Two-pyroxene mafic granulites from Patharkhang, Shillong–Meghalaya Gneissic Complex

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The two-pyroxene mafic granulite of Patharkhang area belongs to the Shillong–Meghalaya Gneissic Complex and includes orthopyroxene–clinopyroxene–hornblende–plagioclase ± quartz as common mineral assemblages, which are stable at thermal peak of regional metamorphism. In this study electron probe microanalysis data have been used to discuss mineral chemistry and pressure–temperature (*P–T*) condition of metamorphism of the mafic granulite. The average *P–T* condition suggests a thermal peak of metamorphism at 1029 ± 62°C/7.6 ± 1.7 kbar.

Keywords: Mafic granulite, metamorphism, mineral assemblages, pressure–temperature condition.

GRANULITES play a vital role in understanding the geodynamic evolution of the crust and upper mantle, as these represent middle to lower crustal rocks of the earth. The coexistence of two-pyroxene is considered to be an important rock-forming mineral of mafic granulite, as it provides vital physico-chemical information about the mafic components of regionally metamorphosed, high-grade crustal rocks. In India, two-pyroxene mafic granulites are found in several localities, such as the southern Granulite Belt[1–3], Eastern Ghats Granulite Belt[4] and Chhotanagpur Granite Gneiss Complex. Though granulite facies rocks from the other parts of India are also reported, the presence of two-pyroxene mafic granulites in the Shillong–Meghalaya Gneissic Complex (SMGC) is rare. Patharkhang village (lat. 25°37′488″N and long. 91°9′467″E) located in the southern part of the West Khasi Hills District, Meghalaya (Figure 1), has a significant exposure of metamorphosed mafic rocks and also constitutes an integral part of the SMGC or Shillong plateau[5,6]. Sonapahar, 80 km NW of Patharkhang, is a part of the SMGC and consists essentially of rocks of upper amphibolite to granulite facies[7,8] flanked on the east by greenschist facies rocks belonging to the Shillong Group of the Precambrian, and to the south by sedimentary rocks and basic volcanics of the Cretaceous[9]. However, no detailed mineralogical and petrological study of the two-pyroxene mafic granulite of Patharkhang has been carried out yet. The main purpose of the present study is to report the occurrence of mafic granulites with their petrology and mineral chemistry, and to estimate the average pressure–temperature (*P–T*) condition of metamorphism of the two-pyroxene mafic granulites.

The area around Patharkhang (lat. 25°37′488″N and long. 91°10′061″E) belongs to the SMGC, which comprises of amphibolite to granulite facies basement gneisses unconformably overlain by the Shillong Group of greenshist facies, intra-cratonic sandy and clayey rocks[9]. The basement rocks of the area around Sonapahar, 80 km NW of Patharkhang (Figure 1), include cordierite-bearing granulites, basic granulites, quartz–sillimanite schist and granite gneiss. The mineral assemblages suggest regional metamorphism in granulite facies condition with two phases of deformation[7,8]. Time relations between the two phases of deformation and metamorphic crystallization, as revealed by Si/Se relationships of the porphyroblastic minerals with the matrix foliation, indicate that the regional metamorphism which initiated with the D_1 deformation and finally outlasted the D_2 deformation, represents a single event, including both prograde and retrograde metamorphic sequences[7]. The local geology of the investigated area includes the basement rocks, mainly amphibolite, mafic granulites and granite gneisses (Figure 2). The mafic granulites contain orthopyroxene–clinopyroxene–hornblende and plagioclase as major constituents and are mostly located in the eastern part of Patharkhang village, as shown in Figure 2.

The two-pyroxene mafic granulites of Patharkhang area are dark grey to dark greenish-grey in colour and are medium to coarse-grained. The rock shows granulitic texture/fabric with granular mosaic of orthopyroxene, clinopyroxene, hornblende and plagioclase (Figure 3 *a* and *b*). Sometimes, weak foliations are present, which are defined by parallel orientation of hornblende, biotite and on the odd pyroxene and plagioclase. During regional metamorphism it appears that the orientation of the fabric has taken place to varying degrees, as commonly seen in the different granulite facies terrains. The metamorphism has perverted, coarse, non-oriented aggregates of grains which may partly follow the oriented fabric. The two-pyroxene mafic granulites of the area around Patharkhang contain the following mineral assemblages: (i) Orthopyroxene-clinopyroxene–hornblende–plagioclase–quartz; (ii) Clinopyroxene–orthopyroxene–plagioclase–hornblende–quartz and (iii) Orthopyroxene–hornblende–plagioclase.

Orthopyroxene includes hypersthene which is pink to dark brown in colour and shows straight extinction under cross nicols of the microscope. Hypersthene is feebly to strongly pleochroic and occur as subidioblastic to idioblastic grains. It shows inclusion of hornblende and quartz (Figure 3 *a*), which provides evidence of prograde reaction such as hornblende + quartz = orthopyroxene + clinopyroxene + plagioclase + H_2O (I).

At some place orthopyroxene is also partially rimmed by hornblende, which suggests the reversal of reaction (I).

Clinopyroxene occurs as a subidioblastic prism and is colourless with inclined extinction. It is mainly diopside

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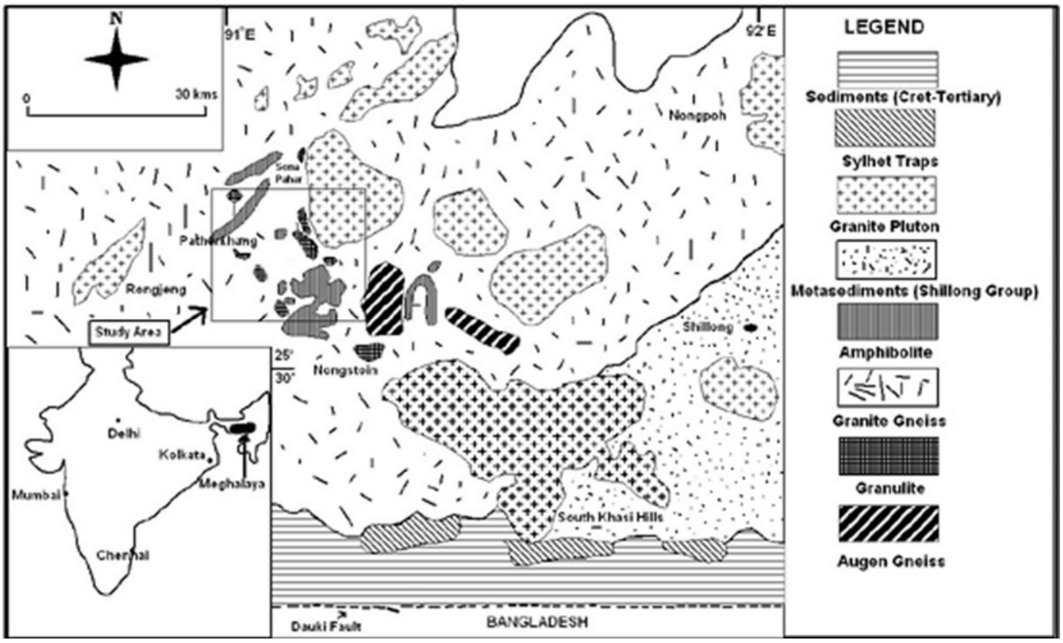

Figure 1. Regional geological map of the western Shillong–Meghalaya Gneissic Complex, Meghalaya, modified after Chakraborty[14].

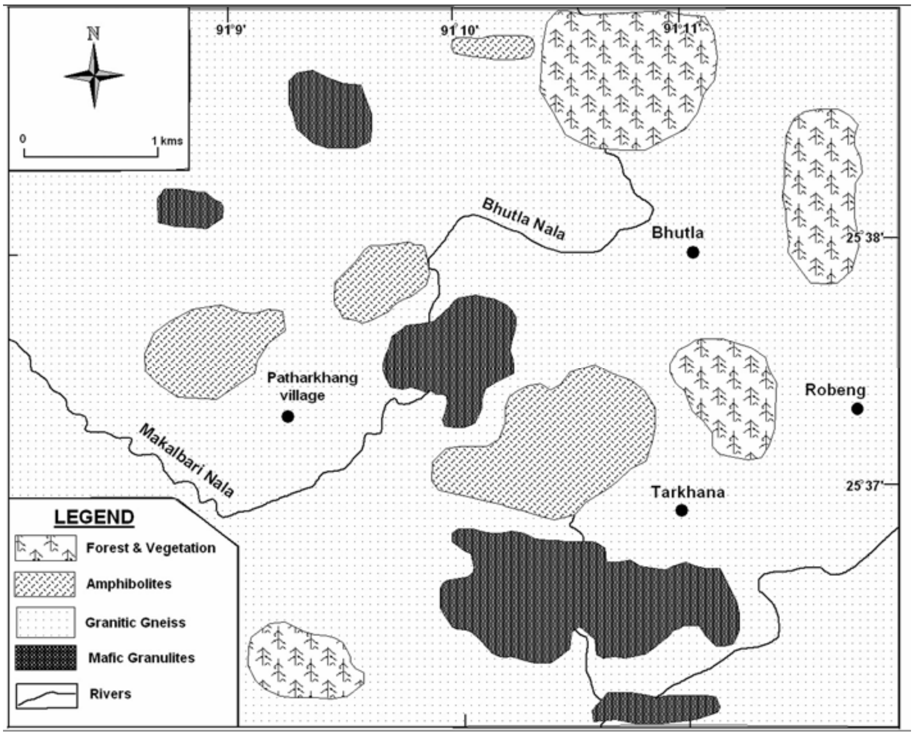

Figure 2. Geological map of the area around Patharkhang.

(Figure 3 *a* and *b*) and contains inclusion of hornblende and plagioclase, which also provides evidence of reaction (I). Some crystals of clinopyroxene show exolution patches of colourless orthopyroxene, and vice versa have also been noted.

Hornblende is strongly pleochroic, green, yellowish-green, bluish-green, dark green or greenish-brown. The pleochroism ranges in horn-blende with modal contents of hornblende present, when present in sporadic amounts it is greenish-brown in colour (Figure 3 *a* and *b*), a feature typical of most hornblende from granulite terrains. Hornblende occurs as armoured relict within the pyroxenes along with quartz, suggesting the occurrence of reaction (I). Hornblende, orthopyroxene and clinopyroxene constitute the mosaic fabric of the granulites and also occur as long prisms defining the foliation.

The An-content of plagioclase ranges from An_{49} to An_{51}, and occurs as granular aggregates or coarse, lath-shaped subidioblastic porphyroblast. Myrmekitic intergrowth of plagioclase and pyroxene is seen. In a few sections, the polysynthetic twin lamellae are slightly deformed indicating post-crystallization deformation.

Quartz occurs as xenoblasts in association with plagioclase, and also along the intergranular space between the prisms of pyroxene. In Figure 3 *a*, the quartz grains occur as inclusion within the pyroxene along with hornblende, providing evidence of prograde reaction (I).

Detailed petrographic studies of rocks of the area have revealed the presence of a number of minerals. The coexisting mineral phases have been analysed by EPMA (Tables 1–3) and back-scattered electron (BSE) image of the mineral phases obtained from EPMA mapping is shown in Figure 3 *b*.

The chemical composition of minerals was determined by CAMERA SX51 EPMA installed at the Indian Institute of Technology, Kharagpur, with accelerating voltage of 15 kV and beam current of 15 mA. X-ray lines used for analyses are Ka 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. EPMA of the coexisting mineral phases with their calculated structural formula (Thermocalc v. 3.1)[10] are given in Tables 1–3 and BSE image in Figure 3 *b*.

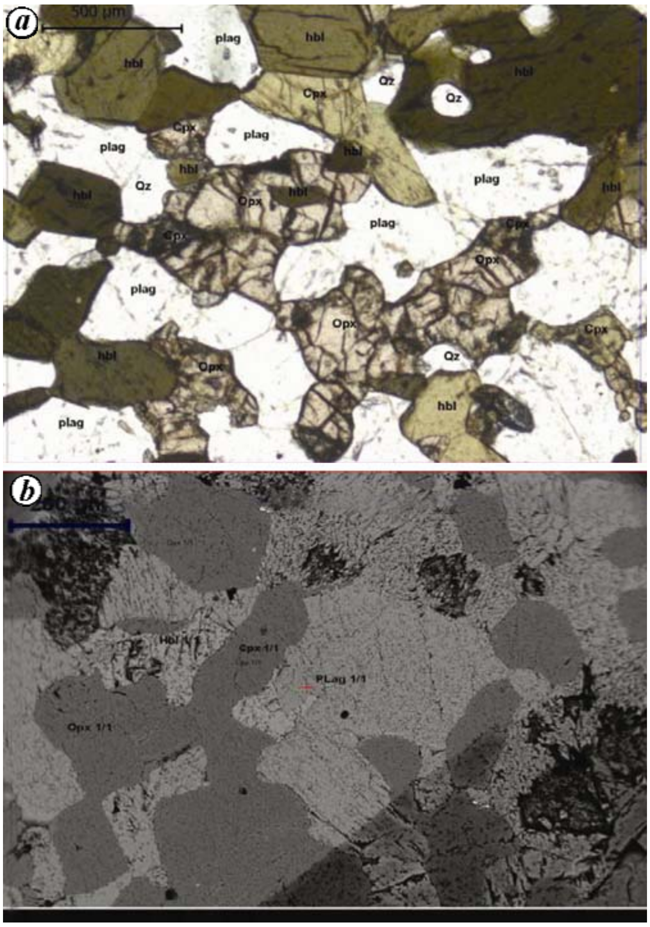

Figure 3. Textural relations in the two-pyroxene mafic granulites of the area around Patharkhang. ***a***, Photomicrograph of coexisting mineral phases under plane-polarized light. ***b***, Back-scattered electron image of coexisting minerals for electron probe microanalysis (EPMA). Opx, Orthopyroxene; Cpx, Clinopyroxene; Hbl, Hornblende; Plag, Plagioclase and Qz, Quartz.

EPMA data of orthopyroxene are plotted in a triangular end-member $CaSiO_3$–$MgSiO_3$–$Fe^{2+}SiO_3$ diagram (Figure 4). The orthopyroxene plot lies at $En_{53–57}$ near the hypersthene, which is the solid solution between Mg and Fe end-members of orthopyroxene. The Al^{VI} of the orthopyroxene varies between 0.01 and 0.031 per formula unit (pfu, on the basis of six oxygen), whereas Al^{IV} varies between 0.008 and 0.023 pfu. The X_{Mg} ranges between 0.56 and 0.57 and corresponds to hypersthene. The hypersthene from basic granulite of Patharkhang contains 0.59–0.99 wt% Al_2O_3, which is significantly lower from the basic granulites of the other terrains (1.02–1.50 wt%, South Indian Granulite)[2].

The coexisting orthopyroxene and clinopyroxene plot in a triangular end-member $CaSiO_3$–$MgSiO_3$–$Fe^{2+}SiO_3$ diagram (Figure 4) lies in the field of salite near the diopside end of the diagram. The X_{Mg} of clinopyroxene ranges between 0.72 and 0.75. It has higher X_{Mg} and Al-content compared to orthopyroxene. Ca content of clinopyroxene varies between 0.893 and 0.934 pfu, that provides evidence of high Ca content of clinopyroxene which is characteristic of mafic granulite assemblages.

The analyses of hornblende show significant amount of Fe_2O_3 wt%, which varies from 1.63 to 3.07. The Al^{IV} and Al^{VI} contents of hornblende vary from 1.347 to 1.493, and 0.01 to 0.31 pfu at 23 oxygen basis respectively. The X_{Mg} of hornblende varies from 0.56 to 0.57, which does not show any significant change. The Ti content of hornblende varies between 0.187 and 0.209 pfu and wt% of TiO_2 varies from 1.66 to 1.83. The Ca content of hornblende varies from 1.828 to 1.893 pfu, suggesting the presence of calcic amphibole.

The microprobe and structural formula of plagioclase are given in Table 2, which shows that the Ca/(Ca + Na + K) ratio of plagioclase from the study area is 0.49–0.51 (i.e. labradorite). Fe is present as Fe^{3+} and is a minor constituent in plagioclase. This may be due to Al^{3+} substitution or due to extremely fine inclusion of opaque in plagioclase.

The *P*–*T* condition of metamorphism of two-pyroxene mafic granulites has been estimated by orthopyroxene–clinopyroxene solves and conventional exchange geothermobarometers, as well as internally consistent dataset (Thermocalc v. 3.21)[10] at 7 kbar (Table 4). The temperature estimates of coexisting orthopyroxene–clinopyroxene from the mafic granulites of the area around Patharkhang vary in the range 833–867°C for core and 766–796°C for rim. The average *P*–*T* condition of metamorphism (P–T_{av})

Table 1. Electron probe microanalysis (EPMA) and structural formula of orthopyroxene, from the two-pyroxene mafic granulite of the study area

Sample	Core 1/1	Rim 2/1	Core 2/2	Rim 2/2	Core 3/1
Orthopyroxene					
SiO_2	51.15	51.16	51.38	52.15	51.34
TiO_2	0.10	0.13	0.10	0.00	0.13
Al_2O_3	0.99	0.79	0.74	0.74	0.59
Cr_2O_3	0.05	0.00	0.00	0.05	0.02
Fe_2O_3	0.00	0.00	0.00	0.45	0.00
FeO	25.88	25.63	25.83	26.52	26.18
MnO	0.80	0.81	0.84	0.82	0.83
MgO	18.35	18.81	18.45	19.18	18.6
CaO	0.65	0.68	0.65	0.59	0.64
Na_2O	0.01	0.00	0.00	0.00	0.02
K_2O	0.00	0.00	0.01	0.02	0.00
Total	98.83	98.92	98.02	100.54	98.34
Six oxygen basis					
Si	1.986	1.984	1.992	1.977	1.988
Al^{IV}	0.014	0.016	0.008	0.023	0.012
$\sum Z$	2	2	2	2	2
Al^{VI}	0.031	0.020	0.026	0.010	0.015
Ti	0.003	0.004	0.003	0.000	0.004
Cr	0.000	0.000	0.000	0.002	0.001
Fe_2	0.841	0.828	0.838	0.841	0.848
Mn	0.023	0.027	0.028	0.026	0.027
Mg	1.062	1.087	1.066	1.084	1.073
Ca	0.027	0.028	0.027	0.024	0.026
Na	0.001	0.000	0.000	0.000	0.002
K	0.000	0.000	0.001	0.001	0.000
$\sum Y$	1.988	1.994	1.989	1.988	1.996
X_{Mg}	0.56	0.57	0.56	0.56	0.56

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

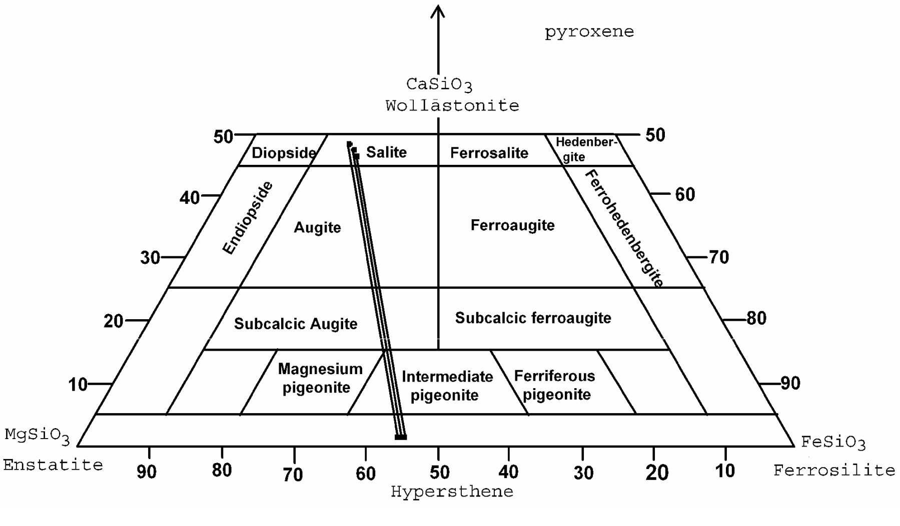

Figure 4. Plot of EPMA data of pyroxene shown in part of triangular diagram $CaSiO_3$–$MgSiO_3$–$FeSiO_3$. The clinopyroxene coexisting with orthopyroxene is joined by a line.

is estimated using Thermocalc v. 3.21 with EPMA data of mafic granulites and with phases involving orthopyroxene, clinopyroxene, hornblende and plagioclase of domain 1/1. It is estimated on the source of end-member diagnostic information of pyroxene, hornblende and plagioclase linking diopside, hedenbergite, Ca-Tschermak pyroxene, enstatite, ferrosilite, Mg-Tschermak pyroxene, tremolite, ferroactinolite, tschermakite, pargasite, anorthite, albite, quartz and water fluid. The average *P–T* condition of metamorphism of two-pyroxene mafic granulites is obtained from the intersection of independent sets of metamorphic reactions and is estimated at 1029 ± 62°C/7.6 ± 1.7 kbar (Table 4), which is within the limit of ultrahigh temperature of regional metamorphism in which crustal rocks are subjected to temperature of 900–1100°C at moderate pressure of 7–13 kbar (ref. 11).

The two-pyroxene mafic granulites of the area around Patharkhang contain the mineral phases orthopyroxene–clinopyroxene–hornblende–plagioclase ± quartz. Orthopyroxene appears in the basic granulite by consumption of hornblende in the presence of quartz through the prograde reaction: Hbl + Qz = Opx + Cpx + Plag + H_2O during D_1 deformation and M_1 metamorphism, which is evident by the relicts of corroded hornblende within the hypersthene (orthopyroxene). Textural relations in which both orthopyroxene and clinopyroxene are partially rimmed by hornblende, suggest retrograde reaction: Opx + Cpx + Plag + H_2O = Hbl + Qz during D_2 deformation and M_2 metamorphism. The detailed petrography of the mafic granulites of the area around Patharkhang indicates that the regional metamorphism which initiated with the D_1 deformation during M_1 prograde metamorphism and finally outlasted the D_2 deformation during M_2 retrograde metamorphism, represents a single event, including both

Table 2. Same as Table 1, but for clinopyroxene and plagioclase

Sample	Core 1/1	Core 1/2	Rim 2/1
Clinopyroxene			
SiO_2	51.70	51.52	51.53
TiO_2	0.09	0.18	0.10
Al_2O_3	1.74	1.39	0.89
Cr_2O_3	0.01	0.00	0.03
Fe_2O_3	1.20	2.20	1.43
FeO	8.88	8.14	7.76
MnO	0.39	0.46	0.26
MgO	12.99	12.91	13.05
CaO	22.09	22.49	22.84
Na_2O	0.24	0.29	0.25
K_2O	0.02	0.00	0.00
Total	99.34	99.57	98.14
Six oxygen basis			
Si	1.951	1.943	1.965
Al^{IV}	0.049	0.057	0.035
$\sum Z$	2	2	2
Al^{VI}	0.029	0.005	0.005
Ti	0.002	0.005	0.003
Cr	0.000	0.000	0.001
Fe_2	0.280	0.257	0.248
Mn	0.012	0.015	0.008
Mg	0.731	0.726	0.742
Ca	0.893	0.909	0.934
Na	0.018	0.021	0.019
K	0.001	0.000	0.000
$\sum Y$	1.966	1.938	1.960
X_{Mg}	0.72	0.74	0.75

Sample	Core 1/1	Core 1/24	Core 2/1
Plagioclase			
SiO_2	55.21	55.67	55.30
TiO_2	0.00	0.00	0.00
Al_2O_3	28.16	27.48	27.89
Cr_2O_3	0.00	0.00	0.04
Fe_2O_3	0.00	0.01	0.24
MnO	0.04	0.03	0.00
MgO	0.00	0.00	0.01
CaO	10.65	10.2	10.42
Na_2O	5.49	5.70	5.54
K_2O	0.23	0.22	0.23
Total	99.78	99.31	99.67
Eight oxygen basis			
Si	2.493	2.522	2.500
Al	1.500	1.468	1.487
Fe_3	0.000	0.000	0.008
$\sum Z$	3.994	3.991	3.997
Ca	0.515	0.495	0.505
Na	0.481	0.501	0.485
K	0.013	0.013	0.013
$\sum X$	1.000	1.009	1.003
X_{ca}	0.51	0.49	0.50

X_{mg} = Mg/(Mg + Fe); X_{ca} = Ca/(Ca + K + Na).

Table 3. Same as Table 1, but for hornblende

Sample	Core 1/1	Core 1/2	Core 2/1	Rim 2/1	Rim 2/2
Hornblende					
SiO_2	43.67	43.21	43.65	43.94	43.39
TiO_2	1.83	1.70	1.66	1.77	1.81
Al_2O_3	9.89	10.01	9.96	9.46	9.91
Cr_2O_3	0.12	0.36	0.08	0.11	0.12
Fe_2O_3	1.63	2.54	3.39	2.34	3.07
FeO	13.72	13.61	13.69	13.39	13.78
MnO	0.29	0.20	0.15	0.35	0.17
MgO	10.97	11.01	11.19	11.23	11.03
CaO	11.25	11.71	11.81	11.48	11.47
Na_2O	1.44	1.46	1.56	1.39	1.56
K_2O	0.97	0.94	0.86	0.92	0.89
Total	95.78	96.74	98.00	96.37	97.21
23 oxygen basis					
Si	6.621	6.517	6.507	6.626	6.517
Al^{IV}	1.379	1.483	1.493	1.374	1.483
$\sum Z$	8	8	8	8	8
Al^{VI}	0.389	0.297	0.257	0.309	0.273
Ti	0.209	0.193	0.187	0.200	0.204
Cr	0.015	0.042	0.009	0.013	0.014
Fe_2	1.739	1.716	1.707	1.689	1.731
Mn	0.037	0.026	0.019	0.045	0.022
Mg	2.479	2.475	2.485	2.524	2.470
Ca	1.828	1.893	1.886	1.855	1.846
Na	0.423	0.427	0.450	0.406	0.455
K	0.187	0.182	0.164	0.176	0.170
$\sum X$	7.306	7.251	7.164	7.217	7.185
X_{Mg}	0.59	0.59	0.59	0.60	0.59

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

Table 4. Temperature estimates of two-pyroxene mafic granulites from solves and exchange conventional geothermometer at assumed pressure and average temperature (T_{av}), average pressure (P_{av}) and average $P–T$ (($P–T$)$_{av}$) from Thermocalc v. 3.21

	Temperature	
Orthopyroxene–clinopyroxene geothermometers	Core (°C)	Rim (°C)
Wood and Banno[15]	833	766
Wells[16]	867	769
Powell[17]	843	796
Average	848 ± 17	777 ± 16
Result of internally consistent dataset (Thermocalc v 3.21)		
T_{aV}	1021 ± 51°C	
P_{aV}	8.45 ± 1.5 kbar	
$(P–T)_{av}$	1029 ± 62°C/7.6 ± 1.7 kbar	

prograde and retrograde metamorphic sequences like M_1 and M_2. The mineral chemistry of pyroxene provides the evidence of hypersthene $En_{53–57}$ appearance as orthopyroxene and salite as clinopyroxene, which is characteristic of mafic granulites. The anorthite content of plagioclase An_{49}–An_{51} suggests the presence of labradorite in the assemblages of mafic granulite. The average $P–T$ condition indicates the thermal peak of metamorphism of two-pyroxene mafic granulites at 1029 ± 62°C/7.6 ± 1.7 kbar, which supports the idea of ultrahigh temperature of metamorphism[11]. The average pressure ~ 8.45 kbar (Table 4) of the basic granulites of the study area corresponds to the ~ 30 km (3.5 km/kbar) thickness of the crust, and if we consider the average crustal thickness of the northeast region of ~ 35 km, then at the time of thermal peak of metamorphism, the crust was ~ 65 km thick. Such a thick crust during formation of two-pyroxene mafic granulites of Patharkhang may be explained on the basis of continent–continent collision or doubly thickened crust model[12,13].

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