CHAPTER – 7

METAMORPHIC CONDITION

7.1 Introduction

An estimate of PT condition is a challenging exercise for the rocks because it underwent different metamorphism episodes. The mineral compositions are not free from re-equilibration during cooling, which affects the peak composition by cation exchanges. It is established that the mineral compositions in natural rocks are difficult to interpret and expected to get the 'preserve equilibrium distributions' of all elements of concern from peak conditions. This 'difficult-to-quantify' compositional variability affects both the precision and accuracy of thermobarometry approaches more seriously than the mineral assemblage (petrogenetic grid) approach.

In this chapter, an attempt has been made to discuss the paragenesis and phase relations of different mineral assemblages of the coexisting mineral phases at varying P-T conditions based on the mineral composition data, along with geothermobarometry and bulk composition modelling of the rock of pelitic granulites and mafic granulites.

PART – A: Phase Petrology

7. A.1 Introduction

The study of various mineral parageneses is generally supported by graphical projections in the pertinent system, known as a phase diagram. These chemographic projections provide an easy tool for understanding the phase compatibility relationships and deducing metamorphic reactions in forming diverse mineral assemblages. Phase relationship and the analyses of coexisting minerals in a pertinent system will provide the data which indicates equilibrium crystallization or any disappearance from chemical equilibrium. If minerals coexist in a rock crystallized in equilibrium, the distribution of elements amongst the minerals could be systematic. The petrogenetic grid has univariant reaction lines that bounded all possible divariant mineral assemblages' fields for a given bulk chemical composition. The univariant reactions curves delineating the stability limit of many end-members mineral equilibrium have been studied experimentally. As more thermodynamic data become available, it will be easier to calculate the stability of minerals theoretically, and this will be probably the main thrust in future studies of metamorphic mineral assemblages.

7. A.2 Phase compatibility relation

7. A.2.1 Mafic granulites

The phase relationships of the mafic granulite have been examined inside the CaO-(MgO+FeO)-Al_2O_3-SiO_2-H_2O model system. Initially, these relationships were visually analysed using the ACF diagram (Figure 7.2). The components within this subsystem were appropriately chosen to reflect the coexistence of opx, cpx, hbl, and plg. Sodium oxide (Na_2O) is present in notable quantities within plagioclase and hornblende minerals, while iron oxide (FeO) and titanium dioxide (TiO_2) are frequently found in hornblende. The occurrence of biotite and K-feldspar in small quantities may be attributed to the non-availability of K_2O. As a result, K_2O has been disregarded in graphical representations. The mineral assemblage consisting of orthopyroxene, clinopyroxene, and plagioclase (as depicted in Figure 7.1) is observed as a result of the decomposition of hornblende. The aforementioned procedure induces the creation of a three-phase domain by perturbing the balance between hornblende-plagioclase, hornblende-clinopyroxene, and hornblende-orthopyroxene, as elucidated by the reaction (7.1). The observed reaction is a continuous process that is predominantly influenced by the presence of quartz, which is essential for the complete decomposition of hornblende. Indeed, the mafic granulites of Betul Belt commonly consist the mineral assemblage; garnet-orthopyroxene-clinopyroxene-hornblende-plagioclase-biotite ilmenite- quartz, depending upon the availability of quartz. Several metamorphic reactions have been observed in mafic granulites, in which a textural relation shows corroded hornblende is present as inclusion in the pyroxene. The reaction is;

Hornblende + quartz → orthopyroxene + clinopyroxene + plagioclase (7.1)

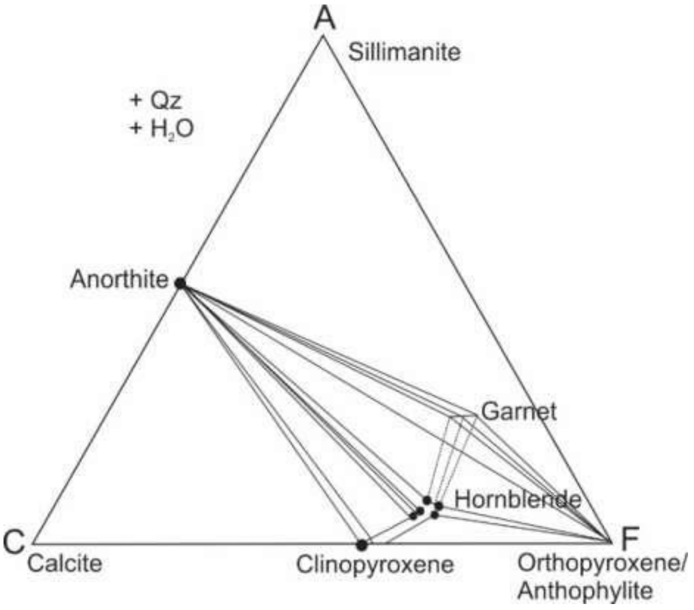

Figure 7.1 The mineral composition of the mafic granulites are shown in ACF diagram where, A = $(Al_2O_3 + Fe_2O_3) - (K_2O + Na_2O)$; C = CaO; F = FeO + MgO + MnO. (A+C+F = 100 mol %)

The reaction is derived from the ACF diagram (Fig.7.1). The hornblende breaks down to form three-phase clinopyroxene-orthopyroxene-plagioclase. The Ti has strongly partitioned in hornblende comparison to pyroxene due to a decrease in a modal constituent that causes the enrichment of Ti in hornblende. Besides, hornblende can be completely used to repel ilmenite granules commonly found adjacent to corroded hornblende. Thus, continuation reaction is:

$Hbl_1 + qtz \rightarrow opx + cpx + plg + hbl_2 + ilm + H_2O$ (7.2)

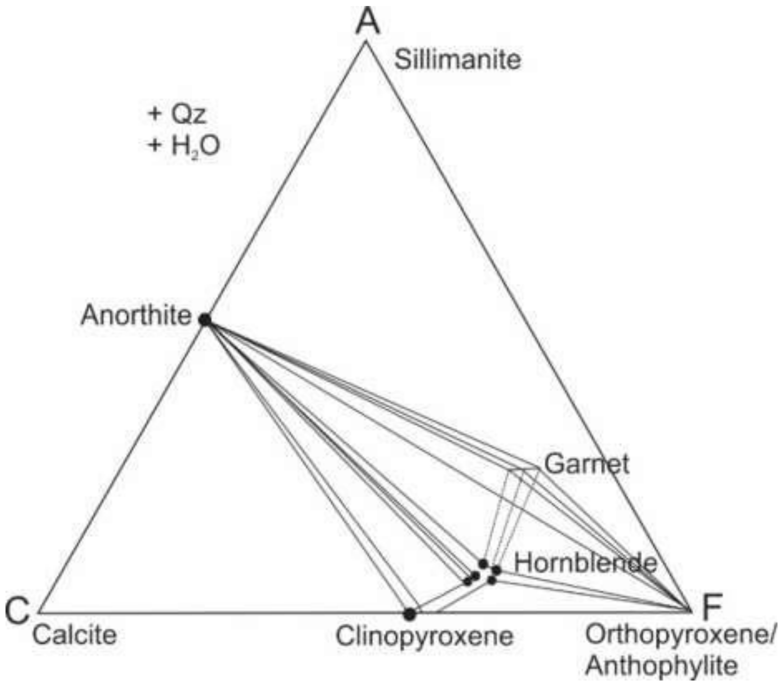

Figure 7.2 The mineral composition of the mafic granulites are shown in ACF diagram where, A = (Al_2O_3 + Fe_2O3) – (K_2O + Na_2O); C = CaO; F = FeO + MgO + MnO. (A+C+F = 100 mol%)

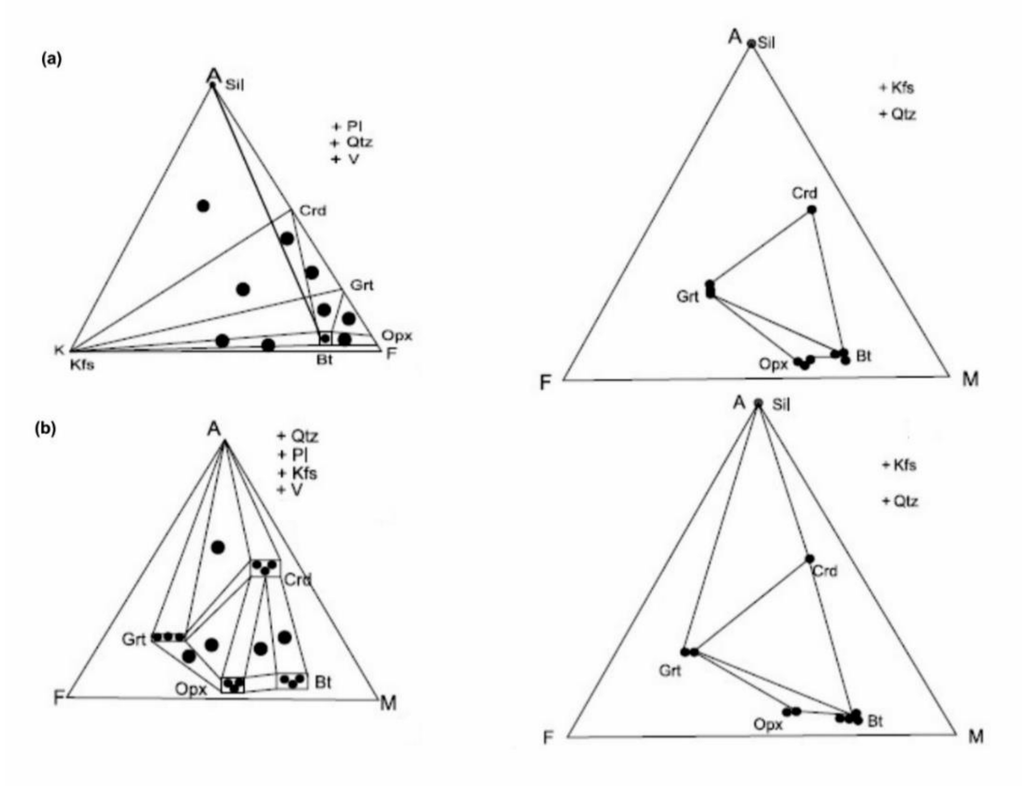

Figure. 7.3. Phase relations for garnet-opx-crd bearing pelitic granulites: small solid circles show mineral compositions and the large solid circles represent the observed mineral parageneses: (a) AKF diagram; note that crossed tie lines reflect divariant assemblages due to Mg and Fe^{2+} exchange; (b) AFM projection from potash feldspar.

7. A.2.2 Pelitic granulites

The four-phase assemblage has less variance, and thus the composition of the phases should be uniquely defined if the rocks have equilibrated at similar pressure and temperature. The three-phase fields of orthopyroxene-cordierite-biotite and garnet-orthopyroxene-cordierite exhibit different FeO/MgO ratio suggesting different externally controlled extensive variables during their crystallization. The Fe-Mg cation exchange among garnet and biotite, evident from the compositional element, suggests crystallization near the thermal peak of metamorphism followed by cooling during which cation exchange reactions continued. In pelitic granulites, the orthopyroxene is formed through the reaction:

Garnet+ quartz+ melt = cordierite + orthopyroxene (7.3)

Biotite + quartz =Cordierite+ orthopyroxene+ K- feldspar+ water (7.4)

Here, one three-phase field of orthopyroxene-cordierite-biotite and it is evident from biotite orthopyroxene join intersected by garnet-K-feldspar joins in the AKF diagram (Fig.7.3). The textural feature such as linear trails of biotite within a aggregates of orthopyroxene and, the evidence is favouring the reaction (7.3).

PART – B: Geothermobarometry

Geothermometry and geobarometry are used for the computing temperature and pressure of metamorphic rocks, where the temperature and pressure dependencies of equilibrium constants are used as the mafic yardstick. Traditionally, the geothermobarometry has described solid-solid reactions, so that the results are independent of the partial pressure of fluid species. The primary approach for estimating the P-T condition is the implementation of equilibrium thermodynamics, in which the mineral assemblages are considered to be in equilibrium, and the conditions of its formation were controlled by the P-T path through which the rock has formed [420]. Values of ΔH, ΔS, ΔCp, and ΔV are known from experimental calibration. The constant equilibrium value is measured for a sample using the electron microprobe analyser (EPMA) data to determine the elemental constituents of coexisting mineral phases. With these data, a line of "equilibrium constant" can be drawn on the P-T diagram and the intersection of the two lines of "equilibrium constant" defines a unique pressure and temperature of equilibration.

7. B.1 Conventional geothermobarometry

Conventional geothermobarometry involves the experimental and empirical thermodynamic calibrations of a specific reaction applied to the natural rock. This method is based on the balanced reaction between the end-member of involved mineral phases in the equilibration volume. The chemical composition of the mineral phases that may be solid solutions of various cations are calculated and the equilibrium relationships among the solid solution minerals serve as geothermometers and geobarometers. During the change in P-T, the Fe-Mg exchange reaction occurs between mineral phases.

7. B.1.1 Temperature estimation

7. B.1.1.a Garnet-orthopyroxene geothermometry

Garnet and orthopyroxene coexisting in garnet bearing mafic granulites can be used to estimate the temperature in metamorphic rocks. The Mg^{2+}-Fe^{2+} exchange has been proposed as a thermometer for the reaction $3MgSiO_3 + Fe_3Al_2Si_3O_{12} \leftrightarrow 3FeSiO_3 + Mg_3Al_2Si_3O_{12}$, which has been formulated by [82-84, 421].

7. B.1.1.b Garnet-cordierite geothermometry

The P-T-X relationship among garnet and cordierite has been the subject of much debate in recent years. The geothermometer has been empirically calibrated by [86, 422]. The mixing in multi-component garnets indicates that the garnets are strongly non-ideal in the Mg-Fe binary [423, 424]. This implies that the Mg-Fe cordierites should also be non-ideal. [86, 88, 95, 425] have reformulated the geothermometer based on a thermodynamic cum statistical treatment of several pairs of naturally occurring garnet and cordierite.

7. B.1.1.c Garnet-biotite geothermometry

It is well known that the garnet-biotite geothermometer is the most widely accepted and is used to estimate the temperature equilibrium of medium grade metapelites and gneisses. Calibrations were pioneered by [426], who considered ideal solutions of these pairs. A revised geothermometry calibration has been done by [427] that takes care of many of the drawbacks of earlier calibration, including non-ideality in garnet and biotite. To have consistent data geothermometric calibrations by [86-89] have been adopted.

7. B.1.1.d Garnet-clinopyroxene geothermometry

Garnet-Clinopyroxene thermometry developed by [428] is based on the experimental Fe-Mg exchange equilibria studies. Thermometric model for the Fe-Mg exchange reaction: $1/3\ Mg_3Al_2Si_3O_{12} + CaFeSi_2O_6 \leftrightarrow 1/3\ Fe_3Al_2Si_3O_{12} + CaMgSi_2O_6$

The distribution coefficient function of temperature, pressure, and X_{Ca} of garnet is given by KD, obtained from the mineral compositions. In the present calculation, the mole fraction of Fe^{2+} in the three equivalent divalent sites of garnet structure and mole fraction of Fe in cpx are considered, assuming the minerals are ideal [428].

7. B.1.1.e Orthopyroxene-clinopyroxene geothermometry

Solvus geothermometers are based on the miscibility gap in a temperature composition (T-X) space between structurally related phases. The calculation of temperature using Opx-Cpx geothermometers is formulated by calibration of the reaction between coexisting Opx and Cpx. [$Mg_2Si_2O_6$ (Opx) ↔ $Mg_2Si_2O_6$ (cpx)]

Several workers have experimentally and empirically studied and modelled thermometry's above reaction [429-431]. The thermometer of [429] was established on the solvus data of [432]. [430] proposed a revised model based on the calibration of a larger data set of [433, 434]. He also expressed the temperature dependence of coexisting Opx-Cpx based on the ideal solution model of [429].

7. B.1.2 Pressure estimation

7. B.1.2. Garnet-cordierite-sillimanite-quartz geobarometers

The geobarometric formulations are expressed in Fe and Mg-end member equilibria. The earlier calibration for Fe end-members equilibria was based on the experimental data of [90], later experimental data of [309] were proposed which are reliable with the internally consistent dataset of [98, 101, and 435]. [96, 97] calibrated barometers for garnet cordierite- sillimanite-quartz, based on the experimental data of [309]. [96, 97] proposed an internally consistent geothermobarometer for GCAQ equilibria from which P-T condition of metamorphism can be estimated simultaneously through the geobarometers plots.

7. B.1.2.b Garnet-clinopyroxene-plagioclase-quartz geobarometers

The garnet-plagioclase-clinopyroxene-quartz assemblage represents potential geobarometer. Thermodynamic calibrations for these assemblages have been formulated by [436] gives consistent results for the samples containing both pyroxenes. For the continuous reaction: $CaAl_2Si_2O_8+Mg_2Si_2O_6 \leftrightarrow 1/3Ca_3Al_2Si_3O_{12}+2/3Mg_3Al_2Si_3O_{12}+SiO_2$

From the activity relations given by [436]: activities of garnet components, plagioclase activities, and diopside (cpx) activities are determined. The ideal two-site model which give good results in many applications are used here for the pyroxene components, for which the cat-ion site assignments for clinopyroxene followed here are: Ca, Na, Mn and Fe^{2+} in M2 site and Al^{vi}, Ti, Fe^{3+}, Mg and the remaining Fe^{2+} in the M1 site.

7. B.2 Average P-T calculation using THERMOCALC

THERMOCALC programme of [437, 438] has been used to compute the average PT using a multi-equilibrium-relationship approach to geothermobarometry. Version 3.47 has been downloaded from the website of Dr. T.J.B. Holland (2020). The computation involves calculating an independent reaction set involving the mineral assemblage's endmembers. The minerals are believed to be in equilibrium condition with each other. If there are ‘n’ reactions present as independent, and then also be ‘n’ equilibrium relationships. If the mineral compositions are known, their activities can be calculated, and hence several unknown ‘n’ equations are understood to characterize the metamorphic conditions. If the metamorphic fluid composition is specified, then pressure and temperature are two variables. The $P\text{-}T_{av}$ is the weighted least squares procedure for calculating an ideal P-T from the ‘n’ equilibrium relationships. Such calculations are always over-determined; a statistical process is used to calculate the unknown's best value, with more constraints than the unknown. The $P\text{-}T_{av}$ involves locating the P-T condition with a small displacement from the P-T lines and representing equilibrium relationships [99, 100]. The P-T conditions were determined by the use of the P_{av}, T_{av}, and PT_{av} methods, employing probe data obtained from minerals and the THERMOCALC software version 3.47 [99]. The thermodynamic dataset used was tc-ds62.txt [80], which was adjusted to adhere to the activity models proposed by [169].

7. B.3 Application of geothermobarometers and Average PT

Precisely determining the pressure-temperature (P-T) conditions is of utmost importance in comprehending the thermal state of the lithospheric mantle, whether in the past or in the present. The acquisition of accurate and precise geothermobarometric data is essential for obtaining trustworthy estimations of pressure-temperature (P-T) conditions. [439].

7. B.3.1 Mafic granulite

Mafic granulites of Betul Belt contain orthopyroxene + clinopyroxene + plagioclase as a dominant assemblage (sample CH-03, CH-06). Hornblende and biotite have low availability in the rock, but their textural relationship with opx and cpx shows prograde metamorphic condition. The temperature conditions at a fixed pressure of 7 kbar were quantified using the clinopyroxene-orthopyroxene conventional geothermometer, as shown in Table 7.1. The temperature range of mafic granulites was seen to fluctuate between 845 and 904°C, as indicated in Table 7.2. Similarly, the temperature conditions associated with the exsolution texture of Opx-Cpx exhibited a range spanning from 811 to 945°C, as documented in Table 7.1. The findings pertaining to the estimated pressure-temperature (P-T) conditions are presented in Table 7.2. The model presented a peak temperature of 945°C, but alternative models (e.g., [429, 430]) yielded lower temperatures in comparison. The Garnet Clinopyroxene geothermometer is employed to determine the temperature conditions, yielding an estimated temperature range of 804–893°C. Additionally, the Garnet-Clinopyroxene-Plagioclase-Quartz geobarometer suggests that the pressure falls within the range of 8.19–8.99 kbar, as indicated in Table 7.3. The T_{av}, P_{av}, and PT_{av} values were determined through the analysis of various metamorphic phases, which involved the consideration of independent reactions (using THERMOCALC) between orthopyroxene, clinopyroxene, plagioclase, and amphibole end member minerals. The T_{av} calculation was conducted assuming a pressure of 7 kbar, taking into account the low activity of H_2O in the mineral phases, with an activity of H_2O equal to 0.25. The obtained T_{av} value was determined to be 899°C, with a standard deviation of 1.03. However, the P_{av} value was determined at a temperature of 800°C, using the same activity of H_2O. The calculated P_{av} value was found to be 8.99 kbar, with a standard deviation of 1.07 (σfit = 1.07). In addition, the pressure-temperature average (PTav) was determined to be 8.66 kbar at a temperature of 900°C, while the fitting standard deviation (σfit) was found to be 1.08.

7. B.3.2 Pelitic granulite

The temperature conditions at a constant pressure of 8 kbar were determined using the garnet-biotite geothermometer. The calculated temperatures ranged from 716 to 806°C, and garnet biotite- plagioclase-quartz geobarometer inferred that the pressure lie at 8.47. However, garnet cordierite geothermometer provides the temperature condition ranges from 661 to 717°C, whereas the pressure estimation was conducted using a garnet-cordierite-biotite-quartz geobarometer, yielding a range of 5.35 to 6.24 kilobars. The P-T condition results are shown in Table 8.3. The T_{av}, P_{av}, and PT_{av} were estimated from different metamorphic phases, including independent reactions among garnet, cordierite, biotite, and plagioclase end-member minerals. The P_{av}, T_{av} and PT_{av}

calculation for peak metamorphism was 5.85±1.86 kbar, 726±86°C and 5.94±1.7kbar/676±86°C, respectively.

PART – C: Bulk Composition Modelling

7. C.1 Application of equilibrium thermodynamics

Advances in the understanding of the thermodynamic behaviour of metamorphic phases, both rock-forming and accessory constituents [98, 103, 437, 440, 441], permit the calculation of average conditions of crystallization and quantitative phase diagrams for mineral systems thought to record chemical equilibrium. This methodology offers a robust tool for determining pressure-temperature trajectories of metamorphic rocks that have undergone exhumation. To calculate geologically accurate P-T-X relations from metamorphic rocks, it is critical that the system's mineral phases are shown to represent a state of thermodynamic equilibrium.

Given that metamorphism is a dynamic process, with P, T and X changing throughout a metamorphic rock's evolution, it is uncertain whether the chemical equilibrium is a valid assumption. The kinetics of intergranular diffusion exerts a dominant control on time and length scales of metamorphic equilibration [442]. Quantitative knowledge of intergranular diffusion rates for major and trace elements remains unknown. However, an intergranular fluid phase is known to promote higher rates of elemental exchange and hence, metamorphic equilibration [443]. Accordingly, prograde (dehydration) metamorphic reactions proceed more rapidly than retrograde (hydration) reactions, accounting for the common preservation of mineral assemblages formed under peak 'T' conditions. Despite theoretical validation of the equilibrium condition, commonly observed coronal microstructures [444,445], linked segregations [446] and pseudomorphous growth structures [447] provide petrographic evidence for chemical disequilibrium, where reactions ceased prior to the total consumption of reactants. Such evidence is most commonly found in H2O under-saturated conditions and suggests sluggish intergranular diffusion kinetics. Accordingly, it is fundamentally essential to screen samples for petrographic evidence of disequilibrium before applying equilibrium thermodynamic principles. The equilibrium model of metamorphism cannot be 'proved' in the same way as disequilibrium; instead, the absence of disequilibrium features is generally taken as supporting evidence. Furthermore, equilibrium assemblages must obey the phase rule ($F = C + 2 - P$, where F = variance, C = number of components, and P = number of phases present) and show consistent element partitioning between co-genetic phases.

Accepting the valid application of equilibrium thermodynamics to metamorphic rocks, thermodynamic descriptions of relevant phases [448] are combined with activity composition models (a-x) describing the energetics of end-member phase interaction, to permit calculation of the assemblage's peak P-T. Initially, this approach was limited to precisely calibrated reactions [426], followed by consideration of numerous reactions, which allowed calculation of average P-T conditions [99,100,440,449]. However, such thermobarometry is limited by a dependence on mineral chemistry-inherent to the method’s inverse nature. Improvements in the quality and breadth of thermodynamic data and a-x relations based on the same phase end-member compositions (internally consistent datasets – [99,101,103], underpinned the development of forwarding phase equilibria modelling, i.e. given a reactive composition, P-T, P-X, or T-X relations (pseudosections) can be calculated for all phases in the system of interest.

7. C.2 Pseudosection modelling

Currently, the most robust technique utilised for extracting pressure-temperature (P-T) data from exposed metamorphic rocks is pseudosection modelling [171,450,451]. Pseudosections arose from the construction of petrogenetic grids, which show all the invariant points and univariant lines for all phases and bulk composition in a chemical system [173,452]. Such grids provide information regarding the absolute stability of assemblages; however, they do not provide information regarding the composition and abundance of phases. Pseudosections provide a means by which the system’s petrogenetic grid is modified for a specific bulk composition-effectively forming a mineral assemblage map in P-T-X space [171].

The validity of the pseudosection approach relies on an accurate determination of the reactive bulk composition. As discussed above, the length scales of diffusive equilibration are poorly constrained in metamorphic rocks, making this the most significant source of uncertainty inherent to the technique. Rocks containing zoned porphyroblasts are particularly challenging to model as the effective bulk composition changes with porphyroblast growth, meaning that pseudosection topology will vary as a function of time. This effect is typified by garnet's growth, which preferentially sequesters Mn during early growth stages [453]. It is possible to mitigate against reactive volume fractionation by selecting a suitable composition of garnet - i.e., from core (initiation of growth) to rim (cessation of growth) portions-to calculate the bulk composition. Pseudosections presented in this chapter are based on bulk compositions calculated from combining mineral modes unless otherwise stated.

7. C.3 Methodology

The phase diagram has been calculated using the Perple_X 6.9.0 program, which includes various sub-programs. The pseudosection is a diagram showing the various reaction conditions in the P-T space, adapted to a particular bulk composition. The bulk rock compositions used for the pseudosection computations were derived from the whole-rock XRF study conducted at the Birbal Sahni Institute of Palaeosciences (BSIP) in Lucknow, India. Initially, it is necessary to execute the Build programme, incorporating computational option files. Subsequently, the Vertex programme should be executed to compute the phase diagram. The "Perple_X solution model glossary" and "Perple_X Updates" provide comprehensive information regarding the solution models. These resources can be accessed at http://www.perplex.ethz.ch/perplex_updates.html. After this, the Pssect program is run that usually takes a long time to generate a postscript plot. The crude diagrams are to be finalized in any other graphic editor software. For the generation of the isopleths, the Pywerami program is employed.

7. C.4 P-T Pseudosections

7. C.4.1 Mafic granulites

In order to examine the pressure-temperature (P-T) conditions of the mafic granulite sample CH-03, a P-T pseudosection was generated using the NCKFMASHTO system ($Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–O$) and the Perple_X 6.9.0 software [78, 79]. The thermodynamic data for the end-members were obtained from [80]. Various solution models were employed to analyse different minerals, including clinopyroxene and amphibole (G: [58]), garnet, orthopyroxene, and biotite (W: [169]), plagioclase (feldspar: [456]), and ilmenite (WPH: [457]). Quartz, on the other hand, was considered as a pure end-member. The weight percent (wt%) of the bulk rock sample N-7A was converted to mol% in the model system. The resulting mol% composition is as follows: SiO_2=51.18, TiO_2=0.56, Al_2O_3=15.07, FeO=11.68, MgO=5.37, CaO=1.04, Na_2O=2.11, K_2O=0.17, H_2O = 1.16, and O_2 = 0.48. The evaluation of the O_2 (Fe_2O_3) involved the integration of mineral compositions and modal abundance data related to the phases seen inside the rock. The determination of H_2O content was conducted by assessing the quantities of hydrous mineral phases, specifically amphibole and biotite. Amphibole, with a water content of approximately 2-3 wt%, and biotite, with a water content of around 5-6 wt%, comprised approximately 15% and 5% of the overall volume of the rock, respectively. Consequently, it was proposed that the bulk rock composition contains around 0.8 weight percent H_2O.

Figure 7.4 displays the PT pseudosection of mafic granulite, specifically referring to sample CH-03. Assemblages containing orthopyroxene were observed to arise at elevated temperatures. The mineral assemblages that were observed through petrographic research were stable within a pressure-temperature (PT) range of greater than 8.0 to 8.5 kilobars and around 700 to 850 degrees Celsius. The peak mineral assemblages were most accurately characterised by the presence of clinopyroxene, orthopyroxene, hornblende, plagioclase, ilmenite, and quartz, as seen in Figure 7.4. The construction of the P-T pseudosection for mafic granulite was undertaken by delineating the X_{Mg} isopleths of Hbl, Opx, and Cpx. Additionally, the P-T conditions were determined using isopleth lines and the presence of quartz, as indicated in Figure 7.4. The isopleth line of orthopyroxene with X_{Mg} values ranging from 0.403 to 0.468, and clinopyroxene with X_{Mg} values ranging from 0.590 to 0.635, was identified as representing a pressure-temperature (P-T) range of 8.0 to 8.5 kbar and a temperature range of 780 to 800ºC. The recognised stability of this mineral phase within the peak host assemblage is characterised by a certain pressure-temperature (P-T) range. Furthermore, the P-T pseudosection reveals the presence of magnetite-bearing fields that occur at lower temperatures.

Figure 7.5 displays the PT pseudosection of mafic granulite, specifically pertaining to sample N-7. Assemblages containing orthopyroxene were observed to arise at elevated temperatures. The mineral assemblages that were observed through petrography were stable within a pressure-temperature (PT) range of greater than 8.0 to 8.5 kilobars and around 750 to 850 degrees Celsius. The field encompassing garnet, clinopyroxene, orthopyroxene, hornblende, plagioclase, ilmenite, and quartz (refer to Figure 7.5) provided the most accurate characterization of the peak mineral assemblages. The construction of the P-T pseudosection for mafic granulite was undertaken by delineating X_{Mg} isopleths for the minerals Grt, Hbl, Opx, and Cpx. Additionally, P-T conditions were determined using isopleth lines and quartz as indicated in Figure 7.5. The isopleth lines of garnet, orthopyroxene, and clinopyroxene were delineated based on their respective X_{Mg} values: 0.257-0.317 for garnet, 0.369-0.408 for orthopyroxene, and 0.561-0.603 for clinopyroxene. These isopleth lines correspond to a pressure range of 8.0 to 8.5 kbar and a temperature range of 790 to 840ºC, thereby defining the P-T conditions within this range. The recognised stability of this mineral phase within the peak host assemblage was seen within a certain range of pressure and temperature (P-T).

7. C.4.2 Pelitic granulite

In this research, we have applied a similar version and model system as that employed for mafic granulites to construct the P-T pseudosection for pelitic granulites. X-ray fluorescence (XRF) analysis was employed to ascertain the weight percentage of the bulk composition of pelitic granulite (BK-5). This data was subsequently translated into mole percentage in order to facilitate the calculation of pseudosections. The composition of the BK-5 sample is as follows: SiO_2 accounts for 63.12 mol%, TiO_2 accounts for 0.24 mol%, Al_2O_3 accounts for 18.21 mol%, FeO accounts for 6.29 mol%, MgO accounts for 1.21 mol%, CaO accounts for 0.36 mol%, Na2O accounts for 2.59 mol%, K_2O accounts for 2.94 mol%, H_2O accounts for 3.74 mol%, and O_2 accounts for 0.52 mol%. Various solution models are employed in the construction of the pseudosection, including garnet, biotite, cordierite [169]; melt [58]; Plagioclase [456]; ilmenite [457], together with some pure end-member phases such as aluminosilicate (sillimanite), quartz, and H2O. The pelitic granulite has a low concentration of MnO, which consequently excludes it as a constituent in the pseudosection computation.

The pseudosection has prominent garnet-bearing domains with a substantial degree of variability, as shown by high variance values ranging from 3 to 6. The pre-peak metamorphic phase is characterised by the presence of cordierite, orthopyroxene, and quartz crystals as inclusions inside garnet. These minerals are observed to exist under conditions of relatively low temperature and pressure. The pre-peak metamorphic conditions are observed at around 4.2 kilobars of pressure and 620°. These conditions are determined by examining the X_{Mg} isopleth contour lines of garnet and cordierite, which closely match the analysed microprobe data. The pressure-temperature stability range for the peak assemblage, consisting of garnet, biotite, orthopyroxene, sillimanite, potassium feldspar, melt, ilmenite, and quartz, spans from 6.8 to 7.2 kilobars and 750 to 800°. The peak metamorphic condition observed in this study is a result of the delineation of the X_{Mg} isopleths line of garnet and biotite, as depicted in Figure 9. The pseudosection is predominantly characterised by the presence of tetravariant fields. The assemblage in NCKFMASHTO exhibits tetravariant behaviour and is characterised by the presence of pentavariant biotite at high temperatures, whereas trivariant magnetite-bearing fields are observed at low pressures and temperatures. The borders between cordierite-in and sillimanite-out assemblages delineate the stability of the assemblage at lower pressure conditions. The phenomenon of isothermal decompression retrograde reaction has been documented through petrographic analysis. This reaction involves the conversion of garnet into cordierite under low pressure conditions. The observed process can be represented as follows: Grt + qz → crd + opx + melt. The presence of garnet, biotite, and sillimanite in mineral assemblages is noted to be stable under high pressure conditions, but cordierite-bearing assemblages are more commonly found in the low-pressure equilibrium region within the pseudosection. In the Pre-peak metamorphic stage, cordierite is observed as an inclusion within garnet porphyroblast, displaying a higher X_{Mg} value in the stable mineral assemblages. In contrast, the retrograde metamorphic stage is characterised by the occurrence of cordierite in the matrix, demonstrating somewhat lower X_{Mg} values. The examination of the textural characteristics suggests that the retrograde metamorphic assemblage inside the P-T pseudosection comprises of garnet (grt), cordierite (crd), biotite (bt), plagioclase (plg), potassium feldspar (kfs), melt, ilmenite (ilm), and quartz (qz). These mineral phases remain stable at a pressure of around 5.5 kilobars and a temperature of around 800°C.

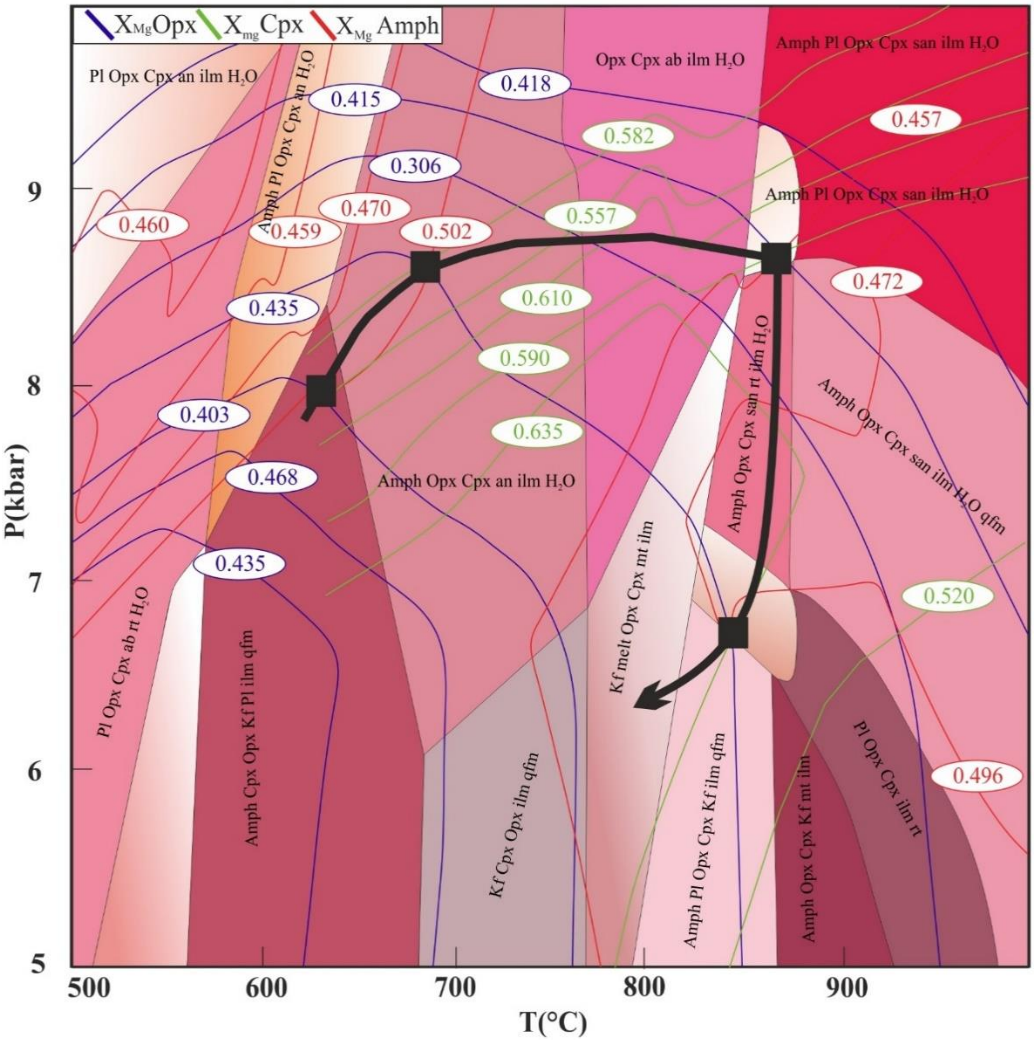

Figure 7.4. P–T pseudosection plot is calculated for mafic granulites from the Betul Belt in the system NCKFMASHTO. The pseudosection is contoured with isopleths of X$_{Mg}$ of Amphibole, Opx and Cpx mineral assemblages. The mineral abbreviations are used by [279].

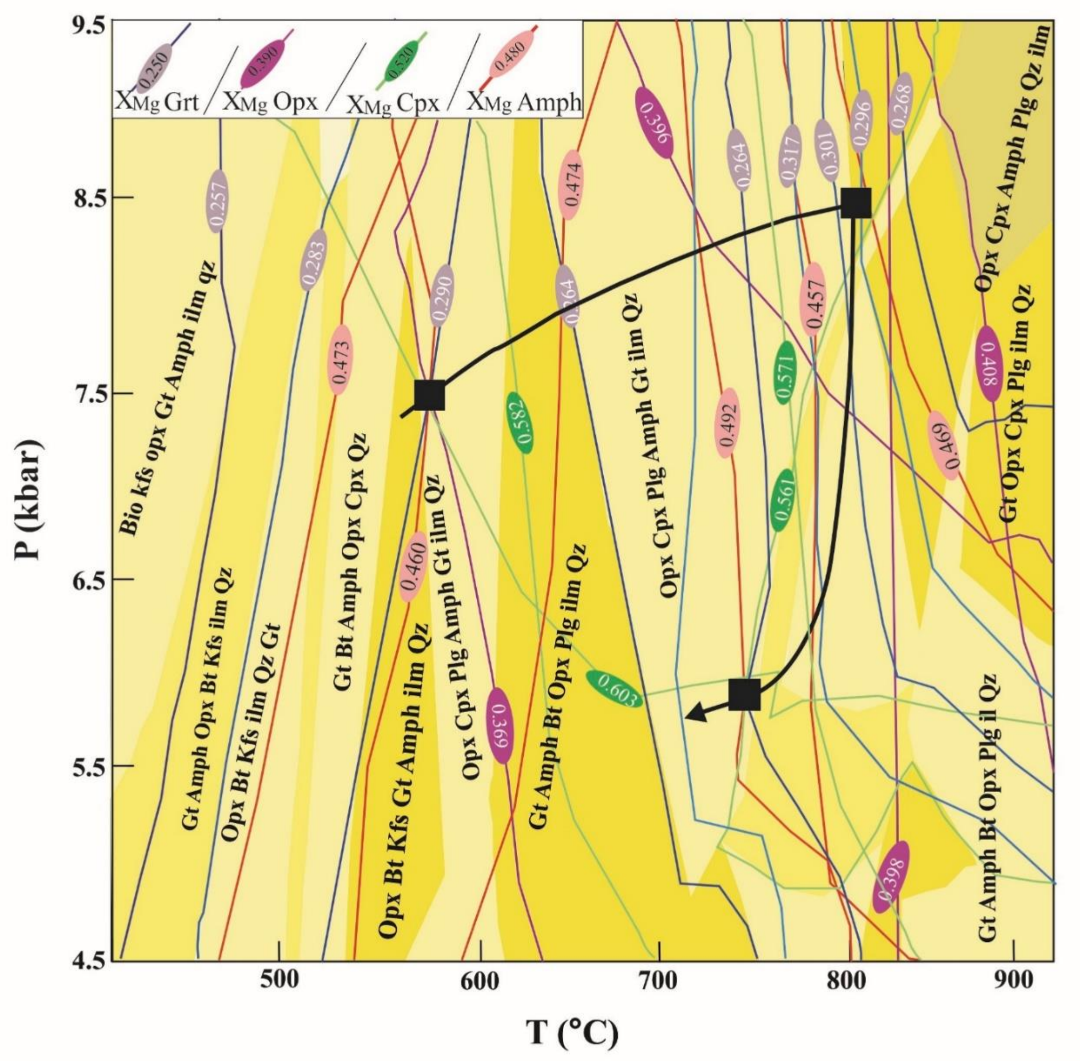

Figure 7.5. P–T pseudosection plot is calculated for mafic granulites from the Betul Belt in the system NCKFMASHTO. The pseudosection is contoured with isopleths of X_{Mg} of Garmet, Amphibole, Opx and Cpx mineral assemblages. The mineral abbreviations are used by [279].

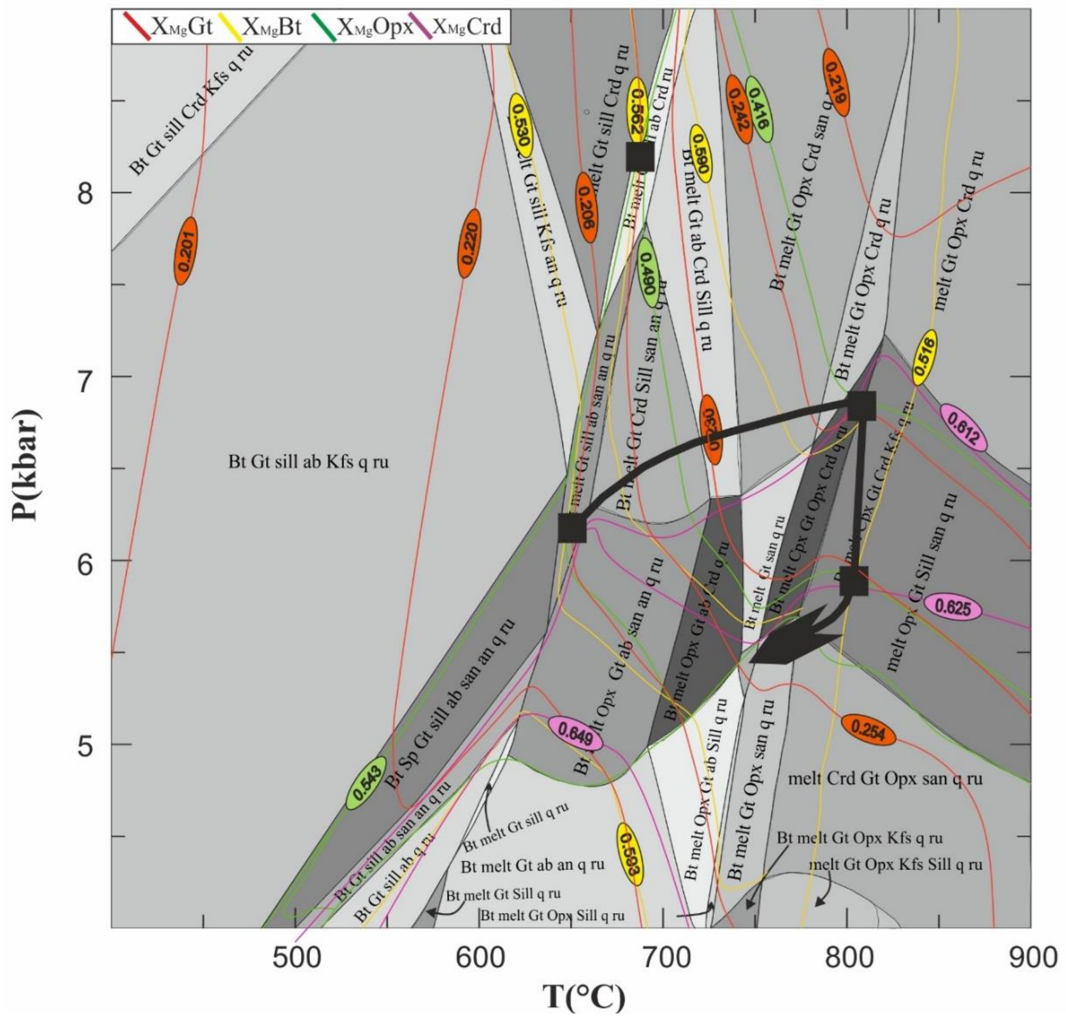

Figure 7.6. P–T pseudosection plot is calculated for pelitic granulites from the Betul Belt in the system NCKFMASHTO. The pseudosection is contoured with isopleths of X_{Mg} of Garnet, Biotite, Opx and Crd mineral assemblages. The mineral abbreviations are used by [279].

Table 7.1. Temperature estimates of mafic granulites of Betul Belt from conventional exchange geothermometer at assumed pressure.

Sample No.	**Models**		
	[429]	[430]	[431]
CH-03	820	867	850
CH-04	832	884	878
CH-06	846	862	897
CH-12	795	829	945
N-14	803	852	876
BG-03	811	879	901
Average	818±25	862±30	892±45

Table 7.2 Pressure and temperature estimates of mafic granulites of Betul Belt using internally consistent dataset by Thermocalc v3.21.

Sample No.	**Average Pressure in kbar (P_{av})**	**Average temperature in °C (T_{av})**	**Average Pressure and Temperature (P-T_{av})**
CH-03	8.58±1.2	845±42	894±45 °C / 9.31±1.5 kb
CH-04	9.43±1.3	963±45	879±55°C / 8.44±1.6 kb
CH-06	8.87±1.5	896±35	905±40 °C / 8.73±1.2 kb
CH-12	9.12±1.5	904±50	927±35°C / 8.24±1.5 kb
N-14	8.98±1.5	892±30	902±30°C / 8.52±1.5 kb
BG-03	9.01±1.5	894±45	890±40 °C / 8.73±1.5 kb
Average	8.99±1.5	899±50	900±25 °C / 8.66±1.5 kb

Table 7.3 Temperature estimates of mafic granulites from conventional garnet – clinopyroxene exchange geothermobarometer at assumed pressure 7 kbar.

N-14				**BG-03**			
	At 7 kbar		**At 800°C**		**At 7 kbar**		**At 800°C**
A	824°C	**A**	8.28 kbar	**A**	838°C	**A**	8.47 kbar
B	853°C	**B**	8.19 kbar	**B**	852°C	**B**	8.62 kbar
C	877°C	**C**	8.57 kbar	**C**	893°C	**C**	8.99 kbar
D	804°C			**D**	821°C		
Average	840±37°C	**Average**	8.34±0.23 kbar	**Average**	851±40°C	**Average**	8.69±0.30 kbar

Note: In Grt-Cpx geothermometry, Models of, A = [428]; B = [458]; C = [459]; D = [460]

In Grt-Cpx-Plg-Qz geobarometry, Models of, A = [461]; B = [98]; C = [462].

Table 7.4 Result of internally consistent geothermobarometry of (mafic granulite) orthopyroxene, clinopyroxene, plagioclase and amphibole as end-member with THERMOCALC v-3.47 [102] for sample CH-03.

(a) Reactions used to calculate **average temperature (T_{av})** (for x(H_2O) = 0.25)			
Independent set of reaction	T in°C	Sd(T)	Sd(lnK)
1) en + 2hed = fs + 2di	864	395	0.39
2) en + fs + 2cats = 2mgts + 2hed	701	728	2.47
3) 5mgts + 5hed + fact = 5fs + 5cats + tr	753	669	5.01
4) 7fs + 10cats + 2tr = 10mgts + 14hed + 2q + 2H_2O	795	351	6.54
5) 3tr + parg = 5en + mgts + 8di + ab + 4H_2O	868	52	2.11
6) 2parg + 6q = 3en + 2di + 2jd + 2an + 2H_2O	803	297	2.13
7) 7tr + 2parg = 12en + 16di + ts + 2ab + 8H_2O	824	167	8.87
8) 2en + 2jd + 2fact = 5fs + 4di +2ab + 2H_2O	796	174	2.96
	T_{av}	sd	σ fit
Average Temp(°C)	849	62	1.12
(b) Reactions used to calculate **average pressure (P_{av})** (for x(H_2O) = 0.25)			
Independent set of reaction	P (kbar)	Sd (P)	Sd(lnK)
9) 8mgts + 8hed + tr + 8q = 8en + fact + 8an	7.2	5.24	5.24
10) 4en + parg + 3an = 4mgts + 3di + jd + tr	6.4	6.47	4.01
11) en + parg + 3an = mgts + 3cats + jd + tr	8.1	2.39	1.54
12) mgts + parg + 4an = en + 4cats + ts + ab	7.8	7.71	7.32
13) 2parg + 6an = 6cats + 2jd + tr + ts	6.1	6.25	7.39
14) 4en + 3hed + 3parg + 5an = fs + 7cats + 6jd + 2tr	8.6	2.98	3.97
15) 25en + 4fact + 5parg + 20an = 25mgts + 20hed + 9tr + 5ab	7.8	8.10	9.84
16) 31cats + 5fact + 15ts + 16ab = 11fs + 12parg + 60an + 10H_2O	6.1	4.26	22.84
	P_{av}	sd	σ fit
Average Pressure in kbar	8.43	2.79	1.24

(c.) Reactions used to calculate **average pressure and temperature (PT_{av})** (for x(H_2O) = 0.25)						
Independent set of reaction						
17) mgts + di + q = en + an						
18) 2mgts + tr + 2q = 5en + 5an + 2H_2O						
19) 5mgts + 5hed + tr + 5q = 5en + fact + 5an						
20) 2mgts + 10hed + 2tr = 5fs + 12di + 2an + 2H_2O						
21) 2mgts + 4hed + ts +4q = 2fs + tr + 4an						
22) 4en + parg + 3an = 4mgts + 3di + jd + tr						
23) 3en + parg + 4an = 3mgts + 4di + ts + ab						
24) en + parg + 3an = mgts + 3cats + jd + tr						
Single end member diagnostic information of (PT_{av})	P_{av}	Sd	T_{av}	Sd	Cor	σ fit
7.79±1.20 kbar/852±55°C	8.39 kbar	1.31	838°C	71	0.151	1.12

NOTE: where mineral abbreviations are; ab = albite, an = anorthite, cats = cassiterite, di = diopside, en = enstatite, fact = ferroactinolite, fs = ferrosilite, hed = hedenbergite, jd = jadeite, mgts = margarite, parg = pargasite, q = quartz, tr = tremolite, ts = tschermakite

Table 7.5 Temperature estimates of pelitic granulites from conventional geothermometery.

Grt-Bt geothermometer (at 8 kbar)			Grt-Crd geothermometer (at 6 kbar)	
Models		BK-5	Models	BK-5
1.	[86]	762°C	[86]	724°C
2.	[426]	745°C	[90]	706°C
3.	[463]	806°C	[91]	708°C
4.	[464]	754°C	[92]	726°C
5.	[87]	736°C	[93]	717°C
6.	[465]	798°C	[84]	737°C
7.	[466]	802°C	[95]	749°C
8.	Average	772±29°C	Average	723±25°C

Table 7.6 Pressure estimates of pelitic granulites from conventional geobarometery.

Grt-Bt-Plg-Qz geobarometer (in kbar) (at 800°C)		
	Model	BK-5
1.	[467]	7.21

Grt-Crd-Sill-Qz geobarometer (kbar) (at 600°C)		
	Models	BK-5
1.	[86]	6.89
2.	[91]	6.95
3.	[96]	6.57
4.	[468]	6.58
5.	[469]	6.65
6.	[84]	7.10
7.	Average	6.79±0.24

Table 7.7 Result of internally consistent geothermobarometry of garnet, cordierite, biotite and plagioclase end-member with THERMOCALC v-3.33 ([103] for sample BK-05.

<table>
<tr><td colspan="7">(a) Reactions used to calculate average temperature (T_{av}) (for x(H_2O) = 0.5)</td></tr>
<tr><td colspan="2">Independent set of reaction</td><td colspan="2">T in°C</td><td colspan="2">Sd(T)</td><td>Sd(lnK)</td></tr>
<tr><td colspan="2">1) 2py + 3fcrd = 2alm + 3crd</td><td colspan="2">752</td><td colspan="2">149</td><td>2.43</td></tr>
<tr><td colspan="2">2) py + ann = alm + phl</td><td colspan="2">649</td><td colspan="2">214</td><td>2.26</td></tr>
<tr><td colspan="2">3) 5alm + 3east + 9q = 2py + 3fcrd + 3ann</td><td colspan="2">723</td><td colspan="2">68</td><td>0.61</td></tr>
<tr><td colspan="2"></td><td colspan="2">T_{av}</td><td colspan="2">sd</td><td>σ fit</td></tr>
<tr><td colspan="2">Average Temp (°C)</td><td colspan="2">708</td><td colspan="2">71</td><td>1.09</td></tr>
<tr><td colspan="7">(b) Reactions used to calculate average pressure (P_{av}) (for x(H_2O) = 0.5)</td></tr>
<tr><td colspan="2">Independent set of reaction</td><td colspan="2">P (kbar)</td><td colspan="2">Sd (P)</td><td>Sd(lnK)</td></tr>
<tr><td colspan="2">4) 3py + 2ann + 3east + 9q = 3crd +5phl</td><td colspan="2">6.17</td><td colspan="2">1.56</td><td>1.79</td></tr>
<tr><td colspan="2"></td><td colspan="2">P_{av}</td><td colspan="2">sd</td><td>σ fit</td></tr>
<tr><td colspan="2">Average Pressure in kbar</td><td colspan="2">6.17</td><td colspan="2">1.56</td><td>1.79</td></tr>
<tr><td colspan="7">(c.) Reactions used to calculate average pressure and temperature (PT_{av}) (forx(H_2O) = 0.5)</td></tr>
<tr><td colspan="7">Independent set of reaction</td></tr>
<tr><td colspan="7">5) 2spss + 6an + 3q = 2gr + 3mncrd
6) py + east + 3q = crd + phl
7) py + ann = alm + phl</td></tr>
<tr><td>Single end member diagnostic information of (PT_{av})</td><td>P_{av}</td><td>Sd</td><td>T_{av}</td><td>Sd</td><td>Cor</td><td>σ fit</td></tr>
<tr><td>6.4±0.8 kbar/680±55°C</td><td>6.40 kbar</td><td>1.7</td><td>676°C</td><td>86</td><td>0.56</td><td>0.82</td></tr>
</table>

NOTE: where mineral abbreviations are; alm = almandine, an = anorthite, ann = annite, crd = cordierite, east = eastonite, fcrd = ferro-cordierite, gr = garnet, mncrd = magnesio-cordierite, phl = phlogopite, py = pyrope, q = quartz, spss = spessartine