0.74	1.29	0.9	0.65	1.02	0.76	0.7	1.15
CaO	1.41	3.51	2.53	3.76	2.63	2.08	2.67	2.4	2.61	3.3
Na ₂ O	5.13	3.11	4.22	4.15	5.18	5.9	4.36	5.66	4.23	4.51
K ₂ O	1.58	3.6	1.39	3.03	1.33	1.4	3.4	1.6	2.51	1.48
TiO ₂	0.33	1.18	0.39	0.54	0.31	0.3	0.53	0.2	0.3	0.37
P ₂ O ₅	0.09	0.54	0.05	0.12	0.1	0.1	0.07	0.03	0.14	0.16
LOI	1.25	1.03	1.05	1.01	1	0.85	0.87	0.67	0.8	0.69
SUM	99.72	99.81	101.42	101.85	97.66	97.05	98.44	98.56	99.58	97.83
Mg#	30	39	33	47	37	36	32	37	31	34
Sc	8.6	10.542	8.062	19.962	13.774	21.495	6.702	6.2	7.9	9.8
Zr	220	189.895	264.579	255.488	134.668	258.068	188.336	192	161	131
V	24	43.874	33.064	42.119	28.867	12.474	58.516	16	27	45
Cr	160	404.423	414.243	300.021	422.223	413.395	336.714	137	120	146
Co	5.7	8.731	6.87	11.274	4.09	6.911	11.97	3.4	7.1	11.9
Ni	16	13.689	4.81	3.415	9.011	25.591	12.273	17	20	25
Rb	74	99.217	121.06	125.741	207.998	129.88	171.838	62	94	87
Sr	224	498.04	201.773	408.573	480.169	666.167	393.243	382	176	175
Y	19	5.046	41.591	14.764	16.512	16.276	25.752	9	16	13
Nb	10	7.754	19.375	10.255	4.386	16.406	27.005	9	11	11
Ba	551	309.713	299.132	789.897	258.926	332.228	789.938	190	515	136

La	72.5	51.072	151.267	50.081	33.292	63.197	112.75	29	49.2	27
Ce	137	87.544	285.174	93.459	61.184	111.092	219.571	50	92.8	51
Pr	13.5	8.411	29.531	9.753	6.394	11.282	23.189	4.7	9.2	5.2
Nd	48.5	29.539	106.629	37.472	24.389	40.274	83.013	17	33.6	19.5
Sm	7.4	4.629	16.32	6.504	4.288	6.449	14.026	2.83	6.22	3.6
Eu	1.1	1.102	2.009	1.7	1.047	1.231	1.657	0.65	0.94	0.77
Gd	6.05	4.832	16.393	6.388	3.843	5.799	13.139	2.26	4.95	3
Tb	0.88	BDL	BDL	BDL	BDL	BDL	BDL	0.3	0.72	0.47
Dy	4.39	3.014	9.304	4.782	2.142	3.67	7.105	1.39	3.44	2.5
Ho	0.88	BDL	BDL	BDL	BDL	BDL	BDL	0.26	0.63	0.5
Er	2.2	1.245	3.937	2.146	0.803	1.683	2.659	0.65	1.48	1.24
Tm	0.31	BDL	BDL	BDL	BDL	BDL	BDL	0.09	0.2	0.18
Yb	1.88	1.151	3.671	2.309	0.675	2.09	2.619	0.69	1.29	1.07
Lu	0.24	0.183	0.577	0.383	0.121	0.327	0.45	0.1	0.18	0.13
Pb	18	20.361	23.099	25.564	17.7	45.144	41.318	28	21	11
Th	17	11.218	51.352	18.042	7.448	23.911	55.696	9	14	5
A/CNK	1.061	1.009	1.114	0.992	1.049	1.073	1.085	0.995	1.048	1.016
Na ₂ O/K ₂ O	3.247	0.864	3.036	1.370	3.895	4.214	1.282	3.538	1.685	3.047
Sr/Y	11.789	98.700	4.851	27.674	29.080	40.929	15.270	42.444	11.000	13.462
Dy/Yb	2.335	2.619	2.534	2.071	3.173	1.756	2.713	2.014	2.667	2.336
(La/Yb) _{CN}	26.197	30.143	27.992	14.734	33.505	20.541	29.245	28.551	25.909	17.142
(Gd/Yb) _{CN}	2.604	3.396	3.613	2.238	4.606	2.245	4.059	2.650	3.104	2.268
Eu/Eu*	2.058	1.419	2.699	1.259	1.298	1.663	2.732	1.320	2.003	1.440
Yb _{CN}	11.677	7.149	22.801	14.342	4.193	12.981	16.267	4.286	8.012	6.646
Zr/Sm	29.730	41.023	16.212	39.282	31.406	40.017	13.428	67.845	25.884	36.389

Table 3. (Continued.)

Type	Potassic Granite										
Sample	HC 12	HC 27	HC 30	BK 1	BK 2	BK 3	BK 4	BK 5	BK 6	BK 8	
North	N25°27'15.7"	N25°11'40.8"	N25°19'49.0"	N25°19'49.0"	N25°19'49.0"	N25°20'49.0"	N25°20'49.0"	N25°23'24.4"	N25°23'24.4"	N25°02'5.4"	
East	E78°9'25.6"	E78°28'40.6"	E79°49'4.2"	E79°49'4.2"	E79°49'4.2"	E79°49'18"	E79°49'18"	E80°0'15.5"	E80°0'15.5"	E79°50'18.0"	
SiO ₂	64.72	66.57	76.73	66.5	67.53	68.19	66.7	66.9	70.63	74.04	
Al ₂ O ₃	14.71	15.65	12.43	14.99	14.58	14.88	14.17	14.29	14.49	14.44	
Fe ₂ O ₃	4.86	4.26	2.96	4.61	4.03	4.03	4.44	4.19	2.92	1.71	
MnO	0.06	0.08	0.03	0.06	0.05	0.05	0.06	0.06	0.06	0.02	
MgO	0.99	0.99	0.46	1.16	0.97	0.95	1.03	1.01	0.99	0.32	
CaO	2.26	2.45	0.78	2.43	2.08	1.99	2.27	2.01	2.46	1.73	
Na ₂ O	3.06	3.31	2.75	3.2	3.14	3.19	3.05	3.1	3.29	3.05	
K ₂ O	4.98	4.21	4.31	5.19	5.42	5.44	5.12	5.34	4.88	5.42	
TiO ₂	0.64	0.77	0.26	0.72	0.6	0.62	0.69	0.61	0.36	0.2	
P ₂ O ₅	0.33	0.29	0.03	0.36	0.3	0.29	0.33	0.29	0.16	0.07	
LOI	0.98	0.93	0.47	0.9	0.82	0.87	0.95	0.94	0.75	0.6	
SUM	97.59	99.51	101.21	99.22	98.7	99.63	97.86	97.8	100.24	101	
Mg#	29	32	24	33	32	32	31	32	40	27	
Sc	7.863	8.249	6.967	6.7	7.2	6.6	6.2	6.5	6	3.4	
Zr	535.277	540.841	570.406	493	450	459	496	443	227	151	
V	47.699	49.041	6.056	52	43	44	48	44	38	23	
Cr	229.189	267.842	473.941	107	120	109	102	118	138	127	
Co	6.492	9.399	5.672	10.1	10.1	8.5	10.7	7.6	9	2.7	
Ni	3.691	3.481	4.69	20	22	19	21	20	19	8	
Rb	197.932	181.391	117.97	206	231	220	202	229	166	181	
Sr	206.771	218.717	75.087	203	177	175	197	180	648	493	

Y	33.918	31.814	49.502	35	38	37	36	37	27	23
Nb	26.522	24	13.105	33	30	31	33	31	24	11
Ba	935.375	926.517	751.257	1001	849	916	1027	852	736	718
La	149.213	82.624	151.379	174	149	173	175	161	74.8	31.7
Ce	279.048	157.816	297.4	336	286	331	341	313	133	51.3
Pr	28.811	16.747	33.2	33.6	28.7	32.4	33.4	31	12.5	5.3
Nd	102.979	63.137	134.159	121	106	115	118	112	43.2	18
Sm	15.603	13.086	25.142	17.3	15.6	16.4	17.7	15.7	5.96	2.66
Eu	1.863	1.316	2.378	1.75	1.5	1.51	1.69	1.48	0.94	0.59
Gd	15.635	13.011	22.948	13.6	12.16	12.68	13.9	12.3	5.08	2.17
Tb	BDL	BDL	BDL	1.9	1.73	1.74	1.93	1.74	0.75	0.32
Dy	8.851	12.243	14.005	9.24	8.66	8.51	9.35	8.43	4.09	1.65
Ho	BDL	BDL	BDL	1.86	1.76	1.71	1.87	1.72	0.92	0.34
Er	3.657	5.35	5.259	4.8	4.5	4.46	4.89	4.43	2.57	1.02
Tm	BDL	BDL	BDL	0.67	0.64	0.61	0.67	0.62	0.43	0.17
Yb	3.413	6.059	4.838	4.34	4.04	3.95	4.31	3.98	2.99	1.23
Lu	0.542	1.016	0.829	0.56	0.52	0.51	0.55	0.51	0.41	0.18
Pb	31.278	27.995	37.409	31	32	34	33	31	43	49
Th	38.002	33.475	37.26	44	46	51	54	46	39	36
A/CNK	1.012	1.083	1.172	0.980	0.984	1.009	0.965	0.983	0.955	1.029
Na ₂ O/K ₂ O	0.614	0.786	0.638	0.617	0.579	0.586	0.596	0.581	0.674	0.563
Sr/Y	6.096	6.875	1.517	5.800	4.658	4.730	5.472	4.865	24.000	21.435
Dy/Yb	2.593	2.021	2.895	2.129	2.144	2.154	2.169	2.118	1.368	1.341
(La/Yb) _{CN}	29.699	9.264	21.256	27.236	25.054	29.753	27.583	27.480	16.994	17.508
(Gd/Yb) _{CN}	3.706	1.737	3.838	2.535	2.435	2.597	2.609	2.500	1.375	1.427
Eu/Eu*	2.780	3.290	3.376	2.980	3.125	3.254	3.156	3.193	1.970	1.378
Yb _{CN}	21.199	37.634	30.050	26.957	25.093	24.534	26.770	24.720	18.571	7.640
Zr/Sm	34.306	41.330	22.687	28.497	28.846	27.988	28.023	28.217	38.087	56.767

Figure 8. Classification of TTGs and K-rich granites from the Bundelkhand craton on feldspar normative An–Ab–Or diagram of O'Connor (1965) with fields from Barker (1979).

Figure 9. Classification of TTGs and K-rich granites from the Bundelkhand craton based on CaO–K₂O–Na₂O diagram of Moyen *et al.* (2003a, b).

TTG in the amphibolites field further supports the earlier inference that they result from partial melting of the basaltic crust. This interpretation is consistent with experimental studies which showed that melting of metabasalts and amphibolites at various P_{H_2O} conditions and depths where garnet and amphibole are stable phases would produce the TTG-like melts (e.g., Rapp *et al.* 1991; Wolf and Wyllie 1994).

Presence of negative Eu anomaly implies plagioclase removal by fractional crystallization or as a residual phase during partial melting. The observed HREE depletion for these samples indicates the potential residual phases of garnet and/or

amphiboles during partial melting or garnet and/or amphibole fractionation during its ascent through mantle. Macpherson *et al.* (2006) have suggested that partial melting with garnet in the residue will effectively increase the Sr/Y, La/Yb, Gd/Yb and Dy/Yb ratios, while if amphibole is the residual phase the melts will have a low Nb/Ta, Gd/Yb and Dy/Yb ratios. In the case of the Bundelkhand TTG rocks, they show moderate $(La/Yb)_{CN}$ values (15–30), Sr/Y ratios (4.9 to 98.7) and low $(Gd/Yb)_{CN}$ ratios (2.2–4.6) and no correlation could be established between Sr/Y ratios and $(La/Yb)_N$ values. This implies that the parental magma of these samples was probably derived from partial melting of a source with both amphibole and garnet in the residue. Based on our inferences it is suggested that Bundelkhand TTG was probably derived by partial melting of hydrous basaltic crust in the late Archaean collisional zone at pressures and depths where garnet and amphibole were stable phases.

6.1.2 K-rich granites

The potassic granite samples of this study have high SiO₂, K₂O and low Na₂O, MgO, CaO contents. They also have LREE-enriched and HREE-depleted patterns (relatively flat) to those of the TTG samples. These REE patterns and high $(La/Yb)_{CN}$ values (25.4–202), Sr/Y ratios (12.8–119) and low $(Gd/Yb)_{CN}$ (2.70–11.1) ratios and the lack of Sr/Y ratios correlation with $(La/Yb)_{CN}$ values indicate the parental magma of these samples perhaps were derived from partial melting of a source with garnet and amphibole in the residue. Negative Eu anomalies observed in these samples possibly suggest plagioclase existing in the residue and/or plagioclase fractionation during magma ascent. The absence of evidence of any preexisting high Sr/Y and La/Yb sources in the Bundelkhand area suggests that these K-rich granites also probably generated from partial melting of hydrous mafic rocks with garnet and amphibole in the residue (e.g., Smithies 2000; Martin and Moyen 2005; Condie 2005). The K-rich granites are generally considered to have generated by partial melting of subducted slab with assimilation/interaction of mantle wedge peridotite or the product of reworking and partial melting of lower crustal materials (Moyen *et al.* 2003a, b; Jayananda *et al.* 2006; Moyen 2011), which is supported by experimental studies (Skjerlie and Johnston 1993; Wang *et al.* 2005; Watkins *et al.* 2007). Most of the potassic granite samples in this study show high

Figure 10. (a) Calc-alkaline natures of TTGs and K-rich granites from Bundelkhand craton can be clearly observed in the A–F–M plot (trends from [Irvine and Baragar 1971](#)). (b) A/NK vs. A/CNK diagram showing the peraluminous nature of the TTGs and K-rich granites from the Bundelkhand craton (after [Maniar and Piccoli 1989](#)).

Figure 11. (a) Chondrite normalized rare earth element plots and (b) primitive mantle normalized multi-element patterns for the representative TTG samples from the Bundelkhand craton. Normalizing values of primitive mantle are after [Sun and McDonough \(1989\)](#) and those of Chondrite are after [McDonough and Sun \(1995\)](#).

SiO₂, K₂O and low MgO, ruling out of the basaltic oceanic crustal source ([Smithies 2000](#)). Therefore, it is suggested that most of the K-rich granites in this area were derived from partial melting of lower crustal sources.

The Bundelkhand K-rich granites differ from their TTG counterparts in having elevated concentrations of incompatible elements like K, Zr, Th and REE. They, however, share some geochemical features including the negative Eu anomalies in chondrite-normalized diagrams, the Nb–Ti anomalies in multi-element spidergrams, plotting mostly

in the volcanic arc granite field with a few straddling the volcanic arc granite field to post-collisional granite field (figure 15). The higher concentrations of the incompatible elements are consistent with their derivation from evolved crustal sources. This is particularly true as the mafic rocks have insufficient K₂O to yield potassic SiO₂-rich granitic magmas as those of the Bundelkhand. When plotted on the experimental melts involving major element oxide ratios (figure 14a, b), the Bundelkhand K-granites plot in the amphibolites field. The most plausible explanation for the

shared geochemical characteristics between the Bundelkhand TTG and K-granites (except for the high concentration of incompatible elements in the later) is that the K-granites were derived by partial melting of the TTG (and greenstones). Thus, the subduction zone signature shown by the K-granites (i.e., the Nb, Ti anomalies and plotting in the volcanic arc granite field) could be attributed

Figure 12. K_2O vs. SiO_2 plot (after [Peccherillo and Taylor 1976](#)) indicates shoshonitic to high K calc-alkaline nature of the potassic granites of the Bundelkhand craton.

to characteristics of the source rocks. Several experimental studies have shown that partial melting of anhydrous metatonalites within the middle or lower crust could produce granitic melts ([Rutter and Wyllie 1988](#); [Skjerlie and Johnston 1993](#); [Patiño-Douce 2005](#); [Watkins et al. 2007](#)). Additionally, [Watkins et al. \(2007\)](#) emphasized that melting of TTGs with high K_2O/Na_2O (>0.3) could generate K-rich granites.

The temperatures of the K-rich granites calculated using this Zr saturation thermometer ([Watson and Harrison 1983](#); [Miller et al. 2003](#)) yield an average temperature of the granitic melts of the rock samples as $865^\circ C$, which is inferred to be the crystallization temperature of magma (table 4).

6.2 Episodic crustal growth in Bundelkhand craton

The major lithological units reported so far from the Bundelkhand craton are as follows:

- The metamorphosed supracrustal rocks (basaltic to basaltic andesitic pillow, massive lava, serpentinitised ultramafic rock, volcanoclastic sediment, tuff) in association with BIF, schist, amphibolites, calc-silicate and interbedded quartzite ([Malviya et al. 2004, 2006](#)). [Malviya et al. \(2006\)](#) have reported that in Spar river section TTG gneisses are seen-cross cutting these

Figure 13. The Bundelkhand craton TTGs and K-rich granites plotted on the (a) $Al_2O_3/(FeO + MgO + TiO_2)$ vs. $Al_2O_3 + FeO + MgO + TiO_2$ and (b) $(Na_2O + K_2O)/(FeO + MgO + TiO_2)$ vs. $(Na_2O + K_2O + FeO + MgO + TiO_2)$ diagrams. Outlined fields show compositions of partial melts obtained in experimental studies by dehydration melting of felsic pelites, metagreywackes, amphibolites–metabasalts and metatonalite sources ([Wolf and Wyllie 1994](#); [Patiño-Douce 1996, 1999](#); [Thompson 1996](#), and references therein).

Figure 14. (a) Primitive mantle normalized multi-element patterns and (b) chondrite normalized rare earth element plots for the representative K-rich granite samples of the Bundelkhand craton. Normalizing values of primitive mantle are after [Sun and McDonough \(1989\)](#) and those of chondrite are after [McDonough and Sun \(1995\)](#).

Figure 15. Nb vs. Y tectonic discrimination diagram for the K-rich granites of the Bundelkhand craton (after [Pearce et al. 1984](#)). Field labels: Volcanic Arc Granite (VAG), Within Plate Granite (WPG), Ocean Ridge Granite (ORG), and Syn-Collisional Granite (Syn-COLG).

rocks, hence based on the observed structural relation suggested that these may be the oldest unit.

- TTG suite ranging in age from 3.59 to 2.6 Ga, wherein most reported ages are in the range of 3.5–3.0 Ga ([Sarkar et al. 1984](#); [Mondal et al. 2002](#); [Kaur et al. 2014, 2016](#); [Saha et al. 2016](#); [Joshi et al. 2016](#)) with a recent report of TTG

age by [Verma et al. \(2016\)](#) of 2.6 Ga. It is worth mentioning that both work of [Saha et al. \(2016\)](#) and [Verma et al. \(2016\)](#) are bereft of any bulk rock geochemical data for TTG classification. [Sharma \(1998\)](#) suggested that the granitic gneiss with TTG affinity (3.3 Ga) intrudes the mafic and ultramafic and metasedimentary supracrustal rocks, hence predates the TTG gneisses of the Bundelkhand craton.

- A metamorphic episode from white mica schist is reported by [Saha et al. \(2011\)](#) of 2.7–2.4 Ga.
- The granites/granitoids/granitic gneisses/granodioritic gneisses ranging in age from 2.7 to 1.9 Ga ([Mondal et al. 2002](#); [Mohan et al. 2012](#); [Kaur et al. 2016](#); [Joshi et al. 2016](#) and references therein).
- The quartz reefs/giant veins of 2.0–1.8 Ga ([Pati et al. 1997](#); [Bhattacharya and Singh 2013](#)).
- The dyke swarms (mafic to ultramafic) –2.0 to 0.9 Ga ([Sarkar et al. 1997](#); [Sharma and Rahman 2000](#); [Rao et al. 2005](#); [Pradhan et al. 2012](#); [Radhakrishna et al. 2013](#)).
- Gwalior basin [2.1–2.0 Ga: [Rao et al. 2005](#); 1.83 Ga: [Ramakrishnan and Vaidyanadhan 2010](#); 1.85 Ga: [Deb et al. \(2002\)](#); 2.0–1.79 Ga: [Absar et al. \(2009\)](#); 1.83 Ga: [Crawford \(1970\)](#)] and the Bijawar basin [1.79 Ga and 1.69 Ga: [Haldar and Ghosh \(2000\)](#)] are of Paleoproterozoic age.

More accurate geochronological data obtained as mentioned above in the last decade from the

Table 4. Cation fractions of 10 major oxides, Zr concentration, calculated values of *M* and *T* in degree celsius using the Zr thermometry of [Watson and Harrison \(1983\)](#) and [Miller et al. \(2003\)](#) for K-rich granites of the Bundelkhand craton.

Sample no.	HC 12	HC 27	HC 30	BK 1	BK 2	BK 3	BK 4	BK 5	BK 6	BK 8
SiO ₂	64.720	66.570	76.730	66.500	67.530	68.190	66.700	66.900	70.630	74.040
Al ₂ O ₃	14.710	15.650	12.430	14.990	14.580	14.880	14.170	14.290	14.490	14.440
Fe ₂ O ₃	4.860	4.260	2.960	4.610	4.030	4.030	4.440	4.190	2.920	1.710
MnO	0.060	0.080	0.030	0.060	0.050	0.050	0.060	0.060	0.060	0.020
MgO	0.990	0.990	0.460	1.160	0.970	0.950	1.030	1.010	0.990	0.320
CaO	2.260	2.450	0.780	2.430	2.080	1.990	2.270	2.010	2.460	1.730
Na ₂ O	3.060	3.310	2.750	3.200	3.140	3.190	3.050	3.100	3.290	3.050
K ₂ O	4.980	4.210	4.310	5.190	5.420	5.440	5.120	5.340	4.880	5.420
TiO ₂	0.640	0.770	0.260	0.720	0.600	0.620	0.690	0.610	0.360	0.200
P ₂ O ₅	0.330	0.290	0.030	0.360	0.300	0.290	0.330	0.290	0.160	0.070
Zr (ppm)	535.277	540.841	570.406	493.000	450.000	459.000	496.000	443.000	227.000	151.000
<i>M</i>	1.568	1.457	1.181	1.623	1.583	1.544	1.616	1.583	1.587	1.414
Temp. (°C)	887.299	898.322	929.742	874.048	868.222	873.535	875.196	866.576	802.739	779.872

granitoids of Bundelkhand craton of central Indian shield, reveals obvious episodic magmatic activities from the region at 3.59–3.0 Ga, 2.6–2.1 Ga and 2.0–0.9 Ga.

The first episode of magmatic activity (3.5–3.0 Ga) is recorded in the TTG gneisses and granodioritic gneisses of the Bundelkhand Craton ([Sharma and Rahman 1995](#); [Sarkar et al. 1996](#); [Mondal et al. 2002](#); [Saha et al. 2011, 2016](#); [Kumar et al. 2011](#); [Kaur et al. 2014, 2016](#)). This can be further classified into two groups. The first subgroup represented by the granitoids formed at 3.59–3.39 Ga ([Kaur et al. 2014, 2016](#); [Joshi et al. 2016](#); [Saha et al. 2016](#)), which are predominantly composed of TTG gneisses and were interpreted as production of partial melting of deep seated mafic crust with abundant garnet and rutile but no plagioclase ([Kaur et al. 2016](#); [Saha et al. 2016](#)). The second subgroup (3.2–3.00 Ga) is represented by minor TTG gneisses and granodiorite gneisses ([Mondal et al. 1998](#); [Kaur et al. 2014, 2016](#)) which exhibit high SiO₂ and low MgO (Mg#) and were explained as the results of partial melting a more shallow, garnet-free, but plagioclase-rich mafic source ([Mondal et al. 2002](#); [Kaur et al. 2016](#)), probably triggered by underplating of basaltic magmas extracted from mantle wedge. However, it has been shown by theoretical modeling and experimental studies that chemical variability/petrological diversity in TTG composition is not necessarily a factor of mineralogy and composition of source rock, the

depth of melting, and the melting reactions but are equally governed by physical processes through which the melt migrates and segregates from its partially molten host ([Jackson et al. 2005](#); [Rushmer and Jackson 2008](#)).

The second episodic magmatic event (~2.6–2.1 Ga) is represented by the TTG, felsic volcanic associated with greenstone belt and K-rich granites from the area ([Mondal et al. 1998, 2002](#); [Kaur et al. 2014, 2016](#); [Singh and Slabunov 2015, 2016](#); [Verma et al. 2016](#); [Joshi et al. 2016](#)). This marks another major crustal growth episode in the Bundelkhand region. These TTG gneisses and K-rich granites are also conjectured as partial melting of lower thickened crust. [Verma et al. \(2016\)](#) suggested that these rocks generated similarly through partial melting of thickened lower crust in a subduction setting.

The third magmatic episode (2.0–0.9 Ga) in the Bundelkhand craton is marked by the giant quartz veins and mafic to ultramafic dykes ([Sarkar et al. 1997](#); [Sharma and Rahman 2000](#); [Rao et al. 2005](#); [Pradhan et al. 2012](#); [Radhakrishna et al. 2013](#)). The quartz veins/quartz reefs are believed to have generated by syntectonic hydrothermal activity ([Pati et al. 2007](#)) or by precipitation of quartz during a later wide scale extensional event ([Bhattacharya and Singh 2013](#)).

More extensive and intensive investigations are needed on the episode of magmatic activity in the Bundelkhand craton as the magmatism in the area is characterized by continuity rather than episodes.

6.3 Implication for geodynamic setting of Bundelkhand craton

The geodynamic setting of the Bundelkhand rocks spanning from Paleo-Mesoarchean through Neoproterozoic to Paleoproterozoic which has undergone extensive magmatism and metamorphism is a long-standing issue in Indian geology. It remains to be robustly constrained due to lack of comprehensive data involving mineral chemistry, isotope and bulk chemistry and geochronological inputs. Nonetheless based on available data, it is more or less agreed upon that this rock combination resulted in an active continental margin or island arc setting.

Sharma (1998) invoked an alternating extensional and compressional environment in the tectonomagmatic evolution of the Bundelkhand craton wherein the extensional regime resulted in the evolution of volcano sedimentary greenstone belts and opening of the basins and the compressional regime resulted in the partial melting of mantle wedge resulting in generation of TTG.

Malviya *et al.* (2006) based on their study on metamorphosed pillow lava and basaltic komatiite from Mauranipur area have commented that this volcano sedimentary greenstone belt has resulted from subduction-related compressional environment and the supracrustal units are remnants of suprasubduction crust of island arcs tectonically accreted to the continent during arc-continent collision. TTG was later generated by partial melting of mafic crust in convergent environment and collision-related K-rich felsic magma was emplaced as granitic plutons post-dating the TTGs. Giant quartz veins according to them mark the late stage hydrothermal activity associated with final felsic intrusion event. They emphasize that the extensional regime ensued only after the final stage of felsic intrusion by a deep-seated mantle plume forming the rift-related marginal basins of Gwalior and Bijawar. The mafic dyke swarms are the last stage of event which took place along weak fractures generated by rifting. In the given context, with the recent report of TTG magmatism of 2.6 Ga by Verma *et al.* (2016) suggesting contemporaneous TTG and felsic magmatism from the regions further studies is a need.

Mohan *et al.* (2012) confirm the generation of Bundelkhand granitoids (diorites, TTG and granites) undoubtedly is subduction derived, but has generated in multi-stage processes in a supra-subduction zone regime. According to them,

in the supra-subduction zone slab dehydration resulted generation of hydrous sub-arc mantle of basaltic source and the low pressure melting at moderate to shallow depths possibly in the lower part of thickened oceanic arc crust has resulted in the petrologically diverse suite of rock in the Bundelkhand craton. The association of the mafic ultramafic units and metasedimentary belts with the TTGs to them represents a subduction accretion-collision of microblocks. The Neoproterozoic and early Paleoproterozoic collision related metamorphism and intrusion of crustally derived granitic melts is the final event of cratonization according to their model.

Large-scale partial melting of crustal materials and widespread metamorphism has been witnessed by Bundelkhand craton is usually envisaged to have been provided by intrusions and underplating of large volume of mantle derived magma which acts as the heat source required for melting to ensue. Variety of environments like hotspots driven by mantle plumes, continental rift environments, subduction related tectonic settings, continental collisional belts can provide the environment required for emplacement of sufficient amount of mantle-derived magma.

Provided these TTGs were formed above hotspots as proposed by Smithies *et al.* (2009), (i.e., melting at base of a thick oceanic plateau crust heated by an upwelling mantle plume), these rocks would have been emplaced in a sequence of mantle plume related ultramafic to mafic rocks including komatiites, continental flood basalts, dyke swarms and layered intrusions (Ernst *et al.* 2008). No such plume-related magmatism has been reported from Bundelkhand craton nor is there a global record of plume activity in the Archean times (Ernst and Bleeker 2010). Therefore, invoking a plume model to account for generation of Paleo-Mesoarchean TTGs in the Bundelkhand region seems inappropriate.

A continental rift environment is not plausible for the Bundelkhand craton as there is lack of alkali intrusive (syenite, nepheline syenite, etc.) of Paleo-Mesoarchean age expected to be associated with rifting (Zhao *et al.* 2001).

Martin *et al.* (2014) and Moyen and Martin (2012) through their work displayed that elevated MgO content, Mg# values, and high Cr and Ni concentrations are the signatures to look for if the TTG were produced through partial melting of subducting or subducted oceanic crust or oceanic plateau materials. However the Paleo-Mesoarchean

(a)

(b)

(c)

TTG rocks in the Bundelkhand region have no obvious geochemical signatures indicating enhanced melt–peridotite interaction (present study; [Mohan et al. 2012](#); [Kaur et al. 2016](#)). Moreover, the Neoarchean TTG and K-rich granites from the region are rather the reworking products of Mesoarchean crustal materials (enriched mafic rocks plus previously emplaced felsic TTG), instead of juvenile addition to the crust as implied by the zircon Hf isotopic compositions ([Kaur et al. 2016](#)). This rules out that these TTGs were generated in subduction related settings (continental or island arcs, thickened arc systems and accretionary orogens), where juvenile mafic rocks act as source rocks ([Martin et al. 2014](#)).

In view of these findings, a continental collision setting is likely to have produced the Paleo-Mesoarchean TTG gneisses in the Bundelkhand craton. Continental collisional zones as primary sites for net continental crustal growth have been discussed by a number of workers ([Niu et al. 2007, 2013](#); [Mo et al. 2008](#); [Niu and O'Hara 2009](#)). It addresses the shortcomings of the standard island arc-model ([Taylor 1967, 1977](#)) and abandons the need of mantle plumes for episodic crustal growth ([Stein and Hofmann 1994](#); [Abbott and Mooney 1995](#); [Pearson et al. 2007](#)).

In our view, the Precambrian basement of the Bundelkhand craton is composed of two major kind of terrane: a high grade metamorphic terrane comprising of tonalite, trondhjemite, granodiorites,

supracrustal rocks (ultramafic to mafic igneous rocks and sedimentary rocks with BIF) and a granitic terrane with no metamorphism all spanning a duration from 3.5 to 2.6 Ga. All of these rocks experienced a granulite facies metamorphism at ~ 2.7 to 2.4 Ga. The contemporaneous plutonic magmatism (2.6–2.5 Ga) and the high grade metamorphism of (2.7–2.4 Ga) as reported by [Saha et al. \(2011\)](#) indicate an intensive tectonothermal event (probably an orogenic event) in the late Neoarchean through the Bundelkhand craton. The associated high K-calc-alkaline granites favour this possibility. Cratonization of the Bundelkhand craton started with collision of micro-continental blocks with ~ 3.6 Ga crustal nuclei.

The Paleo-Mesoarchean TTG granitoids in the Bundelkhand craton were generated through partial melting of Eoarchean enriched mafic crustal sources at different depths coupled with low pressure crystal fractionation, which requires significant crustal thickening through micro-continental collision ([Nutman et al. 2007](#)). The K-rich granites with their intrusive contact with the TTG gneisses and younger age, represent the last pulse of Archaean magmatism in the Bundelkhand craton. These K-rich granites have formed by remelting of Paleo-Mesoarchean TTGs or mafic crustal materials in an extensional/non-compressional environment associated with a post-orogenic or post-collisional stage. A conceptual cartoon illustrating the proposed geodynamic environment corresponding to evolution of TTGs and K-granites of the Bundelkhand craton is shown in figure 16.

The melting of the Paleo-Mesoarchean mafic crust may have been triggered by melts rising from the upwelling mantle, which also modified the compositions of these melts by different degrees resulting in hornblende bearing granites, biotite bearing granites and leucogranites as reported by [Mondal and Zainuddin \(1996\)](#) from the Bundelkhand craton. [Arndt \(2013\)](#) has suggested that the variations in the composition and mineralogy of the source (including the proportion of juvenile magma and reworked crustal rocks), the composition of incoming magmas, the degree of partial melting, and the extent of fractionation crystallisation in crustal magma chambers can all contribute to the diversity of composition of the granitoids. The reported variation of initial Zircon Hf isotopic compositions as discussed by [Saha et al. \(2016\)](#) and [Kaur et al. \(2016\)](#) from TTG and granitoids from Bundelkhand craton is consistent with an increase in reworking processes associated with crustal

Figure 16. A schematic diagram illustrating the proposed geodynamic setting for the evolution of TTG and associated K-granites in the Bundelkhand craton. Stage (a): During this stage, subduction takes place with possible episodic break-off of the slab resulting in a generation (i) juvenile mafic crust over a long period of time and (ii) metasomatism of the overlying mantle due to volatiles released by subducting slab. Stage (b): The first stage ultimately leads to closure of an ocean basin and welding of two proto-continental blocks (continental collision). At this stage, TTG crust formation takes place from the magma generated by partial melting of mafic lower crust triggered by the thickening of crust due to amalgamation. Stage (c): In the late- to post-collisional stage owing to thermal relaxation and extension, melting of the previously generated TTG crust ensues resulting in generation of the K-granites. During both syn collisional and late collisional stages, significant interaction between the mafic melts, TTG crust and metasomatised mantle melt also generates compositionally hybrid granitoid melt. These granitoids are characterized by coeval involvement of metasomatized mantle sources, and intracrustal melting as discussed in [Laurent et al. \(2014\)](#) for modern collisional granitoids.

thickening during collision and melting of the mantle sources. The dyke swarms and the quartz reefs and the marginal basins of Gwalior and Bijawar of this region can be associated with the extensional event which resulted in voluminous potassic granite plutons. However based on the available data from the region, it is hard to precisely constrain the details and configuration of the continental collision model for generation of TTG and associated rocks from the Bundelkhand craton.

We also need to take care of the fact that the Precambrian tectonic styles for continental collision belts are quite different from modern day continental belts as they were formed over a hotter mantle which rendered them to be mechanically weak (Sizova *et al.* 2014, 2015). This ensued frequent slab break off resulting in upwelling and subsequent melting of mantle. Likewise, John-son *et al.* (2017) have advocated a multi-stage process for production and stabilization of the first continents coupled with high geothermal gradient which is incompatible with modern style plate tectonics. They favour formation of TTG near base of thick basaltic crust, hence subduction was not required to produce TTGs in the early Archaean Eon and emphasizes that arc-like signature was inherited from an ancestral source lineage.

7. Conclusion

The geochemical studies of the TTG and K-rich granites of the Bundelkhand craton reveal the following:

- The TTG are composed of recrystallized seriated quartz, large plagioclase crystals that are highly sericitized, biotite, hornblende and minor K-feldspar. The K-rich granites are composed of minerals that have a preferred orientation due to being sheared and are predominated by K-feldspar, biotites, recrystallized quartz and unaltered plagioclase.
- The TTGs and K-rich granites of Bundelkhand craton have a plagioclase composition that varies from $X_{Ab} = 0.70$ – 0.80 and $X_{Ab} = 0.73$ – 0.80 , respectively. The K-feldspars of both the rock types possess near end member composition of $Or_{0.96-0.99}$. Amphiboles of the TTGs are calcic ($Ca = 1.88$ – 1.93 atoms per formula unit) and are hastingsite. The Al in Hornblende barometer produced an average crystallization pressure of 5.94 kbar and calculated temperatures using the

Hornblende–Plagioclase geothermometer ranges from 757 to 777°C. Biotites of both the TTGs and K-rich granites are representative of solid solution of annite–siderophyllite end members.

- The TTG rocks of Bundelkhand craton exhibit geochemical characteristics of other worldwide known TTG including Al_2O_3 contents of 13.49–17.04 wt%; Na_2O/K_2O ratios of 1.28–3.89, low concentration of heavy REE with Y contents of 5–42 ppm and $Yb = 0.3$ – 0.5 ppm leading to high Sr/Y ratios (4.9–98) and $La/Yb = 15$ – 30 , fractionated REE patterns ($La/Yb_{CN} = 15$ – 30), negative anomaly of Nb. These geochemical characteristics have thus been interpreted as having formed by partial melting of the hydrous basaltic crust at pressures and depths where garnet and amphibole were stable phases in the late Archaean continental collisional setting.
- K-rich granites of the Bundelkhand craton differ from their TTG counterparts in having elevated concentrations of incompatible elements like Zr, Th and REE. They however share some similar geochemical compositions including fractionated REE patterns ($La/Yb_{CN} = 10$ – 27), negative anomaly of Nb and have thus been interpreted to have formed by partial melting of the TTG (and greenstones)/mafic crust.
- Two-stage continental accretion (at 3.59–3.33 and 3.2–3.0 Ga) and reworking (at 2.5–1.9 Ga) occurred in the Bundelkhand craton from Archaean to Paleoproterozoic. Our study leads us to propose the development of a continental collisional tectonic regime in the Archaean–Paleoproterozoic for the development of the Bundelkhand craton.

Acknowledgements

Ashima Saikia acknowledges R&D grant for promotion of research, University of Delhi and CSIR Grant vide Project No. 24(0317)/12/EMR-II for carrying out this work.

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