

# **METAMORPHIC EVOLUTION**

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This chapter attempts to discuss the tectono-metamorphic evolution considering petrographic evidence, geochronological evidence, P-T-t path, and geodynamic conditions. The metamorphic evolution of the study area around Makrohar reveals of a wide variety of rocks, which are affected by two stages of metamorphism (M1 to M2). Makrohar area has well preserved the Mesoproterozoic and Neoproterozoic age, and it leads to the CGGC which was the part of Columbia and Rodinia supercontinent.

### **8.1 Metamorphic condition**

Various techniques are employed to uncover the geological history of Makrohar granulite belt, yielding essential datasets that help elucidate its metamorphic evolution. The historical records of granulites are preserved in diverse mineral assemblages and associations found in different rock types, along with their various fabrics and textural relationships. Besides the importance of textural relation, other crucial factors such as the composition of major, trace, and rare earth elements, as well as their isotopic composition, offer valuable insights into the origin and development of the rocks. The primary aim of determining pressure-temperature (P-T) conditions and calculating mineral equilibria is to decipher pertinent details about granulitic rocks, offering reliable information about their burial and exposure at the Earth surface over geological time. To investigate the metamorphic evolution of the Makrohar granulite belt, a comprehensive set of tools was employed, including petrography, mineralogy, geochronology geothermobarometry, phase equilibria

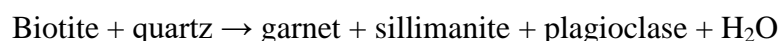
modeling, and geochemistry. Based on these methodologies, the construction of the P-T-t path was undertaken to unveil the metamorphic evolution of study area.

### **8.1.1 Petrographic evidences**

Metamorphic petrology is utilized to decipher the microscopic structural record and mineral compositions left behind on pre-existing sedimentary, igneous, and metamorphic rocks. These imprints show how rocks are formed through subduction, accretion, and collisional orogenesis, which involve burial and exhumation as well as heating and cooling. Petrologists study a various activities, focusing on understanding the pressure-temperature-time (P-T-t) changes that rocks undergo in both spatial and temporal contexts. The P-T-t paths provide data for understanding subduction and collisional orogenesis and by integrating this P-T-t data, we gain insights into the geodynamic and tectono-metamorphic evolution of study area.

#### **8.1.1.a Pelitic granulitePeak assemblage**

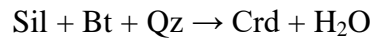
The peak metamorphic stage of pelitic granulite shown by the appearance of garnet + sillimanite + plagioclase by the disappearance of biotite and quartz, this reaction texture is represented by the inclusion of biotite and quartz in the garnet grains where sillimanite laths are present to adjacent with the garnet porphyroblast (Fig.4.2d).



#### **Post-peak assemblage**

The cordierite phase appearance results from isothermal decompression, which is represented by the post-peak assemblage of pelitic granulites, A likely

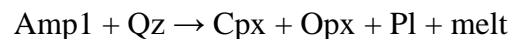
reaction pattern has been observed, as cordierite is formed by the ingesting of needles of sillimanite and biotite flakes (Fig.4.2f).



### **Mafic granulite**

#### **Peak assemblage**

The peak metamorphic assemblage has been recognized as Opx-Cpx-Bt-Amp1-Pl-Ilm-Qz, which contains amphibole and quartz partially or completely rimmed by orthopyroxene and clinopyroxene porphyroblast (Figs.4.3b). These textural features suggest a pre-peak prograde metamorphic condition.



#### **Post peak assemblage**

The post-peak metamorphic assemblage is defined by Amp2-Bt-Pl-Ilm-Qz. The post-peak condition in this rock is indicated by a few reaction textures, where amphibole is formed by the breakdown of orthopyroxene and clinopyroxene. Here amphibole is present as a majority in the matrix phases (Fig.4.3 d-e). The following reactions are inferred



#### **8.1.1.b Amphibolite Peak assemblage**

The formation of clinopyroxene crystals is noticed along with garnet porphyroblasts and amphibole (Fig.4.5d). The Grt-Cpx-Amp-Bt-Pl-Ilm-Qz assemblages in the garnetiferous amphibolites signifies the composition of the peak

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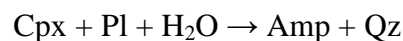
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metamorphic assemblage. The presence of amphiboles and quartz inclusions within garnet porphyroblasts and also amphiboles, which is partially or completely surrounded by clinopyroxene (Fig. 4.5 c,f). It implies that the peak metamorphic assemblage is formed by following reactions



### **Post-peak assemblage**

The mineral assemblages during post-peak metamorphism consist of Amphibole, Biotite, plagioclase, Ilmenite and quartz. The post-peak condition in this rock is signified by a few reaction textures, clinopyroxene and plagioclase partially or completely rimming by amphiboles (Fig.4.5 c- d). The following reactions are inferred the post-peak metamorphic stage



### **8.1.2 Geochronological evidences**

Understanding the tectonic history of a region relies heavily on the timing of sedimentation, the source of the precursor sediments in metapelitic rocks and the subsequent metamorphic changes after deposition are key factors in revealing tectonic history of the area (Dey et al. 2017). There are also Archean to Early Paleoproterozoic age constrain by detrital zircon of the metapelites rocks from NE CGGC near Dumka area, suggesting that sedimentation process lies between 1764 to 1650 Ma (Rekha et al., 2011) and 1696 to 1678 Ma (Dey et al., 2017) and also another age group have also found ~1800 Ma and ~1700 Ma from the northwestern portion of CGGC. The geochronological age data indicate that the northeastern and northwestern part of

CGGC received sediments from a same Paleoproterozoic source. The pelitic granulites found in the northeastern area of CGGC shows evidence of three metamorphic events occurring around 1640 Ma, 1450 Ma, and 950 Ma (Rekha et al., 2011; Dey et al., 2017). Similarly Late Paleoproterozoic (~1655 Ma) age and Neoproterozoic (~910 Ma) age domain are also found in the study area. The interpretations of geochronological age from different adjacent terrains are helpful to understand the source of sedimentary provenances. The protoliths of pelitic rocks deposited before the ~1655 Ma and further it experienced a vast tectonothermal activity during the Columbia assembly at 1655 Ma as M1 metamorphic event. However, rocks from Bundelkhand craton (Rao et al. 2005), Aravalli craton (Kaur et al. 2011, 2013), Lesser Himalaya (Kohn et al. 2010), Eastern Ghat Mobile belt (Bose et al. 2011), Mahakoshal Supracrustal belt (Yadav et al. 2020; Bora et al. 2013; Deshmukh et al. 2017) and Baster craton (French et al. 2008) are preserved ~1800 and ~1700 Ma age, so it is an excellent probability to sediments must have derive from these plausible sources.

Examinations of the pelitic granulites document the second metamorphic and deformation event occur around 910 Ma. The cordierite appearance indicates decrease in pressure conditions, also known as isothermal cooling, implying that this stage may have developed as a result of decompression and subsequent exhumation of pelitic granulites on the surface. The P-T condition and reaction texture are interpreted from the mineral assemblage, which shows that sillimanite and biotite are consumed to produce the garnet + cordierite mineral phases through the retrograde metamorphism.

### **8.1.3 P-T-t Path**

Three different thermodynamic approaches were utilized to estimate the

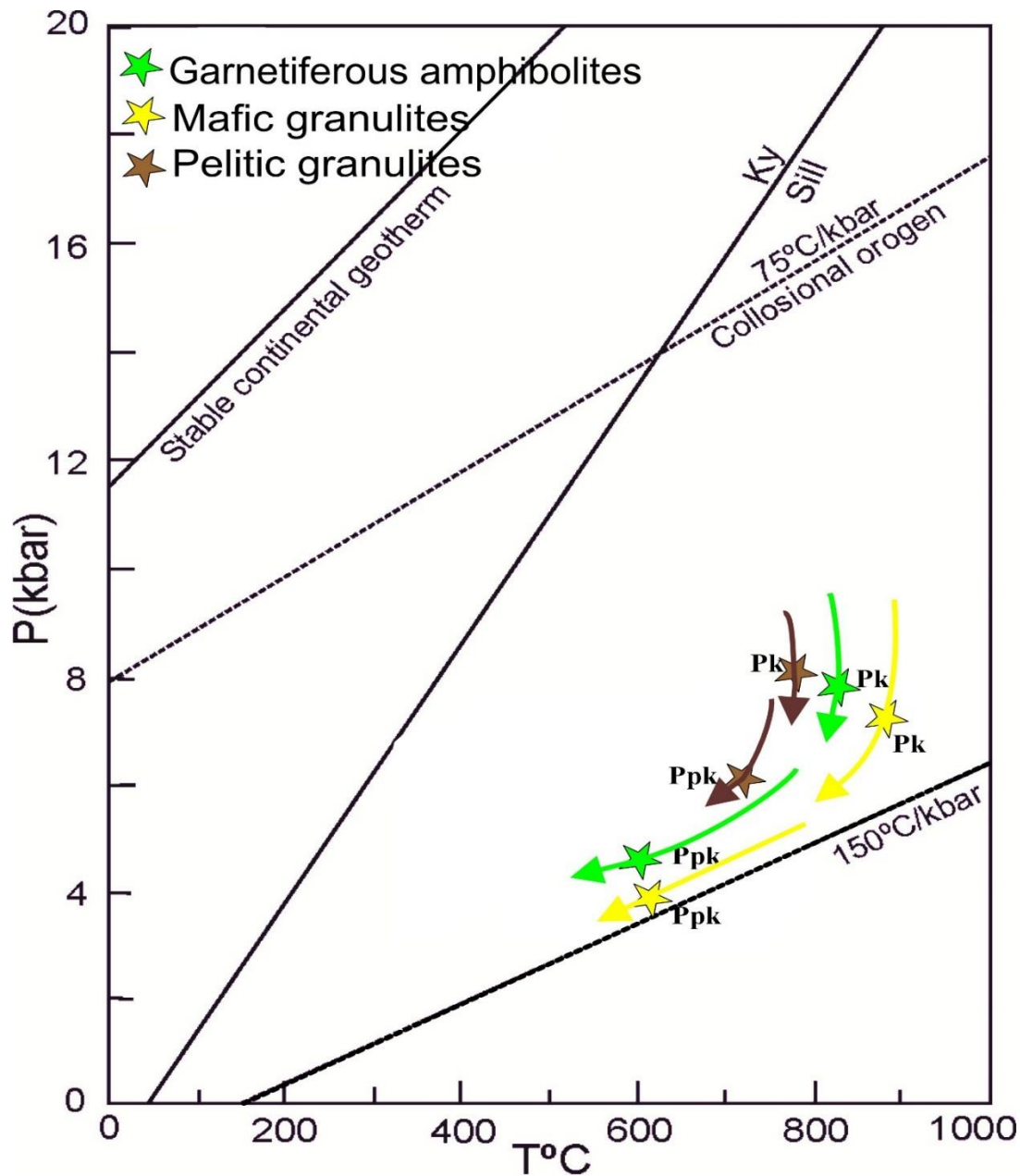
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pressure-temperature (P-T) conditions, including conventional geothermobarometry, multi-equilibrium geothermometry, and forward modeling. These methods yielded relatively consistent results for pelitic granulites, mafic granulites and garnetiferous amphibolites within the Makrohar granulite belt. P-T-t paths represent a trajectory in P-T space over time for a specific metamorphic terrain. They document the sequence of pressure and temperature conditions experienced by a rock types during regional metamorphism. P-T paths can be categorized into two main types: clockwise and counterclockwise. In the clockwise P-T paths, are commonly associated with a near-isothermal decompressional P-T trajectory and normally consists of three parts: Initial heating and compression until arriving a peak, then Near-isothermal decompression after the peak and further decompression and cooling at a slow rate. Whereas in the counterclockwise P-T path are commonly associated with a near-isobaric cooling P-T trajectory and consists of two parts: Initial heating and compression until reaching a peak, a low pressure-high temperature peak is often observed then Near-isobaric cooling after the peak. Accurate understanding of the evolution of P-T paths is essential for constructing tectonic models that explain the development of granulite terrains. P-T paths can be inferred by analyzing temperature and pressure estimates derived from the paragenetic sequence of minerals. The data obtained through geothermobarometry for the metamorphic rocks in the study area suggested that these high-grade rocks have undergone various geodynamic processes involving changes in temperature and pressure throughout Earth history and this metamorphic evolution of high-grade metamorphic rock over time is represented by a P-T-t path. Determining the pressure- temperature path of metamorphic rocks is a critical aspect of understanding their evolution, as it can provide insights into factors such as the

pressure and temperature conditions during peak metamorphism, local structural settings, and tectonic processes. Many researchers have used both qualitative and quantitative methods to calculate the pressure and temperature experienced by metamorphic rocks and their subsequent cooling or decompression during upliftment, contributing to our understanding of orogenic belt evolution over time (Marschall et al., 2003).

A combination of micro-textures, mineral prograde and retrograde reactions, and the  $P$ - $T$  estimates derived from mineral chemistry data of coexisting mineral pairs have been utilized to evaluate the different metamorphism grades  $P$ - $T$ - $t$  paths. Based on geological, petrographic and micro-textural studies, it is inferred that the various rock types in the study area have undergone a granulite facies metamorphism and suggest a distinct near Isothermal Decompression (ITD) path. A  $P$ - $T$ - $t$  path has been constructed for all three studied rocks which show the different metamorphic stages (Fig.8.1). The  $P$ - $T$  path for the Makrohar granulite belt has been determined using three distinct rock types: pelitic granulites, mafic granulite and garnetiferous amphibolites. Based on petrography and textural relations, mineral reactions during both the prograde and retrograde phases, and the  $P$ - $T$  estimations derived from the chemical composition of coexisting mineral pairs has been employed to assess the various grades of metamorphism and the corresponding  $P$ - $T$ - $t$  paths (Figure 8.1).



**Figure 8.1** The  $P$ - $T$  path has been constrained for Makrohar granulite belt, using three different rock types: pelitic granulites, mafic granulites and garnetiferous amphibolite, Where Pk: Peak P-T condition and Ppk: Post peak P-T condition.

### 8.1.3.a Pelitic granulite

The clockwise  $P$ - $T$ - $t$  path was determined through thermodynamic calculations and pseudosection modeling, focusing on pelitic granulites. The metamorphic sequence is as follows: In the peak stage, the rock undergoes burial, marked by significant changes in temperature conditions, indicating an increase in

pressure. During this phase, the P-T conditions reached high-pressure condition, ranging from 7.40 to 6.70 kbar and temperatures between 760 and 740°C during Late paleoproterozoic era. After the peak stage, the rock followed a nearly isothermal decompression path (ITD) as it transitioned into the post-peak stage during Neoproterozoic era. The post-peak stage is characterized by the presence of garnet and cordierite and with P-T conditions falling within the range of 4.80 to 4.60 kbar and 730 to 725°C. The geodynamic interpretation of the peak stage metamorphism in the study area suggests a single-cycle process involving subduction and exhumation, as evidenced by the complete clockwise P-T-t path. Various P-T-t paths have been proposed from different locations within the CGGC with most of them exhibiting characteristics of clockwise paths (Fig. 8.2).

#### **8.1.3.b Mafic granulite**

We have established evidence for two metamorphic stages from mafic granulites of Makrohar area using mineral assemblages, textural relations and conventional geothermobarometry. The clockwise  $P-T$  path is constrained by the conventional geothermobarometry of mafic granulites (Fig. 8.2). This  $P-T$  path generates two prominent metamorphic assemblages. The peak temperature estimates of coexisting orthopyroxene–clinopyroxene was  $887^{\circ} \pm 62^{\circ}\text{C}$  at a fixed pressure of 6 kbar. The pressure condition of the peak metamorphic stage was obtained using the two-pyroxene barometer of Mercier et al. (1984), which provided an estimate of  $6.15 \pm 0.3$  kbar. For the post-peak metamorphic stage, texturally equilibrated mineral assemblages Hbl<sub>2</sub>, Pl and Qz were selected to determine their P-T conditions. The pressure condition of the post peak metamorphic stage was obtained using the aluminum-in-amphibole barometer of Schmidt (1992), which provided an estimate of  $2.28 \pm 0.15$  kbar. The temperature estimates of the Amp–Pl–Qz thermometer of Holland and Blundy (1994), at pressure obtained using the aluminium-in-amphibole

barometer of Schmidt (1992) suggest a range  $593 \pm 50^\circ\text{C}$ .

### **9.1.3.c Amphibolite**

We have established evidence for two metamorphic stages from garnetiferous- amphibolites of Makrohar area using mineral assemblages, textural relations, and  $P$ - $T$  pseudosections. The clockwise  $P$ - $T$  path is constrained by the  $P$ - $T$  pseudosection of fromgarnetiferous-amphibolites (S-9) from the study area (Fig. 8.2). This  $P$ - $T$  path generates two prominent metamorphic assemblages, In the peak stage, the rock characterized by the mineral paragenesis Grt-Amp-Cpx-Bt-Pl-Qz- $\text{H}_2\text{O}$  and this field is stable at a  $P$ - $T$  range of 7.3–7.1kbar/810–790°C. The mineral assemblage of the post-peak metamorphic stage Amp-Bt-Pl-Qz- Ilm is stable at a  $P$ - $T$  range of 4.5 – 4.1 kbar/610–590°C, which acquires a Grt and Cpx freefield. This post-peak stage occurred after the peak stage as a result of a decompression process that resulted in a decrease in pressure conditions, also known as isothermal cooling, implying that this stage may have developed as a result of decompression and exhumation of amphibolites on the surface.

## **8.2 Geodynamic condition**

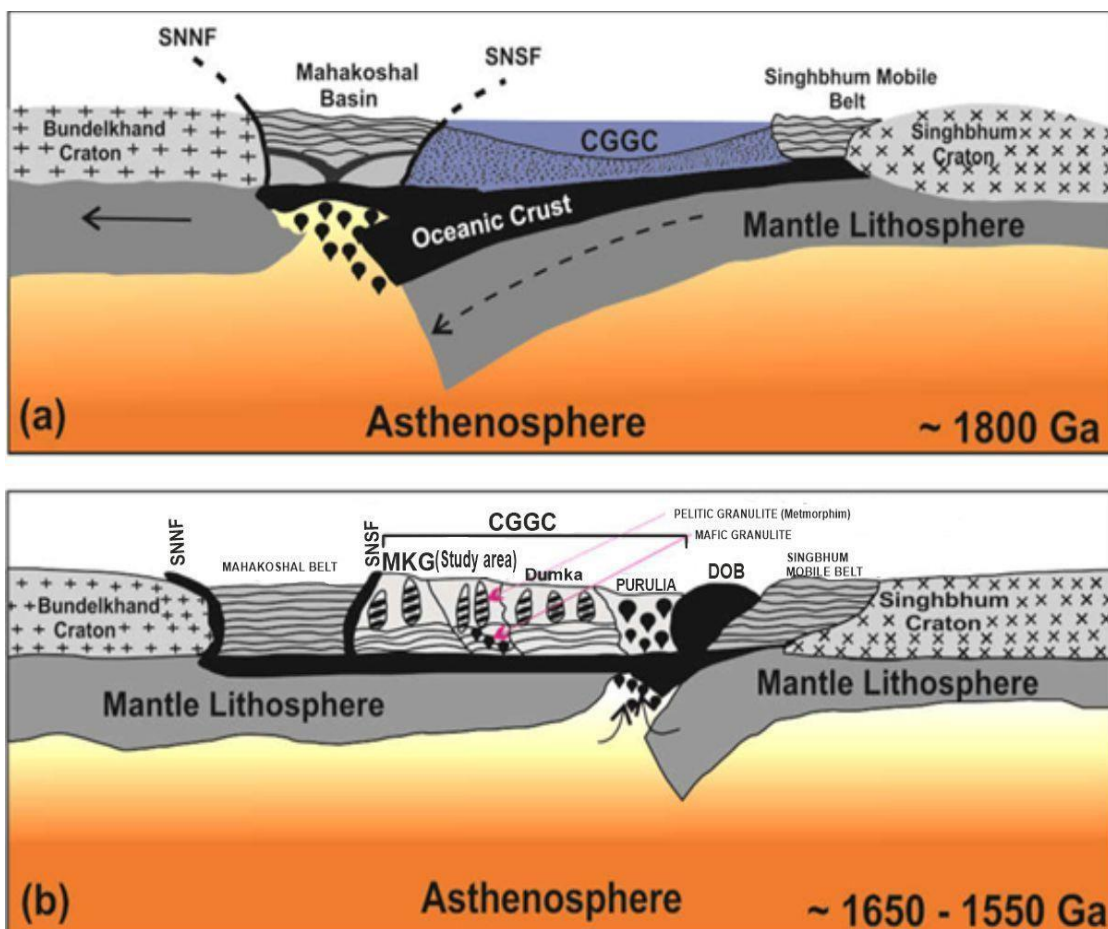
The geodynamic model proposes the existence of two Archean cratons, the Bundelkhand and Singhbhum cratons, alongside the nearby Baster craton. During the late Archean to Paleoproterozoic period, these cratons underwent rifting, resulting in the separation of the Bundelkhand and Singhbhum cratons and subsequently forming a sedimentary basin. The rift portion developed as a sink basin for sedimentation which arrived from the different sources as older Craton and Mobile Belt. The pelitic granulites in the study area exhibit a clockwise  $P$ - $T$  path. However, the peak  $P$ - $T$  conditions range from 6.70 to 7.40 kbar and 740 to 760°C, while the post peak  $P$ - $T$  conditions ranging from 4.60 to 4.80 kbar and 725 to 730°C. A nearly isothermal decompression  $P$ - $T$  path represents the continental collision or overthrusting (Cai et

al.2017).

The pelitic granulite of study area underwent a progressive phase of tectonothermal processes where initially occurrence of crustal thickening (M1) followed by quick exhumation of the crustal lithosphere (M2), these both processes indicate that collision or subduction-related tectonic processes. The presence of felsic magmatism in the northern part of the CGGC (1.76–1.66 Ga (Saikia et al. 2017), as well as in the adjoining area on the northern extent of CGGC (1.69 Ga: (Mukherjee et al., 2005), along with significant magmatic activity in the Mahakoshal Belt ~1.8–1.7 Ma (Yadav et al. 2020), indicates a subduction process. These occurrences point to the tectonothermal changes in the neighboring terrain of the CGGC basin during the late Paleoproterozoic era. Before the ~1.65 Ga age, there was a development of oceanic environment and deposition of the sediments from the adjacent terrain which contains the Paleoproterozoic volcano-sedimentary rocks. Moreover, it was a great chance to develop a rift basin or oceanic basin among the Singhbhum Mobile Belt and Mahakoshal Mobile Belt during the period of 1.86–1.65 Ga (Dey et al. 2020). Various sediment types were deposited within this oceanic basin, coinciding with the formation of HP/MT pelitic granulites around ~1.65 billion years ago due to the subduction of the oceanic lithosphere. This 1.65 billion-year-old age is the earliest metamorphic (M1) age observed in the northwest region of CGGC, where pelitic granulite stands out as the only rock representing the first metamorphism stage. A diagram demonstrates the progress of sedimentation and displays the pelitic granulites' protolith and M1 metamorphic stage, found in patches within the granitic gneisses of CGGC (Fig.8.2). Based on petrological studies, this metamorphic event around 1655 Ma is believed to have peaked at 6.7-7.4 kbar pressures, reaching temperatures of approximately 760 °C. The predominant metamorphic event found in various regions of the CGGC dates back to the early Neoproterozoic era, around 1000-950 million

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years ago (Chatterjee and Ghose, 2011; Karmakar et al., 2011; Sanyal and Sengupta, 2012). Geochronology using monazite dating places the age of this retrograde metamorphism at approximately 910 million years ago. The high-pressure peak metamorphism, followed by a rapid decrease in pressure, is believed to be linked to an exhumation event during the Neoproterozoic era. Similar pressure-temperature paths and conclusions have been reported from different parts of the CGGC by previous researchers (Chatterjee et al., 2010 ; Karmakar et al., 2011).



**Figure 8.2** A diagram demonstrates (a) the progress of sedimentation and displays the pelitic granulites' protolith and (b) M1 metamorphic stage, found in patches within the granitic gneisses of CGGC (modified after Mukherjee et al. 2018; Yadav et al. 2020).

### **8.3 THE CGGC AND THE SUPERCONTINENTAL CYCLE**

#### **8. 3.1. Correlation with the Columbia Supercontinent**

The Late Palaeoproterozoic era of Earth's history was significantly shaped by the emergence and breakup of the Columbia Supercontinent. Initially believed to have amalgamated between 2.1-1.8 billion years ago (Zhao et al., 2004; Rogers and Santosh, 2009)(Fig. 1.1a), recent publications have contested this, proposing a more prolonged joining process, suggesting the final consolidation occurred around 1450 million years ago (Sarkar and Schenk, 2016; Meert and Santosh, 2017). The configuration of this supercontinent remains a topic of debate due to insufficient petrological, geochronological, and paleomagnetic data. Initial configurations positioned the Indian landmass alongside Australia, Madagascar and East Antarctica, against the eastern margin of North America continent (Rogers and Santosh, 2002). This deduction relied on the presence of rift basins of Mesoproterozoic period (around 1.5 billion years old) on the eastern margin of India (Mahanadi and Godavari basins) and comparable rifts in North America (Belt-Purcell and Unita rifts). Subsequent studies, however, placed the Indian landmass nearer to North China and the Canadian Shield (Hou et al., 2008) or in proximity to North China and East Antarctica (Zhao et al., 2004). Despite limited paleomagnetic data, Late Palaeoproterozoic magmatic and metamorphic events indicate pivotal role of India in the formation of the Columbia supercontinent (Rogers and Santosh, 2002; Zhao et al., 2002,2004; Hou et al., 2008). The architecture of the Great Indian Landmass within the supercontinents also sparked substantial discussion. The timing of the Central Indian Tectonic Zone amalgamation, through which various Archaean-Early Palaeoproterozoic cratons of India united, remained uncertain. While earlier

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suggestions indicated a Palaeoproterozoic- Mesoproterozoic (~1.8-1.5 Ga) suturing of two cratons (Roy and Prasad, 2003; Acharyya, 2003; Bhandari et al., 2011), recent propositions lean towards a Neoproterozoic era (1.0-0.95 Ga) assembly of the CITZ (Bhowmik et al., 2012; Chattopadhyay and Khasdeo, 2011). Nonetheless, high-grade metamorphic events occurring around 1800-1600 Ma in the northern and southern portion of CITZ, along with arc magmatism at about 1750 Ma, suggest an accretion orogen (Bhandari et al., 2011; Bora et al., 2013; Deshmukh et al., 2017). Furthermore, Palaeoproterozoic arc magmatism has been observed in various Archaean cratons of India, including the Shillong-Meghalaya Gneissic Complex (SMGC) and the Bengal Basin. The basement rocks of Bengal Basin and Proterozoic rocks of SMGC are believed to be extensions of CGGC (Desikachar, 1974; Hossain et al., 2007; Chatterjee et al., 2007). Mesoproterozoic extension-related ferroan granitoids have been observed across various regions of the globe and are widely regarded as indications of the fragmentation of the Columbia supercontinent (Dall\_Agnol et al., 2012). Beyond the studied Mesoproterozoic ferroan granitoids, the emplacement of the Bengal anorthosite around 1550 Ma in the eastern part of the CGGC also suggests a significant crustal-scale extensional event (Chatterjee et al., 2008). The geochronological data has used to correlate the CGGC and other adjacent terrains with magmatic pulses and metamorphic events. Metamorphism and magmatic activities had been occurred simultaneously around ~1600 Ma in the CGGC, and also recorded in Sausar Mobile Belt [Bhowmik et al. 2014; Bhandari et al. 2011], as well as SMGC [Dwivedi et al. 2020, Chatterjee et al. 2007,2011]. The Singhbhum craton and the North Singhbhum FoldBelt experienced metamorphic activity during the ~1660-1580 Ma [Pal and Rhede, 2013], these geochronological evidence state that

they are tectonically active with the CGGC terrain.

### **8. 3.2. Correlation with the Rodinia Supercontinent**

The discussion regarding the Grenvillian metamorphism at CGGC and its association with the formation of Rodinia, specifically whether Greater Indian Landmass was part of the Rodinia supercontinent assembly remains a topic of contention (Bhowmik et al., 2010). Recent challenges have emerged against the widely held belief that India positions in proximity to Australia and East Antarctica on the outer edges of Rodinia. (Fig1.1b. Torsvik et al., 2001b; Fitzsimons, 2003; Bhowmik et al., 2010), mainly because of the scarcity of paleomagnetic pole data between India and Australia, along with Antarctica, dating back to approximately 1050 Ma (Bhowmik et al., 2010). Based on the available geochronological and paleomagnetic evidence, Bhowmik et al. (2010) suggested the possibility of multiple continental growth nuclei between approximately 1000 to 900 Ma. They argued against the complete integration of the Greater Indian Landmass into the equatorial Rodinia supercontinent (Fig. 1.1b). Chattopadhyay et al. (2015) proposed that Archaean Singhbhum Craton sharing similar tectonothermal histories with the Easternghat mobile belt around 980 Ma. The Chhotanagpur granite gneissic complex located north of the Singhbhum craton, also exhibits evidence of collisional tectonic setting around 950 Ma. The geochronological age data suggests that the Chhotanagpur Granite Gneissic Complex, Easternghat mobile belt and Singhbhum craton were interconnected during early Neoproterozoic period ((Dasgupta and Sengupta, 2003; Bose et al., 2011; Chattopadhyay et al. 2015). This amalgamation supports the idea that the CGGC shares a similar tectonothermal event with the Singhbhum craton, Easternghat mobile belt and the East Antarctica, indicating the involvement of Indian

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landmass in the Rodinia supercontinent from approximately 1000 Ma (Dasgupta and Sengupta, 2003; Bose et al., 2011). The (~1655 Ma) reveals oldest metamorphic and deformation event similar to the rocks of the other area of the CGGC that has been mentioned in Table 3.2. The pelitic granulite facies rock was assumed to be the retrograde metamorphosed during Neoproterozoic era in Makrohar, and exhumed during the assembly of Rodinia. However, more comprehensive petrological and geochronological analyses are needed to firmly establish the link between CGGC, Singbhum craton and EGMB and the subsequent correlations between India and Antarctica (Fig. 1.1b).