High grade metamorphism in the Bundelkhand massif and its implications on Mesoarchean crustal evolution in central India

S P SINGH^{1,*} and S B DWIVEDI²

¹*Department of Geology, Bundelkhand University, Jhansi 284 128, India.*

²*Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi 221 005, India.*

**Corresponding author. e-mail: spsinghbu@rediffmail.com*

The Bundelkhand Gneissic Complex (BnGC) in the central part of the Bundelkhand massif preserves a supracrustal unit which includes pelitic (garnet–cordierite–sillimanite gneiss, garnet–sillimanite gneiss, biotite gneiss and garnet–biotite gneiss) and mafic (hornblende–biotite gneiss and garnetiferous amphibolite) rocks. Granulite facies metamorphism of the complex initiated with breaking down of biotite to produce garnet and cordierite in the pelitic gneisses. Geothermobarometric calculations indicate metamorphic conditions of 720°C/6.2 kbar, followed by a retrograde (687°C/4.9 kbar) to very late retrograde stages of metamorphism (579°C/4.4 kbar) which is supported by the formation of late cordierite around garnet. The P–T conditions and textural relations of the garnet–cordierite-bearing gneiss suggest a retrograde cooling path of metamorphism.

1. Introduction

The Bundelkhand massif is an important cratonic block in the central Indian shield which is separated from the Chhotanagpur Granite Gneiss Complex and Bastar Craton in the south by the east–west trending Son–Narmada lineament, from the Aravalli Fold Belt in the west, by the NE–SW trending Great Boundary Fault (GBF), and from the Gangetic Plains in the north by the WNW–ESE trending Yamuna fault (Singh *et al.* 2007; Basu 2010). Garnet–sillimanite–cordierite-bearing granulite facies supracrustal rocks have been reported from the central part of Bundelkhand massif (Singh and Dwivedi 2009). These rocks are associated with tonalitic–trondhjemite–granodiorite (TTG) gneisses exposed around Mauranipur

(figure 1) and are grouped in the Bundelkhand Gneissic Complex (BnGC) (Singh *et al.* 2007; Mohan *et al.* 2012). Available radiometric age suggests that the TTG rocks were formed during Mesoarchean (Mondal *et al.* 2002) and were subsequently emplaced into high grade metamorphic rocks (Mohan *et al.* 2012). Apart from this, high pressure metamorphism reported by Saha *et al.* (2011) of Mg–Al-rich white schist has opened up new possibilities to constrain the variations in the metamorphic conditions in the Archaean Bundelkhand Craton. In this study, we present the mineralogy, microtextural relations and pressure (P)–temperature (T) evolution of granulite facies supracrustal rocks around Mauranipur area and discuss their significance in Archean crustal evolution of the Bundelkhand Craton.

Keywords. Metamorphism; granulite; Bundelkhand massif; supracrustal rocks; crustal evolution.

2. Geological setting

The Bundelkhand massif covers an area of about 26,000 km² in central India with a semicircular outline (Basu 1986). It is occupied by a vast expanse of hornblende-, biotite- and leuco-granitoids (the Bundelkhand Granite), within which TTG gneisses and high grade supracrustals of pelitic, psammitic, mafic and ultramafic lithologies (BnGC), and low grade supracrustals of banded-magnetite-quartzite and metavolcanic association (BMM) occur as slivers and narrow belts (Sharma 2000; Mondal 2010; Mohan *et al.* 2012) (figure 1). In the central part of the massif, slivers of BnGC and BMM occur together and more or less parallel to each other with general E–W trend (Singh 2012a). The BnGC rocks are strongly deformed with folding of at least five generations (Bhattacharya 1986; Prasad *et al.* 1999). In contrast, the BMM

rocks are relatively less deformed and show three phases of folding. The entire Bundelkhand massif is traversed by numerous NE–SW trending quartz veins and quartz reefs along the NE–SW trending crustal scale shear system (Bhattacharya and Singh 2013) and NW–SE trending mafic dyke swarms (Rao *et al.* 2005; Pradhan *et al.* 2012).

The available geochronological data on TTG of the Bundelkhand Craton include:

- whole rock Sm–Nd isochron age of 3298 ± 11 Ma from Mahoba area (Sharma and Rahman 1995);
- whole rock Rb–Sr isochron age of 3503 ± 99 Ma from Babina area (Sarkar *et al.* 1996);
- ion microprobe Pb–Pb zircon age of 3189 ± 5 Ma from Lalitpur area (Mondal *et al.* 1998);
- ion microprobe Pb–Pb zircon ages of 3297 ± 8 Ma and 3270 ± 3 Ma for gneisses near Mauranipur and Mahoba, respectively, and 3249 ± 5 Ma for

Figure 1. A generalized geological and tectonic map of the Bundelkhand Craton (after Basu 1986; Singh *et al.* 2007; Mohan *et al.* 2012).

amphibolites near Mahoba (Mondal *et al.* 2002); and

- SHRIMP U–Pb zircon age of 3291 ± 5 Ma (Kumar *et al.* 2011). These data indicate that the occurrence of TTG is an important event in the Bundelkhand massif during 3.1–3.3 Ga.

Broadly coeval TTG rocks have been reported from other cratons of the Indian shield including the Rajasthan Craton (Wiedenbeck and Goswami 1994), the Dharwar Craton (e.g., Peucat *et al.* 1993), and the Singhbhum Craton (e.g., Acharyya *et al.* 2010). Recently few occurrences of metamorphosed pelitic rocks from Bundelkhand Craton associated with TTG have been described (Singh and Dwivedi 2009; Saha *et al.* 2011). From the Mg–Al-rich white schist in the Babina area, a well constrained age ~ 2800 Ma (2789 ± 49 Ma, U–Th–Pb monazite and LA-ICPMS U–Pb zircon date, Saha *et al.* 2011) is the only available metamorphic age that comes from the high pressure metamorphic rocks. Not much information is available for the event of high-grade metamorphism of supracrustal rocks; however, based on the intrusive field relationships of TTGs, the granulite facies metamorphism is attributed to Mesoproterozoic event (Singh 2012a). Subsequent to high grade metamorphism, an E–W trending greenstone belt consisting mafic volcanism, banded-magnetite formation, and felsic volcanism (also known as BMM, Singh *et al.* 2007) was developed in the central part during Neoproterozoic (Mondal 2010; Pandey *et al.* 2011; Singh 2012b). The post-greenstone evolutionary stage of Bundelkhand Craton is marked by the large scale granitic activities and cratonization which is interpreted to be ~ 2.5 Ga based on the U–Pb and Pb–Pb ages of the granitoids (Mondal *et al.* 1998, 2002; Kumar *et al.* 2011).

2.1 Lithology and structure of Mauranipur area

The BnGC rocks at the central part of the Bundelkhand Craton appear as an E–W trending septum at the junction of two large granitic batholiths, i.e., coarse-grained grey granite (CGG), and medium-grained grey granite (MGG) in the north and coarse-grained pink granite (CPG), medium-grained pink granite (MPG), and fine-grained pink granite (FPG) in the south. The Bundelkhand Gneissic Complex has its western margin at Babina to the south of Jhansi town and is continuously traceable eastwards through Pura, Gora, Balyara, Simra, Pirhipur to Mauranipur for about 77 km in length in the central part of craton (figure 1).

The Mauranipur area is located in the central part of Bundelkhand massif, where the BnGC rocks are exposed for the most part, while BMM

rocks occur locally (figure 2). The terrain is characterized by a more or less subdued topography except for the ESE–WNW trending small isolated hillocks of banded magnetite quartzite and a NE–SW trending quartz reef near Kuraicha village. Garnet–sillimanite gneiss, garnet–cordierite–sillimanite gneiss, garnet–biotite gneiss, biotite–sillimanite gneiss, calc–silicate gneiss, hornblende–biotite gneiss, amphibolite, garnetiferous amphibolite, garnet–hornblende–biotite gneiss, quartzite, granitic gneiss and migmatite are the major BnGC rock types in the study area. Amphibolite and hornblende–biotite gneiss usually occur in the form of bands or lenticular patches within pelitic gneiss and are cofolded with them (figure 3a, c). Pelitic gneisses often show well developed banding represented by leucosomes and melanosomes of variable thicknesses (figure 3b, d). Small lenses of garnet–hornblende–biotite gneiss and garnetiferous amphibolite are also observed in the pelitic gneiss, where coarse to very coarse grained reddish brown garnet is embedded in the dark coloured matrix of amphibole minerals. In the Saprar river section, the TTG rocks exhibit intrusive relationship with amphibolite and pelitic gneiss. The presence of 2–3 m thick lensoidal bodies of pelitic gneiss within the TTG (Mohan *et al.* 2012) is a good agreement to support the statement that high grade metamorphism is an older event than TTG emplacement.

In general, foliations in the gneisses strike NW–SE to WNW–ESE and dip steeply ($>70^\circ$) towards NE–NNE. Four phases of deformation D_1 – D_4 are identified in the area. The first three phases are recorded as mesoscopic folds of F_1 , F_2 and F_3 generations, respectively, whereas the D_4 deformation has resulted in the development of shear structures in the rocks. Tight to isoclinal folds (F_1) with NW–SE to E–W striking axial planes and plunging towards NW are observed in the hornblende–biotite gneiss. The folds of F_2 generation are tight to closed in nature with NNW–SSE axial trend (figure 3b, c, d), and are locally coaxial with F_1 folds. F_3 folds are usually broad warps. The D_4 deformation is recorded by S–C fabric (figure 3f), sheath folds, and small scale vertical shear zones. This deformation is considered to be synchronous with the regional scale E–W trending vertical shearing in the central part of Bundelkhand massif (Basu 2010; Singh and Bhattacharya 2010).

3. Petrography

Mineral assemblages in the pelitic and mafic rocks of the BnGC are given in table 1. The minerals present in different pelitic assemblages include cordierite, garnet, biotite, sillimanite, K-feldspar,

Figure 2. Geological map of the area around Mauranipur, Bundelkhand Craton showing the distribution of various litho units.

plagioclase, and quartz, whereas those in the mafic rocks include garnet, clinopyroxene, hornblende, biotite, plagioclase, and quartz. Apatite and magnetite are present as accessory phases in both the lithologies. The broad petrographic characteristics of these rocks are outlined below. The mineral abbreviations used in this paper are – alm: almandine; bt: biotite; cpx: clinopyroxene; crd: cordierite; grs: grossularite; grt: garnet; hbl: hornblende; kfs: K-feldspar; liq: liquid; mt: magnetite; plag: plagioclase; prp: pyrope; sil: sillimanite; sps: spessartite, and qtz: quartz.

3.1 Pelitic rocks

Cordierite shows yellow pleochroic haloes and is highly pinitised (figure 4a, c, d). Biotite is commonly pleochroic in shades of reddish brown. In garnetiferous gneisses that lack in cordierite and sillimanite, biotite is pleochroic from pale yellow to greenish brown (figure 4b). Sillimanite commonly occurs as aggregates of small acicular grains.

Sometimes, fibrolitic sillimanite appears to grow from biotite (figure 4c). K-feldspar is commonly perthitic. Both K-feldspar and plagioclase show considerable sericitisation.

In some samples, garnet occurs as poikiloblasts with numerous inclusions of quartz (figure 4b). In others, garnet porphyroblasts locally contain inclusions of biotite, sillimanite, and quartz. The garnet–cordierite assemblage (figure 4a) is interpreted to have formed by the reaction:

This is a reaction which marks the entry of pelites into the granulite facies during prograde metamorphism. In some samples, garnet occurs as corroded relict within cordierite (figure 4d). This cordierite, which is texturally late, is likely to have formed by the reaction:

Figure 3. Field photographs showing: (a) interbanding of amphibolite and pelitic gneiss, both involved in deformation and metamorphism; (b) F_1 and F_2 folds in pelitic gneiss; (c) tight F_2 folds in amphibolite; (d) tight F_2 folds in pelitic gneiss; (e) closed F_2 antiform in amphibolite with intrusion of TTG at the core; (f) S-C fabric in pelitic gneiss related to D_4 deformation.

Textural relations suggest that the cordierite₁ is different from the cordierite₂ but the analytical data of the cordierite₁ have been interpreted in the present study.

3.2 Mafic rocks

Hornblende is the dominant mineral in the assemblages of mafic rocks (figure 4e, f, g, h). Its pleochroism varies from shades of bluish green (figure 4h) to shades of yellowish green (figure 4e, f). The mineral often contains inclusions of quartz

and biotite. Preferred orientation of hornblende defines the foliation in some samples (figure 4h); while in others the mineral shows decussate texture (figure 4g). Garnet in the amphibolites is coarse grained and mainly associated with hornblende and plagioclase. In some amphibolites, garnet occurs as poikiloblasts with numerous inclusions of hornblende, magnetite and quartz. Garnet in hornblende–biotite gneiss occurs as anhedral grains, which are highly fractured and locally replaced by late hornblende and biotite (figure 4e).

Table 1. Mineral assemblages of pelitic and mafic gneisses of BnGC from Mauranipur area.

Rock type Sample no./Minerals	Metapelites				Metabasites				
	M232	M34	M257	M239	M38	M35	M37	M 247	M148
Garnet	✓	✓			✓	✓	✓		
Biotite	✓	✓	✓	✓	✓	✓	✓	✓	
Sillimanite	✓	✓	✓	✓					
Cordierite	✓		✓						
K-feldspar	✓	✓	✓	✓	✓	✓		✓	
Plagioclase	✓	✓	✓	✓	✓	✓	✓	✓	✓
Quartz	✓	✓	✓	✓	✓	✓	✓	✓	
Hornblende					✓	✓	✓	✓	✓
Clinopyroxene									✓
Magnetite	✓	✓		✓	✓	✓	✓	✓	✓
Apatite	✓		✓			✓			
Ilmenite		✓	✓	✓	✓	✓	✓	✓	
Rutile	✓				✓	✓	✓	✓	✓
Zircon	✓	✓	✓						

4. Mineral chemistry

Mineral chemistry of coexisting phases has been determined by a JEOL-JXA-8600M electron probe micro analyzer at the Indian Institute of Technology, Roorkee. Operating conditions were: acceleration voltage 15 kV, probe current 20–50 nA, and beam diameter $\sim 2 \mu\text{m}$. Both natural and synthetic standards were used. Analyses of plagioclase, biotite, cordierite, hornblende, and garnet are given in table 2(a–e).

4.1 Feldspar

Chemical composition of plagioclase is quite uniform (table 2a). Anorthite contents range from An_{40} to An_{50} in the metapelites. In mafic gneisses, the anorthite content of plagioclase is very high (An_{83}) when compared with metapelites.

4.2 Biotite

Biotite has variable TiO_2 content ranging from 1.25 to 1.71 wt%. The $X_{\text{Mg}}(\text{Mg}/\text{Mg}+\text{Fe})$ of biotite ranges between 0.521 and 0.528 for garnet–cordierite–sillimanite gneisses, 0.334 and 0.351 for the biotite gneisses, and 0.345 and 0.375 for the hornblende–biotite gneisses (table 2b). All the biotites show a certain alkali deficiency that is highest in the garnet–cordierite gneisses ($\Sigma\text{Y}=1.226$ to 1.751), lowest for the garnet–hornblende–biotite gneisses ($\Sigma\text{Y}=1.674$ to 1.860) and garnet–biotite gneisses ($\Sigma\text{Y}=1.879$ to 1.948) (table 2b). The Al_2O_3 content ranges from 17.33 to 18.06 wt% for garnet–cordierite gneisses, 15.98–16.40 wt% for biotite–sillimanite–gneisses while it is 15.95–16.30 wt% for garnet–hornblende–biotite gneisses.

Similarly the Al^{VI} ranges from 0.669 to 0.904 p.f.u. for garnet–cordierite–sillimanite gneisses and from 0.491 to 0.566 for biotite–sillimanite gneisses.

4.3 Garnet

Garnet considerably differs in composition in different rock types. Garnet grains from metapelites are richer in almandine ($\text{Alm}_{60-75}\text{Sps}_{1-7}\text{Prp}_{5-25}\text{Grs}_{5-25}$), whereas the garnets from mafic gneisses are rich in grossularite in comparison of minimum content ($\text{Alm}_{63-69}\text{Sps}_{4-7}\text{Prp}_{5-7}\text{Grs}_{16-23}$). Garnets from these gneisses have moderate and relatively constant values of spessartine. The coarse-grained and early-formed garnet in cordierite–sillimanite gneiss is usually rich in MgO and MnO. The granular aggregate of garnets which are involved in the formation of cordierite has usually moderate content of pyrope. This indicates that the Mg-rich garnet was involved in the formation of cordierite. The garnet in biotite–gneisses have high mole% of spessartite and grossularite up to 25 mole% and low pyrope content. Garnets from these gneisses have wide range of chemical compositions depending upon the bulk chemistry of the rocks and also the composition of coexisting mineral parageneses and metamorphic condition.

4.4 Cordierite

Cordierite contains mainly SiO_2 , Al_2O_3 , FeO, and MgO. The larger cations are nearly absent. The Na_2O content is less than 1 wt%. X_{Mg} of cordierite ranges from 0.646 to 0.649. Total oxides never exceed 98% indicating the presence of fluid in the channels of the crystal structure.

Figure 4. Photomicrographs of BnGC rocks from the Mauranipur area. (a) garnet-cordierite-sillimanite-biotite-K-feldspar assemblage in pelitic gneiss; (b) garnet-biotite gneiss showing sieved texture of garnet porphyroblast due to numerous inclusions of quartz; the inclusions trail in garnet are inclined to the foliation in the matrix; (c) biotite being replaced by fibrolitic sillimanite in pelitic gneiss; (d) anhedral relicts of garnet in cordierite in pelitic gneiss; (e) highly fractured garnet in garnet-hornblende gneiss; late hornblende and biotite replace garnet along fractures; (f) hornblende-biotite gneiss showing biotite inclusions in hornblende; (g) decussate texture shown by hornblende grains in amphibolite; (h) hornblende-biotite gneiss showing preferred orientation of hornblende; all photomicrographs except (f) are under plane polarized light; (f) is under crossed nicols. The bar represents the magnification of photomicrograph.

Table 2. *Electron microprobe analytical data of coexisting phases from garnet-cordierite-sillimanite gneisses, garnet-sillimanite-biotite gneisses and garnet-hornblende-biotite gneisses of Mauranipur area.*(a) *EPMA data of plagioclase.*

Rock type	Metapelites						Metabasite
Sample no.	M232/c1	M232/c1/2	M34/c1	M34/c2	M34/c3	M34/c6	M38/C1/1
SiO ₂	55.82	55.78	57.53	57.74	56.80	57.76	42.69
Al ₂ O ₃	27.08	27.42	25.97	26.12	26.89	25.93	30.20
CaO	8.71	9.27	9.07	9.07	9.07	9.07	21.64
Na ₂ O	6.38	6.34	6.86	6.75	6.53	7.01	2.52
K ₂ O	0.06	0.06	0.07	0.04	0.05	0.07	0.43
FeO	0.05	0.11	0.07	0.14	0.12	0.06	0.92
Total	98.10	98.98	99.57	99.86	99.46	99.90	98.40
Cation on 8 Oxygen							
Si	2.550	2.532	2.594	2.595	2.551	2.602	3.096
Al	1.458	1.466	1.378	1.384	1.423	1.377	2.582
Fe	0.000	0.004	0.002	0.005	0.004	0.002	0.056
$\sum Z$	4.008	4.002	3.978	3.984	3.978	3.98	5.734
Ca	0.426	0.451	0.438	0.434	0.473	0.418	1.681
K	0.003	0.003	0.004	0.003	0.003	0.004	0.040
Na	0.565	0.448	0.599	0.588	0.568	0.613	0.355
$\sum X$	0.994	0.902	1.041	1.025	1.044	1.04	2.076
An	0.428	0.500	0.421	0.423	0.453	0.41	0.810

Table 2(b). *EPMA data of biotite.*

Rock type	Metapelites					Metabasites	
	M232	M232	M232	M34/C4	M34/C1	M38	M38
	C1/2	C1/4	C4/2	C4	C1	C1	C4
Sample	Core	Rim	Isolated	Rim	Core		
SiO ₂	37.72	39.20	38.94	34.48	35.85	34.09	35.18
Al ₂ O ₃	17.33	18.06	17.67	15.98	16.40	16.30	15.95
FeO	18.93	18.49	19.01	26.06	25.06	25.35	24.89
MgO	11.84	11.64	11.61	7.33	7.61	8.53	7.35
MnO	0.01	0.03	0.01	0.06	0.04	0.08	0.08
CaO	0.01	0.06	0.07		0.09	0.08	0.05
K ₂ O	8.60	6.26	7.54	9.55	9.16	8.05	9.01
Na ₂ O	0.39	0.18	0.23	0.02	0.17	0.14	0.07
TiO ₂	1.40	1.37	1.36	1.35	1.71	1.52	1.25
Cr ₂ O ₃	0.03	0.01			0.02	0.01	
Total	96.26	95.30	96.44	94.83	96.11	94.15	93.83
Cation on 22 Oxygen							
Si	5.623	5.770	5.730	5.492	5.565	5.411	5.602
Al ^{IV}	2.377	2.230	2.270	2.508	2.435	2.589	2.398
$\sum Z$	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.669	0.904	0.796	0.491	0.566	0.460	0.596
Ti	0.156	0.152	0.151	0.161	0.200	0.181	0.015
Cr	0.003	0.003	0.000	0.000	0.002	0.001	0.000
Fe	2.360	2.276	2.340	3.471	3.253	3.364	3.315
Mg	2.631	2.554	2.546	1.740	1.761	2.018	1.745
Mn	0.002	0.004	0.002	0.008	0.006	0.010	0.100
$\sum X$	5.821	5.893	5.835	5.871	5.788	6.034	5.767
K	1.636	1.175	1.415	1.941	1.813	1.629	1.831
Ca	0.001	0.001	0.011	0.000	0.015	0.013	0.009
Na	0.114	0.050	0.065	0.007	0.051	0.042	0.020
$\sum Y$	1.751	1.226	1.491	1.948	1.879	1.674	1.860
X _{Mg}	0.527	0.528	0.521	0.334	0.351	0.375	0.345

Table 2(c). EPMA data of cordierite.

Rock type Sample no.	Metapelites	
	M232/C1 Rim	M232/C4 Core
SiO ₂	50.05	48.91
Al ₂ O ₃	31.91	31.38
FeO	7.35	7.84
MgO	7.62	8.19
MnO	0.09	0.13
Na ₂ O	1.01	0.32
Total	98.03	96.77
Cation on 18 Oxygen		
Si	5.146	5.104
Al	3.867	3.860
$\sum Z$	9.013	8.964
Fe	0.632	0.689
Mg	1.168	1.274
Mn	0.007	0.012
$\sum X$	1.807	1.975
Na	0.200	0.064
X _{Mg}	0.649	0.646
aCrd	0.467	0.437
afCrd	0.133	0.143

4.5 Amphibole

The calcic amphibole is present in these rocks, in which Al₂O₃ ranges from 11.43 to 17.20 wt% (table 2d). The MnO is always less than 0.5 wt%. The X_{Mg} ranges from 0.245 to 0.290. The Al^{IV} and Al^{VI} content of hornblende ranges from 1.385 to 1.795 and 0.715 to 1.318 pfu, respectively. The Ti content of hornblende varies between 0.025 and 0.1 pfu and wt% of TiO₂ varies from 0.22 to 0.85.

5. P–T conditions of metamorphism and P–T path

The pressure and temperature conditions of metamorphism of the garnet–cordierite–sillimanite gneiss, garnet–sillimanite–biotite gneiss, garnet–biotite gneiss and garnet–hornblende–biotite gneiss have been estimated by Fe–Mg garnet–cordierite and garnet–biotite geothermometry and garnet–biotite–sillimanite–K–feldspar–quartz geobarometry. In addition, sets of independent reactions between mineral end-members were calculated by THERMOCALC v3.1 (Powell and Holland 1988) using the internally consistent dataset of Holland and Powell (1998), and the internally consistent geothermobarometry of Dwivedi *et al.* (1997). The temperature estimates for garnet–cordierite–sillimanite gneiss from the various conventional Grt–Bt geothermometers (table 3) range between 860° and 722°C for the core and between 680° and 610°C for rim compositions of garnet. The

Table 2(d). EPMA data of amphibole.

Rock type Sample no.	Metabasites		
	M35/c1/1	M35/c3/3	M35/c5/4
SiO ₂	42.44	41.60	40.59
Al ₂ O ₃	11.43	15.88	17.20
FeO	24.87	21.23	22.33
MgO	5.71	4.78	4.07
MnO	0.27	0.20	0.28
CaO	9.77	11.35	11.42
K ₂ O	0.28	0.26	0.15
Na ₂ O	1.00	1.11	1.23
TiO ₂	0.85	0.22	0.04
Cr ₂ O ₃		0.02	0.03
ZnO	0.04	0.05	0.06
Total	96.66	96.70	97.40
Cation on 23 Oxygen			
Si	6.615	6.348	6.215
Al ^{iv}	1.385	1.652	1.795
$\sum Z$	8.000	8.000	8.000
Al ^{vi}	0.715	1.205	1.318
Fe	3.242	2.756	2.859
Mg	1.327	1.087	0.928
Mn	0.035	0.026	0.036
Ti	0.100	0.025	0.048
Cr	0.000	0.002	0.004
Zn	0.005	0.005	0.006
$\sum X$	5.424	5.106	5.199
Ca	1.632	1.856	1.873
Na	0.301	0.328	0.365
K	0.056	0.051	0.029
$\sum Y$	1.989	2.235	2.267
$\sum X + \sum Y$	7.413	7.340	7.466
X _{Mg}	0.290	0.284	0.245

variation in the temperature estimates is mainly due to limitation of geothermometers and mixing models of garnet and biotite incorporated for formulation of geothermometers. The temperature obtained by these geothermometers for garnet–sillimanite–biotite–gneiss ranges from 727° to 632°C for core and 700° to 633°C for rim. The garnetiferous amphibolite temperature obtained from Grt–Bt geothermometry ranges between 735° to 660°C and is lower in comparison to the pelitic rocks. The garnet–hornblende–biotite gneiss temperature estimate is always lower than pelitic gneiss and varies from 650° to 549°C (garnet core) and 641° to 551°C (garnet rim) that may be due to retrogression. The temperature obtained from garnet–cordierite–sillimanite gneiss using various calibrations of the Grt–Crd geothermometers (table 3) ranges between 711° and 631°C for the garnet core and between 694° and 603°C for the garnet rim. The average temperature estimate obtained from garnet–cordierite–sillimanite–

Table 2(e). EPMA data of garnet.

Rock type	Metapelites								Metabasites			
	M232	M232/	M232	M232/	M34/	M 34-	M34-	M34-				
	C1/2	C1/4	/C4/1	C4/4	C1/1	C1/2	C4/2	C4/3	M35/C1	M35/C5	M/38/C1	M38/C4
Sample no.	Core	Core	Rim	Rim	Core	Rim	Rim	Core	Rim	Core	Core	Rim
SiO ₂	37.77	37.93	37.54	37.39	37.54	37.41	37.19	37.03	37.33	37.30	37.96	37.11
Al ₂ O ₃	21.11	21.52	21.02	20.99	20.35	20.68	20.63	20.71	20.52	19.91	20.54	20.33
FeO	33.58	31.39	33.80	34.25	29.99	27.34	29.61	31.90	28.62	29.64	31.39	31.13
MgO	4.17	6.56	3.91	3.65	2.00	1.56	1.36	1.85	1.33	1.94	1.60	1.50
MnO	1.62	0.82	1.77	1.72	2.36	3.48	2.73	2.15	3.17	1.91	3.28	3.13
CaO	2.26	2.19	2.01	2.04	7.62	8.78	7.82	5.98	8.39	7.56	5.78	6.13
TiO ₂	0.01	0.12	0.01	0.03	0.04	0.02	0.04	0.04	0.05	0.03	0.05	0.04
Cr ₂ O ₃	0.00	0.02	0.00	0.02	0.00	0.00	0.05	0.00	0.00	0.01	0.01	0.00
NiO	0.00	0.01	0.00	0.02	0.04	0.01	0.01	0.00	0.00	0.01	0.00	0.00
ZnO	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.04	0.03	0.00	0.03
Total	100.52	100.58	100.07	100.11	99.94	99.28	99.44	99.67	99.45	98.34	100.61	99.40
Cation on 12 Oxygen												
Si	3.041	3.001	3.042	3.036	3.055	3.053	3.046	3.034	3.053	3.039	3.078	3.054
Al	1.952	1.961	1.956	1.957	1.902	1.937	1.939	1.948	1.927	1.912	1.912	1.920
Ti	0.001	0.007	0.001	0.002	0.002	0.001	0.002	0.002	0.002	0.002	0.003	0.003
Cr	0.000	0.001	0.000	0.001	0.000	0.000	0.003	0.000	0.000	0.001	0.001	0.000
Fe	2.203	2.030	2.232	2.266	1.989	1.818	1.975	2.128	1.907	2.019	2.073	2.086
Mg	0.488	0.756	0.460	0.431	0.236	0.185	0.162	0.220	0.158	0.235	0.189	0.179
Mn	0.107	0.054	0.118	0.115	0.159	0.234	0.185	0.145	0.214	0.132	0.219	0.213
Ca	0.190	0.181	0.170	0.173	0.647	0.748	0.668	0.512	0.716	0.660	0.489	0.527
Zn	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.002	0.002	0.000	0.002
Ni	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Prp	16.33	25.02	15.43	14.43	7.78	6.19	5.41	7.33	5.28	7.72	6.35	5.96
Alm	73.72	67.20	74.89	75.92	65.63	60.90	66.07	70.81	63.67	66.28	69.80	69.42
Sps	3.58	1.78	3.97	3.87	5.23	7.85	6.17	4.83	7.14	4.33	7.37	7.09
Grs	6.35	6.00	5.72	5.78	21.35	25.05	22.35	17.02	23.91	21.66	16.46	17.54

biotite gneiss ranges between $773 \pm 41^\circ$ and $675 \pm 31^\circ\text{C}$ from Grt–Bt and Grt–Crld geothermometers for the assemblages Grt–Bt–Sill–Plag–kfs–Qz and Grt–Crld–Sill–kfs–Qz respectively. However, some temperature estimates are exceptionally high between 790° and 860°C using garnet–biotite pair (Thompson 1976; Ferry and Spear 1978; Aranovich *et al.* 1988), which possibly imply lack of equilibrium between the two phases at places.

Pressure estimates for garnet–cordierite–sillimanite gneiss vary between 3.05–5.88 kbar (Fe end member reaction) and 4.44–6.59 kbar (Mg end member reaction) using garnet–cordierite–sillimanite–quartz geobarometer, while the pressure estimates for garnet–hornblende gneiss and garnet amphibolites ranges between 3.9–4.0 kbar and 5.4–4.3 kbar respectively using garnet–biotite–K-feldspar–quartz geobarometer (table 3). The model of Koziol and Newton (1988) geobarometer estimates low pressure ~ 4.5 kbar for the garnet–plagioclase–sillimanite–quartz bearing assemblage of pelitic rock. P–T estimates of garnet–cordierite–sillimanite gneiss from the internally consistent

geothermobarometry and internally consistent dataset range between $720^\circ\text{C}/6.2$ kbar and $687^\circ\text{C}/4.9$ kbar for the assemblages Grt–Crld–Sill–Kfs–Qz using the core composition of garnet. The mafic gneisses (garnet–hornblende–biotite gneiss and garnetiferous amphibolites) based on the independent set of mineral end-member reactions (given as Appendix) also records low estimates of P–T ranges by the internally consistent geothermobarometry and ranges from $579^\circ\text{C}/4.4$ to $545^\circ\text{C}/4.3$ kbar.

Based on textural relations between coexisting mineral phases and geothermobarometry estimates from garnet–cordierite–sillimanite gneiss, a P–T path has been constructed. The assemblage garnet–cordierite–sillimanite $\pm$ biotite–K-feldspar–quartz appears in the pelitic gneisses at $\sim 720^\circ\text{C}/6.2$ kbar and is followed by retrograde evolution at $687^\circ\text{C}/4.9$ kbar, indicating a retrograde cooling path (figure 5). The internally consistent geothermobarometry estimates for mafic rocks ranges between $579^\circ\text{C}/4.4$ and $545^\circ\text{C}/4.3$ kbar may be accorded to the P–T retrograde trajectory

Table 3. Estimates of P - T conditions of metamorphism of pelitic and mafic rocks of BnGC from Mauranipur area, Bundelkhand Craton.

Sample no.	Metapelites						Metabasites		
	Garnet–cordierite–sillimanite gneisses				Garnet–sillmanite–biotite gneisses		Garnetiferous amphibolite	Hornblende–biotite gneisses	
	Grt–Crd geothermometers		Grt–Bt geothermometers		Grt–Bt geothermometers			Grt–Bt geothermometers	
	M232		M232		M34		M35	M38	M38
	Core	Rim	Core	Rim	Core	Rim	Core	Core	Rim
A	655	632	800	626	655	638	685	573	556
B	644	623	860	618	656	633	697	549	528
C	710	694	722	643	707	672	735	616	610
D	658	635	775	610	671	636	634	577	558
E	688	663	790	669	727	700	682	650	641
F	631	603	740	627	640	620	679	562	551
G	711	688	759	635	632	635	661	562	562
H	710	689	738	680	635	645	660	580	568
Average T(°C)	675±31	653±33	773±41	638±23	665±32	647±24	679±28	583±31	571±34
Garnet–biotite–K–feldspar–quartz geobarometer (Wu <i>et al.</i> 2004)									
	5.4	5.1			5.1	5.3	4.3	3.9	4.0
Garnet–cordierite–sillimanite–quartz geobarometer									
	P–Mg	P–Fe							
a	6.59	5.88							
b	6.06	5.62							
c	4.44								
d	4.67	3.05							
Average P (kbar)	5.44±1	4.85±0.8							
Result of internally consistent geothermobarometry									
X			720°C/6.2 kbar				579°C/4.4 kbar	545°C/4.3 kbar	
Y			687°C/4.9 kbar						

where Grt–Bt, A=Thompson (1976), B=Ferry and Spear (1978), C=Perchuk *et al.* (1985), D=Dasgupta *et al.* (1991), E=Aranovich *et al.* (1988), F=Bhattacharya *et al.* (1992a), G=Holdaway (2000), H=Dwivedi *et al.* (2007); In Grt–Crd, A=Thompson (1976), B=Perchuk *et al.* (1985), C=Bhattacharya *et al.* (1992b), D=Perchuk (1991), E=Aranovich and Podlesskii (1983), F=Nichols *et al.* (1992) G=Dwivedi (1996), H=Dwivedi *et al.* (1998); In Grt–crd–sill geobarometer, a=Thompson (1976), b=Wells (1979), c=Perchuk *et al.* (1985), d=Aranovich and Podlesskii (1983); X=Thermocalc Win 2007, Y=Dwivedi *et al.* (1997).

proposed for pelitic rocks. The estimates of temperature from 665 $\pm$ 32 $^{\circ}\text{C}$ (core) to 647 $\pm$ 24 $^{\circ}\text{C}$ (rim) of garnet–sillimanite–biotite gneiss and 583 $\pm$ 31 $^{\circ}\text{C}$ (core) to 571 $\pm$ 34 $^{\circ}\text{C}$ (rim) of garnet–hornblende–biotite gneiss (table 3) could be a possible segment of proposed cooling path with high brackets or may be an independent window.

6. Discussion

Geochronological data of TTG rocks of Mauranipur (Kuraicha) indicates 3297 $\pm$ 8 Ma (Mondal *et al.* 2002) age of crystallization which is more or less contemporaneous with the TTGs of Bundelkhand massif exposed at other places (Mondal 2010; Saha *et al.* 2011; Kumar *et al.* 2011). Medium pressure granulite facies metamorphic conditions of 6.2 kbar and temperature estimates between 773 $^{\circ}\text{C}$ and 720 $^{\circ}\text{C}$ from pelitic rocks of Mauranipur

area is very much comparable to several high-grade Mesoarchean metamorphic rock (Peucat *et al.* 1993; Diener *et al.* 2005; Brown 2006; Moyen *et al.* 2006; Lana *et al.* 2010) from several cratons in the time and space. The pelitic and quartzofelspathic rock sequences exposed at Mauranipur (figure 2) appear as the oldest supracrustal rock sequences that have been deformed and metamorphosed into granulite facies condition. Textural study, mineral assemblages, pressure and temperature estimates calculated from the pelitic gneisses, garnetiferous amphibolite and garnet–hornblende–biotite gneiss of Mauranipur preserve prograde and retrograde stages of metamorphism. The prograde metamorphic history is very fragmentary and is mainly characterized by the association Grt–Bt–Sill–Kfs–Plag–Qz. The thermal peak stage is related to the granulite facies condition and is defined by the garnet core temperature of 773 $^{\circ}\text{C}$ $\pm$ 41 $^{\circ}\text{C}$ /5.4 $\pm$ 1 kbar for thermal peak assemblages

Figure 5. P–T path of the gneisses of Mauranipur in Bundelkhand Craton showing evolution of retrograde stages of metamorphism, where (1) triple point of Holdaway (1971), (2) H₂O-saturated pelite solidus (Thompson 1982) and (3) biotite + aluminosilicate + plagioclase + quartz = garnet + K-feldspar + liquid (Le Breton and Thompson 1988).

Grt–Sil±Bt–Kfs–Plag–Qz. The growth of cordierite around garnet (figure 4a and c) and appearance of assemblage Grt–Crd± Bt–Sil–Kfs–Qz at 720°C/6.2 kbar estimates the lower temperature due to retrograde metamorphism. The geothermobarometry deduced for these two distinct assemblages could not be precisely explained due to larger bracket of pressure and temperature estimates for core composition. The lower P–T estimates of 679°C ± 28°C/4.3 kbar in garnetiferous amphibolites, 665°C ± 32°C/5.1 kbar in garnet–sillimanite–biotite gneiss, and 583°C ± 31°C/3.9 kbar in garnet–hornblende–biotite gneiss (table 3) may appear to be a part of the segments of the same cooling path of late retrograde metamorphism at Mauranipur (figure 5).

Textural and field studies of the pelitic and mafic gneisses of Mauranipur show that these rocks have attained granulite facies metamorphic conditions. The drop in the pressure from 6.2 to 4.9 kbar calculated from internally consistent geothermobarometry (table 3) suggest that the rocks underwent cooling with decompression (figure 5). The estimates of pressure at ~6.2 kbar for the pelitic gneisses of Mauranipur indicate that these rocks were situated at a depth of about 22 km (3.5 km/kbar) at the metamorphic peak. If we consider present crustal thickness of the Bundelkhand as ~35 km in the central zone (Gokarn *et al.* 2013;

Murthy *et al.* 2010), then crust thickness could be predicted as about 57 km at the time of thermal peak of the metamorphism. It is now generally accepted that regional granulite facies metamorphism require an input of extra heat which could be provided by the thickened crust. In order to get the thermal peak ~773°C for the pelitic rocks, the total heat budget may be derived from upwelling of mantle magma or high geothermal gradient during Mesoarchean.

A discordant field relationship between TTG and gneisses (figure 3e) recorded from Mauranipur area points out that the undeformed TTG suite was emplaced later than the D₂ event in gneisses. The geochronological data of 3297 ± 8 Ma of the TTG rocks of Mauranipur (Mondal *et al.* 2002) and the systematic isotope studies of TTG and pelitic gneisses (Mohan *et al.*, in preparation) indicate that the metamorphism in gneisses possibly occurred during the Mesoarchean time and the high-grade pelitic rocks of Mauranipur are older than the emplacement of the TTG suite. The deduced P–T trajectory of the lower crust of BnGC is the first direct evidence of the earliest event of crustal evolution. Thus occurrences of cooling signatures in metapelite rocks of granulite facies along the E–W trending crustal scale shear zones (Singh and Bhattacharya 2010) together constitute a system of very large scale structures in Bundelkhand Craton.

7. Conclusion

The field relation, textural study, phase relationship, and metamorphic conditions based on geothermobarometry along with inputs of structural data reveal that BnGC rocks at Mauranipur area in the central part of Bundelkhand massif are definitely composite in nature, and metamorphosed under the granulite facies conditions.

Acknowledgements

SPS is thankful to the Ministry of Mines, Govt. of India, New Delhi and SBD is thankful to DST, Govt. of India for financial support. They are grateful to anonymous reviewers for the constructive review of the manuscript.

Appendix

The P–T conditions of the garnet–hornblende–biotite gneisses is estimated by average P–T calculation of THERMOCALC v.3.1 involving the independent set of reactions

- (1) $2\text{Prp} + 4\text{Grs} + 3\text{Ts} + 12\text{Qz} = 3\text{Tr} + 12\text{An}$,
- (2) $3\text{Grs} + 5\text{Ts} + 11\text{Qz} = 3\text{Tr} + 13\text{An} + 2\text{H}_2\text{O}$,
- (3) $6\text{Fac} + 21\text{An} = 11\text{Grs} + 10\text{Alm} + 27\text{Qz} + 6\text{H}_2\text{O}$,
- (4) $3\text{Tr} + 6\text{Parg} + 18\text{An} = 4\text{Prp} + 8\text{Grr} + 6\text{Ts} + 3\text{Gln}$,
- (5) $\text{Prp} + 2\text{Grs} + 3\text{Eas} + 6\text{Qz} = 3\text{Phl} + 6\text{An}$,
- (6) $3\text{Eas} + 3\text{Tr} + 3\text{Parg} + 9\text{Ab} = 2\text{Prp} + 4\text{Grs} + 3\text{Phl} + 6\text{Gln}$,
- (7) $3\text{Alm} + 3\text{Eas} + 3\text{Tr} + 3\text{Parg} + 9\text{Ab} = 5\text{Prp} + 4\text{Grs} + 3\text{Ann} + 6\text{Gln}$.

The average P–T obtained from the involved single end-member diagnostic information lie between $545 \pm 50^\circ\text{C}/4.3 \pm 1.1$ kbar and $579 \pm 56^\circ\text{C}/4.4 \pm 1.1$ kbar for sample nos. 35 and 38 (table 3).

References

- Acharyya S K, Gupta A and Orihashi Y 2010 New U–Pb zircon ages from Paleo Mesoarchean TTG gneisses of the Singhbhum Craton, Eastern India; *Geochem. J.* **44** 81–88.
- Aranovich L Ya and Podlesskii K K 1983 The cordierite–garnet–sillimanite equilibrium: Experiments and application; In: *Kinetics and Equilibrium in Mineral Reactions* (ed.) Saxena S K (Berlin: Springer-Verlag), pp. 173–198.
- Aranovich L Ya, Lavrent'eva I V and Kosyakova N A 1988 Biotite–garnet and biotite–orthopyroxene geothermometers: Calibrations accounting for the Al variations in biotite; *Geokhim.* **5** 668–676.
- Basu A K 1986 Geology of parts of the Bundelkhand granite massif, central India; *Record Geol. Surv. India* **117** 61–124.
- Basu A K 2010 Precambrian geology of the Bundelkhand terrain, central India and adjacent part of western India; *J. Econ. Geol. Georesource Manag.* **7** 1–53.
- Bhattacharya A R 1986 Wavelength-amplitude characteristics of polyphase folds in the Precambrian Bundelkhand Complex, India; *Tectonophys.* **128** 121–125.
- Bhattacharya A R and Singh S P 2013 Proterozoic crustal scale shearing in the Bundelkhand massif with special reference to Quartz Reefs; *J. Geol. Soc. India* **82** 474–484.
- Bhattacharya A, Mazumdar A C and Sen S K 1992a Fe–Mg mixing in cordierite: Constraints from natural data and implication for cordierite–garnet geothermometry in granulites; *Am. Mineral.* **73** 338–344.
- Bhattacharya A, Mohanty L, Maji A, Sen S K and Raith M 1992b Non-ideal mixing in the phlogopite–annite binary solution: Constraints from experimental data on Mg–Fe partitioning and a reformulation of the biotite–garnet geothermometers; *Contrib. Mineral. Petrol.* **111** 87–93.
- Brown M 2006 Duality of thermal regims is the distinctive characteristic of plate tectonics since the Neoproterozoic; *Geology* **34** 961–964.
- Dasgupta S, Sengupta P, Guha D and Fukuoka M 1991 A refined garnet–biotite Fe–Mg exchange geothermometer and its application in amphibolites and granulites; *Contrib. Mineral. Petrol.* **109** 130–137.
- Diener J F A, Stevens G, Kisters A F M and Poujol M 2005 Metamorphism and exhumation of the basal parts of the Barberton greenstone belt, South Africa: Constraining the rate of Mesoarchean tectonism; *Precamb. Res.* **143** 87–112.
- Dwivedi S B 1996 Non-ideal Mg–Fe binary mixing in cordierite: Constraints from experimental data on Mg–Fe partitioning in garnet and cordierite and a reformulation of garnet–cordierite geothermometer; *J. Earth Syst. Sci.* **105** 365–377.
- Dwivedi S B, Mohan A and Lal R K 1997 Internally consistent geothermobarometers in the system FeO–MgO–Al₂O₃–SiO₂–H₂O involving garnet, cordierite, aluminosilicate and quartz and their application to metapelites; *J. Geol. Soc. India* **49** 647–669.
- Dwivedi S B, Mohan A and Lal R K 1998 Recalibration of the Fe–Mg exchange reaction between garnet and cordierite as a thermometer; *Eur. J. Mineral.* **10** 281–289.
- Dwivedi S B, Lalnunmawia J, Vanthangliana V and Lal S N 2007 A refined garnet–biotite thermometer: Constraints from empirically derived Margules parameters for garnet and biotite; *The Indian Mineral.* **41** 97–111.
- Ferry J M and Spear F S 1978 Experimental calibration of the partitioning of Fe and Mg between biotite and garnet; *Contrib. Mineral. Petrol.* **66** 113–117.
- Gokarn S G, Rao C K, Selvaraj C, Gupta G and Singh B P 2013 Crustal evolution and tectonics of the Archean Bundelkhand Craton, central India; *J. Geol. Soc. India* **82** 445–460.
- Holdaway M J 1971 Stability of andalusite and the aluminium silicate phase diagram; *Am. J. Sci.* **271** 97–131.
- Holdaway M J 2000 Application of new experimental and garnet margules data to the garnet biotite geothermometer; *Am. Mineral.* **85** 881–892.
- Holland T J B and Powell R 1998 An internally-consistent thermodynamic dataset for phases of petrological interest; *J. Meteor. Geol.* **16** 309–344.
- Holland T J B and Powell R 2001 Calculation of phase relations involving haplogranite melts using an internally consistent data set; *J. Petrol.* **42** 673–683.
- Koziol A M and Newton R C 1988 Redetermination of the anorthite breakdown reaction and improvement of

- the plagioclase–garnet– Al_2SiO_5 –quartz barometer; *Am. Mineral.* **73** 216–223.
- Kumar S, Yi K, Raju K, Pathak M, Kim N and Lee T H 2011 SHRIMP U–Pb geochronology of felsic magmatic lithounits in the central part of Bundelkhand Craton, central India; In: *7th Hutton Symposium on Granites and Related Rocks, Avila, Spain* (eds) Molina J F S, Bea F and Montero P, 83p.
- Lana C, Kisters A and Stevens G 2010 Exhumation of Mesoarchean TTG gneisses from the middle crust: Insights from the Steynsdorp core complex, Barberton granitoid–greenstone terrain, South Africa; *Bull. Geol. Soc. Am.* **122** 183–197.
- Le Breton N and Thompson A B 1988 Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis; *Contrib. Mineral. Petrol.* **99** 226–237.
- Malviya V P, Arima M, Pati J K and Kuneko Y 2006 Petrology and geochemistry of basaltic pillow lava and basaltic komatiite in the Mauranipur area: Subduction-related volcanism in the Archaean Bundelkhand Craton, central India; *J. Mineral. Petrol. Sci.* **101** 199–217.
- Mohan M R, Singh S P, Santosh M, Siddiqui M A and Balaram V 2012 TTG suite from the Bundelkhand Craton, central India: Geochemistry, petrogenesis and implications for Archean crustal evolution; *J. Asian Earth Sci.* **58** 38–50.
- Mondal M E A 2010 Geochemical evolution of the Archaean–Paleoproterozoic Bundelkhand Craton, central Indian shield: Revisited; *J. Econ. Geol. Georesour. Manag.* **7** 69–80.
- Mondal M E A, Sharma K K, Rahman A and Goswami J N 1998 Ion microprobe $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages for the gneiss–granitoid rocks from Bundelkhand massif: Evidence for the Archaean components; *Curr. Sci.* **74** 70–75.
- Mondal M E A, Goswami J N, Deomurari M P and Sharma K K 2002 Ion Microprobe $^{207}\text{Pb}/^{206}\text{Pb}$ ages of zircons from the Bundelkhand massif, northern India: Implications for crustal evolution of the Bundelkhand–Aravalli protocontinent; *Precamb. Res.* **117** 95–110.
- Moyen J F, Stevens G and Kisters A F M 2006 Record of mid-Archaean subduction from metamorphism in the Barberton terrain, South Africa; *Nature* **443** 559–562.
- Murthy A S N, Pandey O P and Sarkar D 2010 Seismic crustal structure of central India and an insight into geodynamic evolution of Bundelkhand Craton; *J. Econ. Geol. Georesour. Manag.* **7** 91–107.
- Nichols G T, Berry R F and Green D H 1992 Internally consistent granitic spinel–cordierite–garnet equilibrium in the FMASHZn system, geothermobarometry and application; *Contrib. Mineral. Petrol.* **111** 362–373.
- Pandey U K, Bhattacharya D, Sastry D V L N and Pandey B K 2011 Geochronology (Rb–Sr, Sm–Nd and Pb–Pb), isotope geochemistry and evolution of the granites and andesites hosting Mohar cauldron, Bundelkhand granite complex, Shivpuri district, central India; *Explo. Res. Atom. Min.* **21** 103–116.
- Perchuk L L 1991 Derivation of a thermodynamically consistent set of geothermometers and geobarometers for metamorphic and magmatic rocks; In: *Progress in Metamorphic and Magmatic Petrology* (ed.) Perchuk L L, Cambridge University Press, pp. 93–111.
- Perchuk L L, Aranovich LYa, Podlesskii K K and Lavrenteva I V 1985 Precambrian granulites of the Alden Shield, Eastern Siberia USSR; *J. Metamor. Geol.* **3** 265–310.
- Peucat J J, Mahabaleswar B and Jayananda M 1993 Age of younger tonalitic magmatism and granulite metamorphism in the amphibolite–granulite transition zone of Krishnagiri and comparison with the older gneisses from Gorur Hassan area; *J. Metamor. Geol.* **11** 879–888.
- Powell R and Holland T J B 1988 An internally consistent thermodynamic dataset with uncertainties and correlations. III. Application methods, worked examples and a computer program; *J. Metamor. Geol.* **6** 173–204.
- Pradhan V R, Meerta J G, Pandit M K, Kamenova G and Mondal M E A 2012 Paleomagnetic and geochronological studies of the mafic dyke swarms of Bundelkhand Craton, central India: Implications for the tectonic evolution and paleogeographic reconstructions; *Precamb. Res.* **198–199** 51–76.
- Prasad M H, Hakim A and Rao B K 1999 Metavolcanic and metasedimentary inclusions in the Bundelkhand granitic complex in Tikamgarh district, Madhya Pradesh; *J. Geol. Soc. India* **54** 359–368.
- Rao M J, Rao G V S, Poornachandra Widdowson M and Kelley S P 2005 Evolution of Proterozoic mafic dyke swarms of the Bundelkhand Granite Massif, central India; *Curr. Sci.* **88** 502–506.
- Saha L, Hofmann A, Xie H, Hegner E, Wilson A, Wan Y, Liu D and Kröner A 2010 Zircon ages and metamorphic evolution of the Archaean Assegai–De Kraalen granitoid–greenstone terrain, southeastern Kaapvaal Craton; *Am. J. Sci.* **310** 1384–1420.
- Saha L, Pant N C, Pati J K, Upadhyay D, Berndt J, Bhattacharya A and Satyanarayanan M 2011 Neoproterozoic high-pressure margarite–phengitic muscovite–chlorite corona mantled corundum in quartz-free high-Mg, Al phlogopite–chlorite schists from the Bundelkhand Craton, north central India; *Contrib. Mineral. Petrol.* **161** 511–530.
- Sarkar A, Paul D K and Potts P J 1996 Geochronology and geochemistry of the Mid-Archaean trondhjemitic gneisses from the Bundelkhand Craton, central India; In: *Recent Researches in Geology and Geophysics of the Precambrians* (ed.) A K Saha, *Geol. Soc. India* **16** 76–92.
- Sharma K K 2000 Evolution of Archaean Palaeoproterozoic crust of the Bundelkhand Craton, northern Indian shield; In: *Research Highlights in Earth System Science* (eds) Verma O P and Mahadevan T M, Special Publication of the Indian Geological Congress, Roorkee, pp. 95–105.
- Sharma K K and Rahman A 1995 Occurrence and petrogenesis of Loda Pahar trondhjemitic gneiss from Bundelkhand Craton, central India: Remnant of an early crust; *Curr. Sci.* **69** 613–616.
- Singh S P 2012a Archean geology of Bundelkhand Craton, central India: An overview; *J. Gondwana Geol. Mag. Spec. Publ.* **13** 125–140.
- Singh S P 2012b Geochemical signatures of Archean felsic volcanism in the central part of Bundelkhand Craton, central India; *Int. J. Adv. Earth Sci.* **01** 20–32.
- Singh S P and Bhattacharya A R 2010 Signatures of Archaean E–W crustal-scale shears in the Bundelkhand massif, central India; *J. Earth Sci. India* **3** 217–225.
- Singh S P and Dwivedi S B 2009 Garnet–sillimanite–cordierite–quartz bearing assemblages from the early Archean supracrustal rocks of Bundelkhand massif, central India; *Curr. Sci.* **97** 103–107.
- Singh S P, Singh M M, Srivastava G S and Basu A K 2007 Crustal evolution in Bundelkhand area, central India; *J. Him. Geol.* **28** 79–101.
- Thompson A B 1976 Mineral reaction in pelitic rocks: I Prediction in P–T–X (Fe–Mg) phase relations. II. Calculations of some P–T–X (Fe–Mg) phase relations; *Am. J. Sci.* **276** 401–454.

- Thompson A B 1982 Dehydration melting of pelitic rocks and the generation of H₂O undersaturated granitic liquids; *Am. J. Sci.* **282** 1567–1595.
- Wells P R A 1979 Chemical and thermal evolution of Archean sialic crust, southern Greenland; *J. Petrol.* **20** 187–226.
- Whitney D L and Evans B W 2010 Abbreviations for names of rock-forming minerals; *Am. Mineral.* **95** 185–187.
- Wiedenbeck M and Goswami J N 1994 High precision ²⁰⁷Pb/²⁰⁶Pb zircon geochronology using a small ion microprobe; *Geochim. Cosmochim. Acta* **58** 2135–2141.
- Wu C M, Zhang Z and Ren L D 2004 Empirical garnet–biotite–plagioclase quartz (GBPQ) geobarometry in medium to high-grade metapelites; *J. Petrol.* **45** 1907–1921.

MS received 26 June 2013; revised 6 July 2014; accepted 17 August 2014