Metamorphic evolution of mafic granulites from Tiyara area, Makrohar granulite belt, Singrauli district, Madhya Pradesh, India

Vikas Pandey* and S. B. Dwivedi

Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi 221 005, India

The mafic granulite rocks from the Makrohar Granulite Belt of the Chotanagpur Granite Gneissic complex (CGGC) have been studied with reference to their petrography, mineral chemistry and pressure–temperature (*P–T*) conditions of metamorphism. The common mineral assemblage observed within different thin sections is orthopyroxene–clinopyroxene–hornblende–plagioclase–biotite–quartz. The average *P–T* condition of the mafic granulites in the study area suggests a peak of metamorphism at 799° ± 40°C/6.3 ± 0.9 kbar. However, the peak *P–T* estimate obtained from the conventional two-pyroxene thermobarometer is 5.83–6.47 kbar and 887° ± 62°C at a fixed pressure of 6 kbar, followed by post-peak *P–T* conditions of metamorphism at 590°–693°C/2.1–2.4 kbar.

Keywords: Mafic granulites, metamorphic rocks, mineral assemblage, pressure, temperature.

GRANULITES represent middle to lower crustal rocks and hence their study helps in understanding crustal evolution, nature and composition of the lower crust, and also magmatic processes responsible for evolution of the lower crust[1]. In mafic granulites, the presence of characteristic mineral assemblage, viz. plagioclase, clinopyroxene (augite) and orthopyroxene (hypersthene), represents the granulite facies condition during regional metamorphism in the metamorphic complex[2]. Two-pyroxene mafic granulites have been reported from different Precambrian terrains in India: (i) The Shillong Meghalaya Gneissic Complex[3,4], (ii) The Southern Granulite Belt[5] and (iii) The Eastern Ghats Granulite Belt[6,7]. However, a detailed mineralogical and petrological study of two pyroxenes bearing mafic granulite of the Makrohar area has not been carried out so far. To fulfil the research gap in the study of mafic granulites, the main aim of the present study is to discuss the petrography, mineral chemistry and geothermobarometry of mafic granulites in the Makrohar Granulite Belt.

Geological setting

The study area is situated at the Tiyara village, Singrauli district, Madhya Pradesh in the northwestern portion of Chotanagpur Granite Gneiss Complex (CGGC) and occurs as a tongue parallel to the Son Narmada South Lineament[8] (Figure 1 *a*). The Proterozoic CGGC is a sub-arcuate belt in the eastern part of the Central Indian Peninsular Shield and spreads over 100,000 km^2 from the eastern part of Madhya Pradesh to Bihar, Chhattisgarh, West Bengal and Jharkhand[9,10] (Figure 1 *b*). CGGC consists of granite gneisses

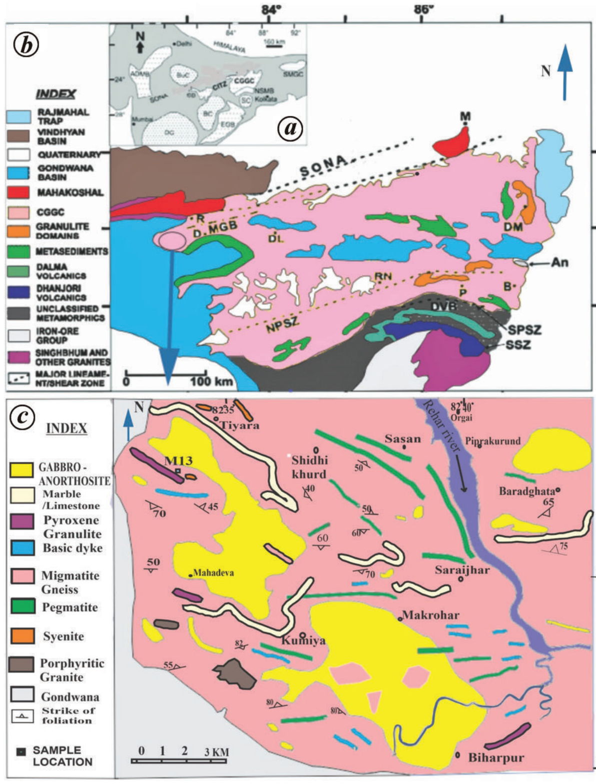

Figure 1. ***a***, The proterozoic mobile belts of India, including Chotanagpur Granite Gneiss Complex (CGGC), Eastern Ghats Belt (EGB), Singhbhum Mobile Belt (SMB), Central India Tectonic Zone (CITZ), Aravalli Delhi Mobile Belt (ADMB), Shillong Meghalaya Gneissic Complex (SMGC). Archean cratonic nuclei of India, Deccan (DC), Bundelkhand (BuC), Bastar (BC) and Singhbhum (SC) cratons, modified after Chatterjee *et al.*[28]. ***b***, Geological map of CGGC: DL – Daltonganj, DVB – Dalma Volcanic Belt, NPSZ – North Purulia Shear Zone, P – Purulia, SSZ – Singhbhum Shear Zone, SONA – Son Narmada Lineament, SPSZ – South Purulia Shear Zone, R – Rihand–Renusagar Area, M – Munger, An – Anorthosite, B – Bankura, RN – Ranchi, MGB – Makrohar Granulite belt, DM – Dumka and D – Dudhi, modified after Chatterjee and Ghose[29]. ***c***, Geological map of the Makrohar area, Singrauli, Madhya Pradesh; modified after Pichaimuthu[13].

*For correspondence. (e-mail: vikaspandey.rs.civ17@itbhu.ac.in)

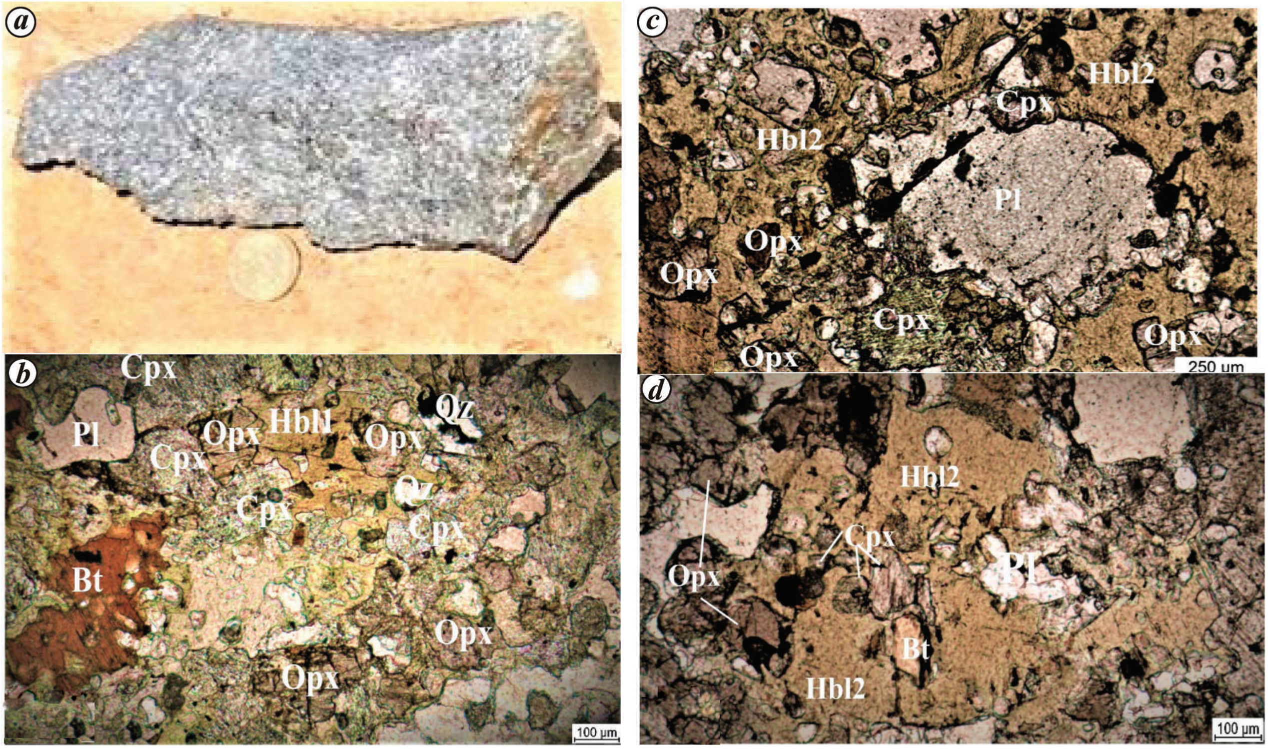

Figure 2. ***a***, Photograph of hand specimen of mafic granulite. ***b–d***, Photomicrographs: (***b***) clinopyroxene coexisting with orthopyroxene and comprising an inclusion of hornblende and quartz under plane polarized light; (***c***) inclusions of orthopyroxene, clinopyroxene and plagioclase in hornblende under PPL and (***d***) orthopyroxene, clinopyroxene and biotite occurring as inclusions in hornblende and coexisting with quartz and plagioclase. Cpx – Clinopyroxene, Opx – Orthopyroxene, Bt – Biotite, Hbl – Hornblende, Qz – Quartz and Pl – Plagioclase; after Whitney and Evans[30].

and migmatites with enclaves of metasedimentary and metaigneous rocks[11]. Three separate lithologies have been found in the Makrohar Granulite Belt by earlier researchers[12–14]. These are: (a) granite gneiss and migmatite, (b) metamorphosed lithopackage comprising marble, sillimanite quartzite, two-pyroxene granulite, pelitic schist, garnetiferous metabasic, including amphibolites and hornblende schist, and (c) meta-igneous rocks which include porphyritic granitoid and gabbro-anorthosites[12–14]. The mafic granulites are dark greyish in colour, hard, compact and medium to coarse-grained (Figure 2 *a*). The rocks show the granulitic fabric and have polygonal grains with weak foliation in some thin sections due to the parallel orientation of amphibole and biotite flakes. On the basis of texture and geothermobarometric studies, three metamorphic stages of the evolution of pelitic granulites and garnet–metabasic rocks were established. These are 800°C and 9 kbar for peak metamorphic conditions followed by an isothermal decompression through 740°C at 6.5 kbar and a final re-equilibrium at 685°C (ref. 14). A granitoid of this area which contains the enclaves of metapelites yielded Rb–Sr date of 1.73 Ga (refs 15, 16).

Textural relationships and interpretation of metamorphic reaction

The common mineral assemblage observed in the mafic granulites was mainly clinopyroxene–orthopyroxene–amphibole–biotite–plagioclase with quartz as a minor constituent. Hornblende showed pleochroism from light green to greenish-brown.

Two generations of hornblende (Hbl1, Hbl2) were observed. Hbl1 showed a corroded border and occurred as inclusion in orthopyroxene and clinopyroxene (Figure 2 *b*). On the other hand, Hbl2 was surrounded partially or completely by pyroxenes, indicating that it was formed in the late stage during retrogression (Figure 2 *c*).

Orthopyroxens are mainly hypersthene in composition. Orthopyroxenes are subidioblastic to idioblastic and show light green to light pink colour. Orthopyroxene contained the inclusions of corroded Hbl1 and quartz (Figure 2 *b*), providing evidence of a prograde reaction that occurred during the peak stage of metamorphism.

$$\text{Hornblende1} + \text{quartz} = \text{clinopyroxene} + \text{orthopyroxene} + \text{plagioclase} + H_2O. \quad (1)$$

This reaction can also be evidenced by hornblende1, which is partially or completely surrounded by clinopyroxene (Figure 2 *b*).

At some spots, orthopyroxene and clinopyroxene were also partially or completely rimmed by Hbl2 (Figure 2 *c* and *d*), indicating that a late stage of the retrograde metamorphic reaction occurred during the post-peak metamorphic stage.

Table 1. Electron probe microanalysis and structural formula of pyroxene from the mafic granulites (sample no. M-13) of study area on six-oxygen basis

Domain	Core1/1	Rim1/1	Core2/1	Rim2/1	Core1/1	Rim1/1	Core2/1
Oxide	Orthopyroxene	Orthopyroxene	Orthopyroxene	Orthopyroxene	Clinopyroxene	Clinopyroxene	Clinopyroxene
SiO_2	51.89	50.26	49.16	50.5	50.34	51.07	50.88
TiO_2	0.15	0.1	0.39	0.2	0.25	0.38	0.28
Al_2O_3	0.69	0.19	0.39	0.54	0.97	1.12	1.49
Cr_2O_3	0.18	0.12	0.15	0.13	0.15	0.15	0.09
FeO	29.45	32.49	32.67	32.07	12.79	12.67	13.24
MnO	0.91	1.01	1.28	0.89	0.57	0.38	0.32
MgO	15.44	15.21	14.34	15.22	12.23	12.25	12.49
CaO	1.18	0.41	1.25	0.10	21.64	21.78	21.36
Na_2O	0.07	0.00	0.03	0.00	0.15	0.16	0.16
K_2O	0.01	0.03	0.01	0.00	0.02	0.02	0.02
Total	99.97	99.79	99.67	99.65	99.11	99.98	100.33
Si	2.01	1.98	1.95	1.98	1.94	1.94	1.93
Ti	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Al	0.03	0.01	0.02	0.02	0.04	0.05	0.07
Cr	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{+2}	0.95	1.07	1.09	1.05	0.41	0.40	0.42
Mn	0.03	0.03	0.04	0.03	0.02	0.01	0.01
Mg	0.89	0.89	0.85	0.89	0.70	0.70	0.71
Ca	0.05	0.02	0.05	0.00	0.89	0.89	0.87
Na	0.01	0.00	0.00	0.00	0.01	0.01	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.97	4.01	4.02	4.00	4.03	4.02	4.03
Wo	2.54	0.86	2.63	0.21	44.16	44.49	43.37
En	46.18	44.41	41.95	45.03	34.73	34.82	35.29
Fs	51.28	54.73	55.42	54.76	21.11	20.70	21.34
X_{Mg}	0.48	0.45	0.44	0.46	0.63	0.64	0.63

X_{Mg} = Mg/(Mg + Fe).

$$\text{Clinopyroxene + orthopyroxene + plagioclase + } H_2O = \text{hornblende2 + quartz.} \quad (2)$$

Clinopyroxene is augite which is colourless to light green and shows slight pleochroism under plane-polarized light. These are subidioblastic grains with inclined extinction, and exhibit corroded and embayed borders where orthopyroxene is developed (Figure 2 *c*).

Biotite is a medium to coarse-grained and shows strong pleochroism from light brown to reddish-brown. Microfolded biotite occurs as an inclusion in Hbl2 (Figure 2 *d*). Plagioclase occurs as idioblastic to subidioblastic porphyroblast and shows lamellar twinning. Plagioclase in association with quartz occurs as xenoblast and also present in the intergranular space between the prisms of pyroxene.

Mineral chemistry

Electron probe microanalysis (EPMA) of mafic granulites was carried out using the CAMECA SX-5 instrument at the Department of Geology, Institute of Science, Banaras Hindu University, Varanasi. The operation was carried out using 15 kV accelerating voltage and 10 nA beam current. X-ray lines used for analyses were Kα for Si, Al, Na, Mg, Fe, Mn, Cr, Zn, Ba, P, K Ca and Ti with standard zedite, orthoclase, Al_2O_3, MgO, Fe_2O_3, Zns, $BaSO_4$, apatite, wollastonite and rutile.

The standards used for quantification and routine calibration were halite for Cl, apatite for P, rhodonite for Mn, corundum for Al, wollastonite for Si and Ca, periclase for Mg, chromite for Cr, rutile for Ti, orthoclase for K, hematite for Fe and pure metals of Ni and V.

Tables 1–4 show EPMA data of mineral phases and their structural formula.

The EPMA data of pyroxene were plotted in the $CaSiO_3$–$MgSiO_3$–$FeSiO_3$ triangular diagram (Figure 3 *b*). The plot shows that clinopyroxene from the mafic granulites falls in the field of augite composition (X_{Mg} = 0.63–0.64). The Al content of clinopyroxene varies between 0.04 and 0.07 per formula unit (pfu, based on six oxygen) (Table 1).

The orthopyroxene plot from mafic granulites lies at En42-46 near hypersthene and falls in the middle zone on the enstatite–ferrosilite line. X_{Mg} of orthopyroxene varies between 0.44 and 0.48, and Al content between 0.01 and 0.03 pfu (Table 1). Based on EPMA data and textural relations of hornblende in mafic granulites, it is evident that two generations of hornblende are present (Table 2). The Al content of Hbl1 varies between 0.44 and 0.64 pfu, and it is prograde. The Al content of Hbl2 varies between 1.06 and 1.22 pfu, and it is a product of the retrograde metamorphic

Table 2. Electron probe microanalysis and structural formula of hornblende from the mafic granulites (sample no. M-13) of study area on 23 oxygen basis

Domain	Core1/1	Rim1/1	Core1/1	Rim1/1	Core2/1	Rim2/1
Oxide	Hornblende1	Hornblende1	Hornblende2	Hornblende2	Hornblende2	Hornblende2
SiO_2	52.36	51.28	48.15	47.19	48.13	46.68
TiO_2	0.17	0.35	1.24	1.25	0.91	0.9
Al_2O_3	2.58	3.69	6.35	5.99	6.17	6.89
Cr_2O_3	0.13	0.53	0.37	0.32	0.2	0.29
FeO	13.58	13.62	13.29	14.3	14.06	15.85
MnO	0.33	0.27	0.18	0.26	0.2	0.26
MgO	14.66	14.03	12.72	12.91	13.33	11.92
CaO	12.55	12.11	13.04	12.41	12.69	12.02
Na_2O	0.27	0.44	0.81	0.81	0.71	0.76
K_2O	0.12	0.23	0.65	0.62	0.49	0.64
Total	96.75	96.55	96.8	96.06	96.89	96.21
Si	7.66	7.55	7.13	7.07	7.10	7.01
Ti	0.02	0.04	0.14	0.14	0.10	0.10
Al	0.44	0.64	1.11	1.06	1.07	1.22
Cr	0.02	0.06	0.04	0.04	0.02	0.03
Fe^{+3}	0.09	0.00	0.00	0.14	0.20	0.17
Fe^{+2}	1.57	1.68	1.65	1.66	1.54	1.82
Mn	0.04	0.03	0.02	0.03	0.02	0.03
Mg	3.20	3.08	2.81	2.88	2.93	2.67
Ca	1.97	1.91	2.07	1.99	2.01	1.93
Na	0.08	0.13	0.23	0.24	0.20	0.22
K	0.02	0.04	0.12	0.12	0.09	0.12
Total	15.10	15.15	15.33	15.35	15.30	15.34
X_{Mg}	0.67	0.65	0.63	0.63	0.65	0.59

X_{Mg} = Mg/(Mg + Fe).

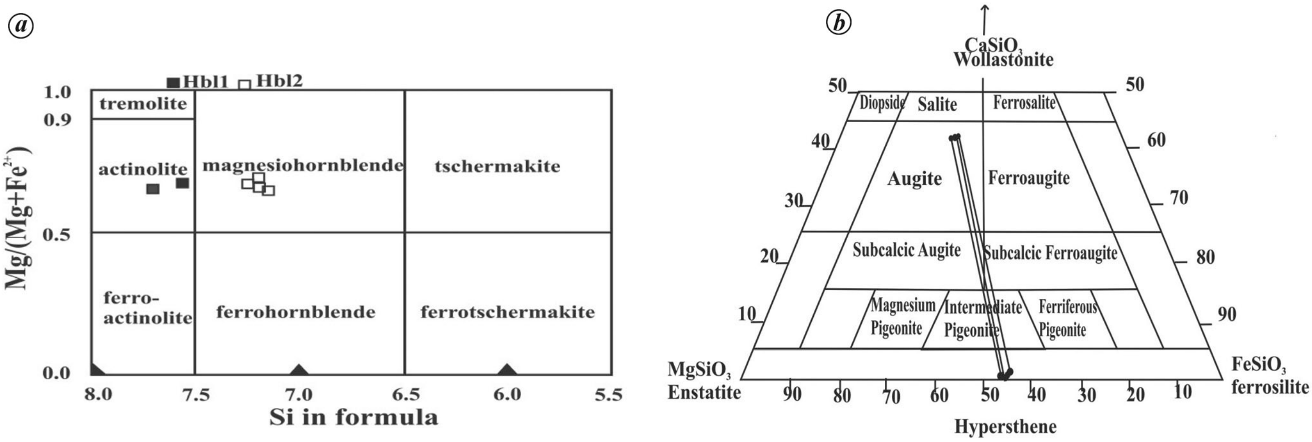

Figure 3. Plots of electron probe microanalysis data: (***a***) amphiboles, modified after Leake *et al.*[17] and (***b***) pyroxenes shown in the triangular diagram $CaSiO_3$–$MgSiO_3$–$FeSiO_3$.

reaction. The overall X_{Mg} varies between 0.59 and 0.67, and Ti content between 0.02 and 0.14 pfu (Table 2). The EPMA data were plotted for the classification of amphiboles, modified after Leake *et al.*[17] (Figure 3 *a*).

The EPMA data of biotite show that it is richer in magnesium than iron. EPMA data of biotite also show small variations in X_{Mg} ratio, ranging from 0.68 to 0.69, while TiO_2 in biotite ranges from 4.31 to 4.57 wt% (Table 3). The EPMA data suggest that plagioclase is andesine to labradorite in composition in mafic granulites. The Ca content varies between 0.48 and 0.52 pfu, while Na content between 0.48 and 0.54 pfu (Table 4). The An content of plagioclase varies between An46 and An52, as obtained from Ca/(Ca + Na + K).

Pressure–temperature conditions

P–T conditions of the mafic granulites were determined using orthopyroxene–clinopyroxene conventional exchange geothermobarometers. The peak temperature (M1) estimate of coexisting orthopyroxene–clinopyroxene of the Tiyara area was 887° ± 62°C at a fixed pressure of 6 kbar (because this value of pressure was observed within the pelitic granulite adjacent to the study area by Solanki *et al.*[14]). The pressure condition of the prograde metamorphic stage was obtained using the two-pyroxene barometer of Mercier *et al.*[18], which provided an estimate of 5.83–6.47 kbar. Peak assemblage of Cpx, Opx, Hbl1, Bt, Pl and Qz was used to estimate the *P–T* conditions employing an internally consistent thermodynamic dataset of Holland and Powell[19] and the software THERMOCALC ver. 3.21 (ref. 20). The estimated average *P–T* condition was 6.3 ± 0.9 kbar and 799° ± 40°C for an (H_2O) = 1. For the post-peak metamorphic stage (M2), texturally equilibrated mineral assemblages Hbl2, Pl and Qz were selected to determine their *P–T* conditions. The pressure condition of the M2 metamorphic stage was obtained using the aluminum-in-amphibole barometer of Schmidt[21], which provided an estimate of 2.14–2.43 kbar. The temperature estimates of the Hbl–Pl–Qz thermometer of Holland and Blundy[22] at pressure obtained using the aluminium-in-amphibole barometer of Schmidt[21] suggest a range 590°–693°C. The uncertainties of the estimated pressure were ± 0.6 kbar for the barometer of Schmidt[21] and ± 100°C for the thermometer of Holland and Blundy[22]. The *P–T* condition for the post-peak metamorphism was recorded at 590°–693°C/2.14–2.43 kbar (Table 5).

Table 3. Electron probe microanalysis and structural formula of biotite from the mafic granulites (sample no. M-13) of study area on 22 oxygen basis

Domain	Core1/1	Rim1/1	Core2/1	Rim2/1
Oxide	Biotite	Biotite	Biotite	Biotite
SiO_2	38.18	37.85	38.45	37.58
TiO_2	4.57	4.49	4.48	4.31
Al_2O_3	14.3	14.17	14.35	14.18
FeO	12.51	12.73	12.66	13.03
MnO	0.17	0.13	0.15	0.16
MgO	15.71	15.48	15.53	15.72
CaO	0.00	0.00	0.00	0.00
Na_2O	0.22	0.21	0.19	0.17
K_2O	8.89	8.76	9.08	8.93
Cl	0.081	0.0854	0.09	0.0912
F	0.53	0.65	0.69	0.47
Total	95.16	94.55	95.67	94.65
Si	5.66	5.66	5.68	5.62
AlIV	2.34	2.34	2.32	2.38
AlVI	0.15	0.15	0.18	0.12
Ti	0.51	0.50	0.50	0.48
Fe^{+2}	1.55	1.59	1.56	1.63
Mn	0.02	0.02	0.02	0.02
Mg	3.47	3.45	3.42	3.50
Ca	0.00	0.00	0.00	0.00
Na	0.06	0.06	0.05	0.05
K	1.68	1.67	1.71	1.70
Cl	0.02	0.02	0.02	0.02
F	0.25	0.31	0.32	0.22
Total	15.45	15.44	15.44	15.51
X_{Mg}	0.69	0.68	0.69	0.68

X_{Mg} = Mg/(Mg + Fe).

Discussion and conclusion

The mafic granulites around Makrohar contain the mineral phases clinopyroxene–orthopyroxene–hornblende–biotite–plagioclase–quartz. Based on textural relations and mineral chemistry, it is suggested that hornblende1 becomes unstable in association with quartz and recrystallizes as clinopyroxene, orthopyroxene and plagioclase feldspar through the following prograde reaction: Hbl1 + Qz = Cpx + Opx + Pl + H_2O during M1 metamorphism. In a few places, orthopyroxene and clinopyroxene are also partially or completely rimmed by hornblende2, providing evidence of the following retrograde reaction: Cpx + Opx + Pl + H_2O = Hbl2 + Qz during M2 metamorphism. The presence of two pyroxenes in mafic granulites reveals the average *P–T* condition of granulite formation at 799° ± 40°C and 6.3 ± 0.9 kbar, which indicates the depth of burial of about 23 km (3.5 km/kbar) of the protolith rock. The lower temperature estimation of mafic granulites indicates that the area was affected by retrograde metamorphism during M2. The granulite metamorphic age is considered to be older than 1.73 Ga (Rb–Sr whole rock) because it occurs as enclaves within the granite which was reported to be 1.73 Ga (refs 15, 16). The *P–T* studies by Dey *et al.*[23] for the garnet-bearing mafic granulites from the northeastern part of the CGGC revealed that garnet + clinopyroxene + plagioclase + rutile + quartz constituted the peak metamorphic mineral

Table 4. Electron probe microanalysis and structural formula of plagioclase from the mafic granulites (sample no. M-13) of the study area on eight oxygen basis

Domain	Core1/1	Rim1/1	Core2/1	Rim2/1
Oxide	Plagioclase	Plagioclase	Plagioclase	Plagioclase
SiO_2	55.21	55.49	56.28	56.1
TiO_2	0.00	0.00	0.00	0.00
Al_2O_3	27.71	27.82	26.78	26.73
FeO	0.03	0.08	0.00	0.00
CaO	10.74	10.63	9.8	9.89
Na_2O	5.64	5.47	6.17	5.98
K_2O	0.02	0.07	0.15	0.11
Total	99.35	99.56	99.18	98.81
Si	2.50	2.51	2.55	2.55
Ti	0.00	0.00	0.00	0.00
Al	1.48	1.48	1.43	1.43
Fe^{+2}	0.00	0.00	0.00	0.00
Ca	0.52	0.51	0.48	0.48
Na	0.50	0.48	0.54	0.53
K	0.00	0.00	0.01	0.01
Total	5.00	4.99	5.01	5.00
An	51.21	51.57	46.35	47.45
Ab	48.66	48.02	52.81	51.92
Or	0.13	0.41	0.83	0.64

Table 5. Results of *P–T* (pressure–temperature) estimation for mafic granulite samples from the study area

Peak stage (M1)	Temperature (°C) at 6 kbar
Opx–Cpx geothermometer	
Wood and Banno[25]	815
Wells[26]	861
Powell[27]	984
Average	887 ± 62
Opx–Cpx geobarometer	
Mercier *et al.*[18] (kbar)	5.83–6.47
Result of internally consistent dataset (Thermocalc v 3.21)	a (H_2O) = 1
$(P–T)_{av}$	799 ± 40°C/6.3 ± 0.9 kbar
Post-peak stage (M2)	
Hbl–Pl–Q thermometer	
Schmidt[21] (kbar)	2.14–2.43
T (HB_1)[22] at pressure by Schmidt[21] (°C)	590–693

Independent set of reactions used to estimate average pressure–temperature ($P–T_{av}$).

For a (H_2O) = 1:

1. 2fact + 5mgts + 5di + 5q = 2tr +5 fs + 5an.
2. 2fact + 2mgts = en + 4fs + 2hed + 2an + $2H_2O$.
3. 3mgts + 3hed + ann + 3q = 3fs + phl + 3an.
4. parg + 4mgts + 5hed +9q = fact + 4en + 5an + ab.
5. 2parg + 6hed + 8 east + 16q = 3fs + 8phl +10an + 2ab + $2H_2O$.

Symbols. HB_1, Holland and Blundy[22] thermometry calibration reaction ed + q = tr + ab.
Hed, Hedenbergite; di, Diopside; en, Enstatite; tr, Tremolite; fs, Ferrosilite; ts, Tschermakite; fact, Ferroactinolite; an, Anorthite; ed, Edenite; parg, Pargasite; q, Quartz; H_2O, Water fluid; ab, Albite.

assemblage of mafic enclaves. It also indicated that metamorphism occurred at high-pressure granulite facies conditions at 12 ± 1 kbar and 800° ± 50°C, followed by a strongly decompressive retrograde path at 7.5 ± 0.5 kbar and ~700° ± 50°C through the replacement of garnet + clinopyroxene by orthopyroxene + plagioclase symplectites. The geothermobarometric studies by Kumar and Dwivedi[24] for the two-pyroxene mafic granulites from the Daltonganj area of CGGC suggested an average peak condition ($P–T_{av}$) at 6.7 ± 1.19 kbar/814° ± 60°C, followed by a retrograde evolution at a lower temperature (~540°C) and pressure (~4.5 kbar). The above studies are consistent with the peak temperature estimate of 887° ± 62°C and peak pressure estimate of 5.83–6.47 kbar for the present study.

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