CHAPTER 6

METAMORPHIC EVOLUTION OF THE ASSOCIATED ROCKS

Apart from the aluminous granulite, metamorphic history of the Phulbani domain can be constrained from the rocks associated in the lithological assemblage. These rocks include the calc-silicate granulite, the coarse-grained charnockite, the fine-grained charnockite gneiss, migmatitic felsic gneiss and felsic augen gneiss. These rocks provide important information regarding the post-peak metamorphic history, fluid-rock interaction and metasomatic changes of the lower crust exposed in the Phulbani domain.

6.1 EPMA methodology

Chemical data for samples of the calc-silicate granulite, coarse-grained charnockite and fine-grained charnockite gneiss were analyzed using a CAMECA SX-100 EPMA at the Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, India. Operating condition was 15 kV accelerating voltage, 15 nA beam current and 1–2 µm beam diameter. Natural silicate and oxide standards were used for calibration in both instruments and the raw data were corrected using the ZAF program. The mineral chemistries of the associated rocks are mentioned in Table 6.1. The textural characters of the associated rocks are described below and summarized in Table 6.2.

6.2 Textural characters of the associated rocks

6.2.1 Calc-silicate granulite

The calc-silicate granulite is composed of scapolite (Scp), clinopyroxene (Cpx), wollastonite (Wo), garnet (Grt), plagioclase (Pl), calcite (Cal), quartz (Qtz) and titanite (Ttn). This rock is characterized by a prominent gneissosity (S_2/S_3) and the gneissic foliation is defined by alternate greenish and greyish layers (Fig. 6.1a). The greenish layers are composed of Scp, Cpx, Pl, Cal with/without Qtz showing granoblastic texture whereas thin Grt corona (up to 100 µm thick) develops surrounding Scp, Cpx, Pl, Cal and Wo in the greyish layers (Fig. 6.1b). Grt is characteristically absent in the greenish layers which implies participation of Wo in the formation of this phase. Modal percentage of Cpx is higher in the greenish layers compared to the greyish layers. Assuming the fact that the gneissic fabric (S_2/S_3) was imposed during peak/near-peak metamorphic stage (M_2), the peak metamorphic assemblage of the rock can be identified as Cpx + Wo + Scp + Pl + Qtz ± Cal. Garnet composition is grossular-andradite-almandine solid solution with insignificant pyrope and spessartine components (Table 6.2). Compositional variation exists in terms of andradite (13-29 mole%) and grossular (69-84 mole%) components. Grt corona at the contacts of Cpx is andradite-rich (25-32 mole%) compared to one occurring away from latter phase (13-22 mole%). Scp is meionitic with X_{Mei} (Ca/Ca+Na) varying within the range of 0.80-0.83. Small amount of marialite component is present which accounts for minor Cl contents (0.01-0.04 wt%). Pl is almost pure anorthite (96 to 99 mole% An). Cpx is dominantly diopside-hedenbergite solid solution with wide variation of X_{Mg} (0.50-0.63). A rim-ward decrease of Mg and corresponding increase of Fe^{2+} has been noted in porphyroblastic grains surrounded by Grt corona. Cpx grains occurring within the greenish layer are relatively Fe-rich (0.60-0.63). Wo is almost pure phase with minor FeO (up to 0.44 wt%). The occurrence of Grt corona in the greyish layers can be explained by the reaction

Cpx + Wo ± Scp ± Cal ± $O_2 \rightarrow$ Grt ± Qtz ± CO_2………………. (6.1)

Cpx + Wo ± Pl ± Cal ± $O_2 \rightarrow$ Grt ± Qtz ± CO_2………………... (6.2)

Grt grains produced by above reactions are usually characterized by significant amount of andradite component. It is important to note that the Fe_2O_3 content of such Grt presumably comes from the essenite component of adjacent clinopyroxene (Harley and Buick, 1992; Fitzsimons and Harley, 1994; Bhowmik et al., 1995; Sengupta et al., 1997). However, it is observed that Grt having no physical contacts with Cpx, is also andradite-rich. This can only be explained by the presence of an oxidizing fluid (Harley and Buick, 1992; Dasgupta, 1993; Buick et al., 1994). Notably, similar Grt corona has been described from the calc-silicate granulites from the Domain 2 of EGB where such texture is interpreted to have formed during near-isobaric cooling from the UHT peak condition (Dasgupta and Pal, 2005 and references therein).

6.2.2 Coarse-grained charnockite

The coarse-grained charnockite contains K-feldspar (Kfs), plagioclase (Pl), orthopyroxene (Opx), quartz (Qtz), ilmenite (Ilm), biotite (Bt) with/without garnet (Grt) and hornblende (Hbl). It contains a crude gneissic foliation (S_4) in most places, but the rock also occurs as massive in other places. In the foliated variety, dynamically recrystallized Qtz and Kfs grains constitute the leucocratic layers. The melanocratic layers are composed of Grt, Opx, Hbl and Bt. In the massive variety, relic igneous textures like subhedral Kfs, Pl and Opx grains are preserved. Pl grains in such texture occasionally show oscillatory zoning. Grt occurs as corona with Qtz at the contacts of Opx and/or Ilm against Pl (Fig. 6.1c). Bt and Hbl are present around Opx. Grt composition is dominantly almandine-grossular-pyrope solid solution ($Alm_{65-69}Grs_{21-24}Py_{6-8}$) with negligible spessartine (<3 mole%) and andradite components (<3 mole%). Opx is low in Al (<1 wt% Al_2O_3) and Fe-rich (X_{Mg} = 0.27-0.32). Pl shows minor compositional variation ($Ab_{50-52}An_{46-49}$), while K-feldspar is dominantly orthoclase-rich (~82 mole%). Bt (X_{Mg} = 0.60-0.62) and Hbl (X_{Mg}

= 0.43-0.50) contain variable amounts of TiO_2 (3.5-4.0 wt% and 1.3-1.6 wt% TiO_2, respectively).

Formation of Grt (+Qtz) corona can be explained by the reaction

Opx ± Ilm + Pl → Grt + Qtz…………………… (6.3)

This reaction occurs during isobaric cooling (M_{2R} in the present study) similar to those identified from different localities of Domain 2 of the EGB (Bose et al., 2003).

At places, where this rock intruded the calc-silicate granulite, an array of intergrowth textures developed. This will be described in a later section.

6.2.3 Fine-grained charnockite gneiss

The fine-grained charnockite gneiss is composed of K-feldspar (Kfs), plagioclase (Pl), orthopyroxene (Opx), ilmenite (Ilm), quartz (Qtz), garnet (Grt), hornblende (Hbl) and biotite (Bt). The gneissic foliation (S_2/S_3) of this rock is defined by the alternate melanocratic and leucocratic layers. Stretched Opx and Ilm grains constitute the dark-colored layers while the leucocratic layers are composed of Qtz, Kfs and Pl. Kfs and Pl grains show granoblastic polygonal texture. Corona of Grt (+ Qtz) is present around Opx and Ilm at their contacts with Pl which could have been developed by the reaction (6.3) during near isobaric cooling (M_{2R}). Retrograde Bt and Hbl grains are present around Opx (Fig. 6.1d). Grt composition is Fe-rich ($Alm_{72-74}Grs_{18-19}Py_{3-4}$) compared to that of the coarse-grained charnockite. Opx is Al-poor (<1 wt% Al_2O_3) and Fe-rich (X_{Mg} = 0.16-0.19). Pl is rich in albite component ($Ab_{66}An_{33}$), while Kfs is dominantly orthoclase-rich (~80 mole%). Bt (X_{Mg} = 0.43-0.47) is Ti-rich (4.9-5.4 wt% TiO_2) whereas Hbl (X_{Mg} = 0.34-0.37) contains 1.1-1.3 wt% TiO_2.

6.2.4 Migmatitic felsic gneiss

Felsic gneiss having migmatitic character is most dominant at the Phulbani domain and appears to be the host of aluminous granulite, calc-silicate granulite and mafic granulite. This rock is composed of quartz (Qtz), K-feldspar (Kfs) and porphyroblastic garnet (Grt) and biotite (Bt) with minor amounts of plagioclase (Pl) and sillimanite (Sil). An earlier formed gneissic foliation (S_3) is dominantly present in this rock and defined by alternate mafic and felsic bands. The mafic bands are composed of Grt porphyroblasts and matrix Bt with/without fibrous Sil whereas the felsic bands are characterized by Qtz, Kfs, Pl and minor Bt (Fig. 6.1e). Granoblastic polygonal texture appears to be the dominant texture of the felsic band. It is important to note that this rock is also affected by crystal plastic deformation ($D_{4'}$: resultant S_{4S} mylonitic foliation) at the central part of the study area. The details of the microstructures related to this deformation are discussed in chapter 7. In migmatitic felsic gneiss, inclusions of Bt, Qtz and Kfs are common within porphyroblastic Grt. Zircon, ilmenite and apatite constitute the accessory phases of this rock. The textures and mineral chemistries of this rock are discussed in details in chapter 5.

6.2.5 Felsic augen gneiss

Felsic augen gneiss is also present in the study area but do not contain any migmatitic characters. This rock is composed of quartz (Qtz), K-feldspar (Kfs) and porphyroblastic garnet (Grt) with minor amounts of plagioclase (Pl) and biotite (Bt). Despite of having similar mineralogy, migmtitic felsic gneiss and felsic augen gneiss can be distinguished based on the differences in grain size and appearances in outcrop-scale. In the felsic augen gneiss, feldspar grains are much larger (up to 4 cm along the maximum dimension) and occasionally appear as augen (Fig. 6.1f). Modal amount of Grt is notably low in this rock. Additionally, these Grt grains are smaller than those of the migmatitic felsic gneiss. It is important to note that the felsic augen gneiss is the prominent rock type only at the vicinity of the RSZ and it contains the conspicuous S_{5S} mylonitic foliation which is defined by recrystallized quartz and feldspar grains (Fig. 6.1f). Pl grains of this rock are sometimes oscillatory zoned.

6.2.6 Mafic granulite

Mafic granulite mostly occurs as enclaves and boudinaged layers within the migmatitic felsic gneiss and coarse-grained charnockite. On the other hand, metamorphosed mafic dykes occur within the felsic gneiss in the Putudi dam area within the RSZ. This latter variety preserves a conspicuous S_{5S} mylonitic foliation. Mafic granulite is composed of plagioclase (Pl), clinopyroxene (Cpx), orthopyroxene (Opx), hornblende (Hbl) with minor biotite (Bt), ilmenite (Ilm), garnet (Grt) and quartz (Qtz). Both foliated and massive varieties of this rock are present in the study area. Foliation in the former case is defined by alternate mafic and felsic layers (Fig. 6.1g). The mafic layers are rich in Cpx, Hbl and Bt while the felsic layers are Pl-rich. In the mafic layers, Hbl and Bt are only present around Opx and Cpx. Granoblastic polygonal texture is the dominant texture in both varieties of this rock. The S_{5S} mylonitic foliation in mafic granulite dykes is defined by recrystallized Cpx and Pl grains (Fig. 6.1h). Cpx grains of the mylonitized mafic granulite are partially replaced by Hbl and Bt. The latter minerals are sometimes surrounded by tiny vermicular to granular Grt grains (Fig. 6.1i, j).

Presence of Hbl around Opx and Cpx in the mafic granulite xenoliths can be explained by the retrograde reaction

Opx + Cpx + Pl + H_2O = Hbl + Qtz ………………….. (6.4)

Tiny vermicular Grt grains around Hbl and Bt in the mafic granulite dykes were developed by the prograde reaction

Hbl/Bt + Qtz + Pl = Grt + Ilm + H_2O/melt ………………….. (6.5)

6.3 Geothermobarometry of the associated rocks

Geothermobarometric data of the rocks described in the present chapter is summarized in Table 6.3. Several models were used for estimating temperature and pressure of metamorphism of these rocks. In the calc-silicate granulite, scapolite (meionite) composition with X_{Mei} of 0.80-83 suggests temperature in excess of 800°C (Harley, 1989). The garnet-orthopyroxene-plagioclase-quartz thermobarometry of Pattison et al. (2003), which takes into account the late Fe^{2+}-Mg exchange, yielded temperatures of 681-693°C and pressure of 6.2 kbar for the coarse-grained charnockite. Using the same model, the temperatures and pressures were estimated to be 735-770°C and 6.4-6.8 kbar for the fine-grained charnockite gneiss. In both the cases, higher temperatures were estimated using the core compositions of orthopyroxene grains. The estimated pressure is slightly lower (ΔP= 1.5 kbar) compared to the pressure estimated for the peak M_2 metamorphism from aluminous granulite and migmatitic felsic gneiss.

6.4 Phase diagram modeling

To understand the post-peak metamorphic evolution of the associated rocks, only the calc-silicate granulite was chosen due to the occurrence of multiple reaction textures. Phase diagram modeling was carried out using the Perple_X ver 6.7.5 (Connolly and Petrini, 2002; Connolly, 2005, 2009). The internally consistent thermodynamic dataset of Holland and Powell (1998) was utilized for construction of these phase diagrams.

Before phase diagram analysis, the bulk composition for phase diagram modelling was calculated by the method discussed in chapter 5. This bulk composition was used to construct T-X_{CO2} phase diagrams in NCFMASTO-HC system at 8 kbar to model the development of Grt corona around Scp, Cpx, Wo, Pl and Cal (Reactions 6.1 and 6.2) in the greyish layers of the calc-silicate granulite. For the chosen bulk composition, Grt becomes a stable phase throughout the phase diagrams for $O_2 \geq 0.1$ wt% (Fig. 6.2a). This does not match with the textural data as Grt only appeared as coronal phase and was not stable at the peak metamorphic stage. Therefore, the O_2 value during the peak stage must be lower than 0.1 wt%. Hence, T-X_{CO2} phase diagrams were constructed for O_2 values of 0.05 wt% and 0 wt% (Figs. 6.2b and c). In the first case, although Grt becomes stable throughout the phase diagram, Scp-bearing mineral assemblages becomes stable at much lower X_{CO2} of 0.6 (at 900°C) if compared with the phase diagram having O_2 value of 0.1. In the second case, Grt appears only at lower temperature (<900°C) and Scp, Cpx, Wo and Pl bearing mineral assemblage becomes stable between X_{CO2} of 0.65-0.95 at the temperature in excess of 900°C which possibly best represents the peak metamorphic condition of the calc-silicate granulite. This latter phase diagram also suggests that the above mineral assemblage was stabilized in an environment where free oxygen was negligible. It is important to note that Cal is not stable within T-X interval mentioned above and becomes stable only at lower temperature. In the calc-silicate granulite, Cal is indeed present, but very low modal amount of this mineral suggest that most of the calcite grains were consumed during prograde metamorphism to produce the Scp, Cpx, Wo and Pl-bearing peak mineral assemblage above 900°C. Grt became a stable phase along with this mineral assemblage only below 900°C which suggest that coronal Grt development occurred during cooling following the granulite facies condition.

6.5 Metasomatic replacement at the contact of the calc-silicate granulite and coarse-grained charnockite

Fragments of aluminous granulite and calc-silicate granulite are present within the coarse-grained chranockite of the study area and other parts of the Phulbani domain. Although the contact zones of aluminous granulite and the coarse-grained charnockite do not have any textures related to metasomatic replacement, the contact zones (up to 4 mm in width) of calc-silicate granulite and the coarse-grained charnockite have textures related to the metasomatic reactions. The textural characters of the contact zones of the latter rocks are described in detail below.

The contact zones are characterized by myrmekite-like intergrowth and defined by vermicular, globular and rod shaped quartz grains within the Pl grains (Figs. 6.3a, b, c). The shape and size of the Pl grains which belong to such intergrowth are similar to that of the coarse-grained charnockite located several micrometers away from the contact zones. Pl grains of the intergrowth have conspicuous patchy zoning defined by differences in Ca and Na content (Figs. 6.3d, e, f). It is additionally important to note that such plagioclase grains are dominantly Na-rich ($An_{54-65}Ab_{34-43}Or_{0.4-1.1}$) when occurring close to quartz-deficient domains, but are relatively Ca-rich ($An_{67-85}Ab_{15-31}Or_{0.2-0.6}$) where quartz grains are adequate. The composition of these Na-rich zones is similar to the plagioclase grains ($An_{54-65}Ab_{35-45}Or_{0.3-1.1}$) of the coarse-grained charnockite which do not have the intergrowth and located away from the contact zone. The above evidences point toward the reaction (6.6) between coarse-grained charnockite and calc-silicate granulite.

$2NaAlSi_3O_8 + Ca^{2+} = CaAl_2Si_2O_8 + 4SiO_2 + 2Na^+$………………….. (6.6)

Plagioclase grains of the coarse-grained charnockite have K-feldspar lamellae which are crystallographically oriented (Fig. 6.3d) and often arranged in braided fashion (Fig. 6.3g). In the latter case, portions of the plagioclase grains located at the immediate vicinity of such lamellae are relatively Ca-rich ($An_{78-80}Ab_{19-21}Or_{0.2-0.5}$) and gradually become Na-rich ($An_{56-61}Ab_{38-43}Or_{0.4-0.9}$) away from the lamellae (Figs. 6.3 h, i, j). Locally the K-feldspar lamellae appear to be coalesced to form K-feldspar patches within plagioclase grains (Fig. 6.3k). It is pertinent to mention that these K-feldspar lamellae and patches have high Ba content (BaO: 1.0-6.0 wt%) and sometimes are characterized by conspicuous Ba zoning. Thin films of plagioclase feldspar (up to 4 µm) locally exist around the K-feldspar lamellae and patches mentioned above (Fig. 6.3g, k). Due to very narrow width, the composition of such films could not be measured by EPMA except for a single instance which indicates that these are Na-rich plagioclase ($An_{24.75}Ab_{70.97}Or_{4.2}$). The orthopyroxene grains of the coarse-grained charnockite are rimmed by clinopyroxene at the contact zone (Fig. 6.3l).

The pegmatoidal metasomatic rock which occurs at the contact zone of the calc-silicate granulite and the coarse-grained charnockite are dominantly composed of K-feldspar (Kfs), clinopyroxene (Cpx) and plagioclase (Pl) with minor amount of quartz (Qtz), titanite (Ttn) and apatite (Ap) (Fig. 6.3m). Cpx grains are Fe-rich in composition (X_{Mg}: 0.39-0.42). Kfs grains are larger than the Pl grains and recrystallized in all instances. Recrystallized Kfs grains are characterized by straight grain boundaries to develop granoblastic polygonal texture (Fig. 6.3n). Myrmekitic intergrowth is present at the contacts between the Pl ($An_{79-82}Ab_{17-20}Or_{0.1-0.4}$) and Kfs grains ($An_{0-0.03}Ab_{9-11}Or_{89-91}$). Such intergrowth also occurs at Kfs boundaries where Pl grains are notably absent. In such case the boundaries of the intergrowth which are stemmed to the Kfs grains are always characterized by transgressive fronts which appear to invade into the latter (Fig. 6.3o). Compositional variations exist in terms of differences in Ca and Na content in the Pl grains which belong to such intergrowth (Figs. 6.3p, q). Pl grains which are located away from the Kfs contact are Ca-rich ($An_{64-83}Ab_{17-35}Or_{0.25-0.47}$) with respect to those which are located just at the contact ($An_{44-57}Ab_{42-55}Or_{0.3-0.7}$). Thin films of albitic Pl exist between the recrystallized Kfs grains (Fig. 6.3r). These films are interconnected with each other to produce networks which are sometimes connected to the albitic lamellae present within the host Kfs grains. The exact compositions of the albitic films or the lamellae could not be measured due to their narrow width.

Development of myrmekite-like intergrowth and pegmatoidal metasomatic rock and its textures at the contact between the calc-silicate granulite and the coarse-grained charnockite possibly developed due to mutual element transfer between these two rocks. Such element transfer must have occurred along a chemical gradient between the calc-silicate granulite and the coarse-grained charnockite and defined by differences in Ca, Na and K concentrations between these rocks. Ca must have been sourced from the calc-silicate granulite because of the abundance of Ca-rich minerals such as calcite, scapolite, clinopyroxene, plagioclase and wollastonite while the source of Na and K was coarse-grained charnockite. This kind of metasomatic change has never been reported from the EGB, but similar features are documented from the high-grade rocks of the Bamble sector of South Norway (Engvik et al., 2011, 2014) where albitite layers developed due to regionally extensive Na-metasomatism in the presence of brine solution. Such brine solution is known for enhancing element mobility and could have played pivotal role during elements transfer between the two rocks. The possible nature and chemistry of the fluid phase will be described in detailed in chapter 8.

6.6 Summary

1. Textural and phase diagram modeling suggest that scapolite-, clinopyroxene-, plagioclase- and wollastonite-bearing mineral assemblage of the calc-silicate granulite stabilized above 900°C at the X_{CO2} of 0.65-0.9. Garnet corona developed around these minerals during near-isobaric cooling (M_{2R}) below 900°C from the peak metamorphic condition with or without the presence of an oxidizing fluid.
2. Garnet (+quartz) corona in coarse-grained charnockite and fine-grained charnockite gneiss suggest isobaric cooling (M_{2R}) below 700°C and a pressure decrease of ca. 1.5 kbar from the peak metamorphic condition.
3. Biotite-bearing mineral assemblage in the felsic gneiss possibly developed at the late M_{2R} stage around 500°C.
4. Metasomatic reactions occurred at the contact of the calc-silicate granulite and the coarse-grained charnockite which is thought to responsible for the development of myrmekite-like intergrowth where plagioclase grains of the coarse-grained charnockite becomes Ca-rich and show patchy Ca and Na-rich zones. This additional Ca must have been sourced from the adjacent calc-silicate granulite while K and Na were sourced from the corase-grained charnockite to form the pegmatoidal metasomatic rock. Such lower crustal metasomatic replacement possibly occurred in the presence of brine solution.