CHAPTER–3

GEOLOGICAL SETTING

3.1 Introduction

The Chhotanagpur Granite Gniess Complex (CGGC) is a sub-arcuate mobile belt in the eastern portion of the Central Indian Peninsular Shield and spreads over 100,000 km^2 from the eastern part of Madhya Pradesh to Bihar, Chhattisgarh, West Bengal and Jharkhand (Mahadevan, 2002) (Fig. 3.1 b). The northern boundary of CGGC is delineatedby Gangetic alluvium, while the northeast boundary is covered by Rajmahal basalt. The southeastern boundary is overlained by tertiary deposits of West Bengal and towards the east lies an alluvial deposit of the Ganges-Brahmaputra (Chatterjee et al., 2008). In the southern part, there is a significant shear zone known as the Tamar-Porapahar-Khatra Shear zone or South Purulia Shear Zone which demarcates the contact between Proterozoic rocks of the North Singhbhum Fold Belt and Chhotanagpur Granite Gneiss Complex (Mazumdar, 1988). Finally, the western border of CGGC is adjacent to the Gondwana sediments and the palaeoproterozoic Mahakoshal Group comprising supracrustal rocks and granitoids. This zone serves as a demarcation between the CGGC and central CITZ, while its northwestern margin is concealed by Vindhyan sediments (Mukherjee et al., 2018). The Chhotanagpur Granite Gneiss Complex (CGGC) is high- grade terrain consisting of supracrustal metasedimentary enclaves with basement gneisses as well as multiple intrusions of various generations and compositions (Fig. 3.1b). These intrusions range from acidic to ultramafic and from ultrapotactic to sodic. It consists of migmatites and granite gneisses with enclaves of meta-igneous and metasedimentary rocks (Roy et al., 2003).

3.2 Classification of Chhotanagpur Granite Gneiss Complex

In the last two decades, there have been taken multiple attempts to categorize CGGC rocks. Previous researchers divided these rocks into three main lithostratigraphic units: the crystalline basement, older metasediments, and late intrusives (Banerji, 1991; Ghose, 1992). These units are thought to result from three prominent geological processes: the Chhotanagpur orogeny (~1600–1500 Ma), Satpura orogeny (950–850 Ma) and Munger orogeny (420–350 Ma). Singh, (1998) suggested that CGGC rocks should be classified through lithogenic subdivisions because they do not consistently follow the principle of superposition. Another classification of the Chhotanagpur Granite Gneiss Complex was

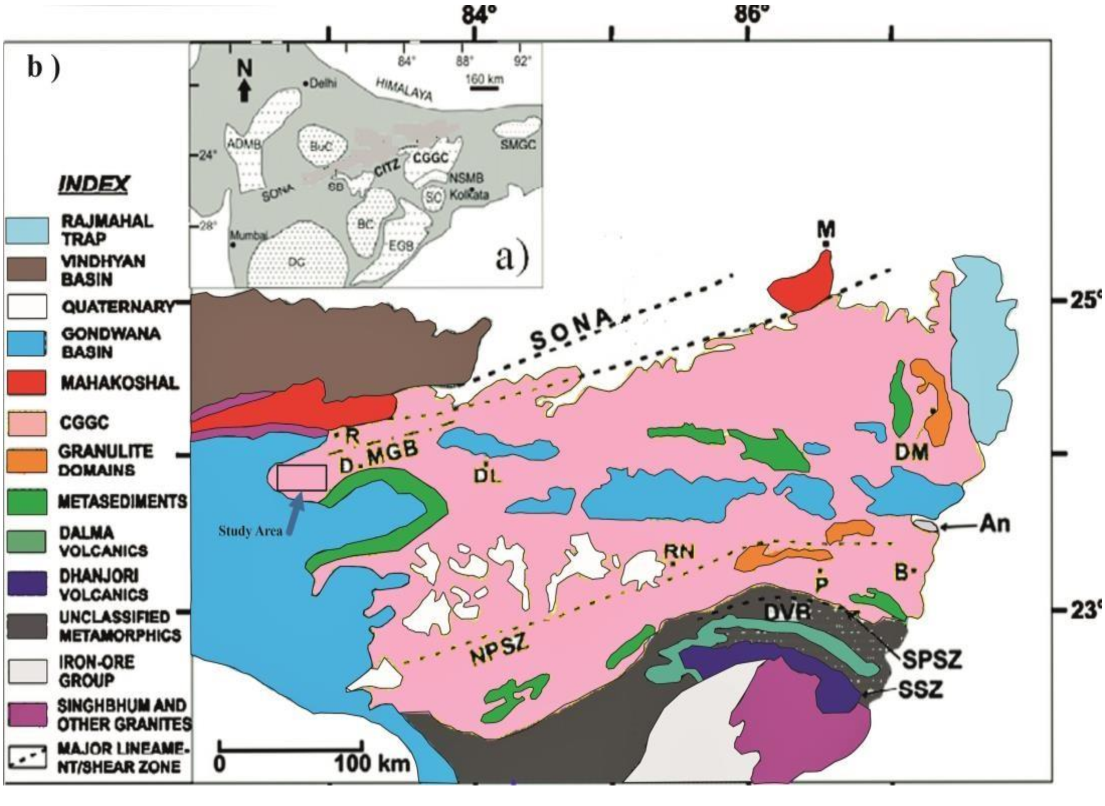

Figure 3.1 (a) The inset shows the Proterozoic mobile belts of India, including the CGGC: Chhotanagpur granite gneiss complex, EGB: Eastern Ghats Belt, SMB: Singhbhum Mobile Belt, CITZ: Central India Tectonic Zone, ADMB: Aravalli Delhi Mobile Belt, SMGC: Shillong Meghalaya Gneissic Complex. Archean Cratonic nuclei of India, DC: Deccan, BuC: Bundelkhand, BC: Bastar and SC: Singhbhum craton, modified after Chatterjee et al. (2008) (b) Geological map of the Central granite gneiss complex and the study area is marked within the map. The abbreviations used are: DL-

Daltonganj, DVB -Dalma Volcanic Belt, NPSZ -North Purulia Shear Zone, P -Purulia, SSZ -Singhbhum Shear Zone, SONA-Son Narmada Lineament, SPSZ -South Purulia Shear Zone, R -Rihand-Renusagar Area, M -Munger, An -Anorthosite, B - Bankura, RN -Ranchi, MGB -Makrohar Granulite belt, DM -Dumka, D -Dudhi, modified after Chatterjee and Ghosh (2011).

Proposed by Sanyal and Sengupta (2012), into various sectors where detailed petrological, structural, and geochronological research has been conducted in recent decades (Fig. 3.2).

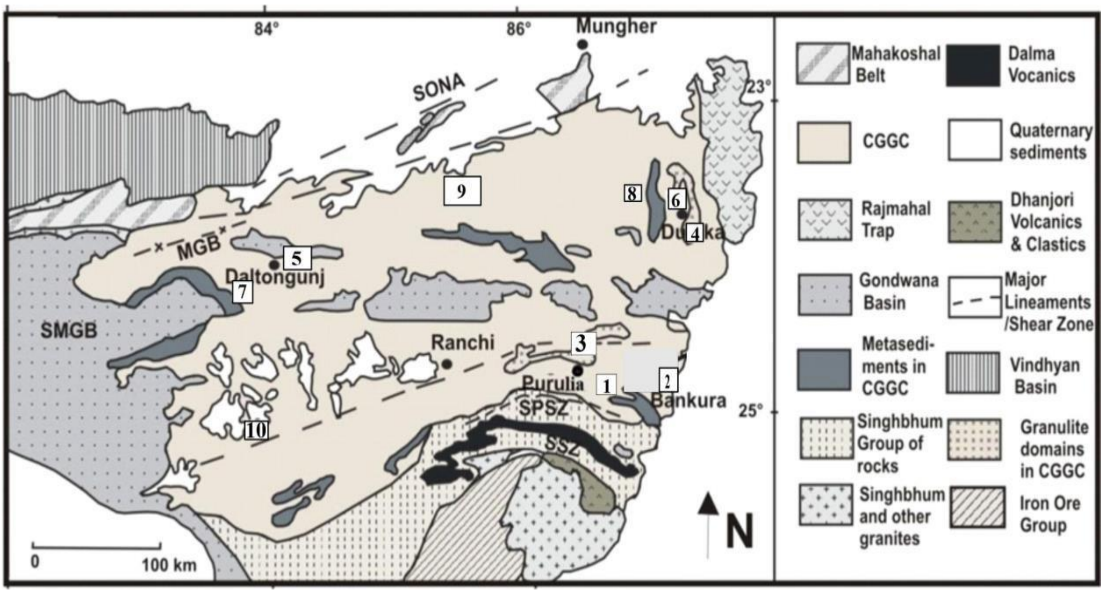

Figure 3.2 Geological map of the Chhotanagpur Granite Gneiss Complex (CGGC) and Dalma Volcanic belt, modified after Acharyya, 2003. SSZ: Singhbhum shear Zone; SPSZ: South Purulia Shear Zone (1) MPR sector; (2) BSS sector;(3) JBN sector; (4) MBR sector; (5) GB sector; (6) DJG sector; (7) RT sector; DJR sector; (9) BMB sector; (10) RK sector.

1. Murguma-Purulia-Raghunathpur (MPR) sector, West Bengal;
2. Bero-Saltora-Santuri (BSS) sector near Bankura, West Bengal;
3. Jabarban-Belamu-Nawahatu (JBN) sector, West Bengal;
4. Massanjor-Baglan-Rangaliya (MBR) sector, Jharkhand;
5. Garu-Baresanr (GB) sector, Jharkhand;
6. Dumka-Jamua-Ghormara (DJG) sector, Jharkhand;
7. Ramanujganj-Tatapani (RT) sector, Chattisgarh;
8. Deoghar-Josidihi-Rohini (DJR) sector, Jharkhand;
9. Bihar Mica Belt (BMB), Bihar;
10. Raikera-Kunkuri (RK) sector, Chattisgarh.

1. The Murguma-Purulia-Raghunathpur (MPR) Sector:

The Murguma-Purulia-Raghunathpur area situated in the southern portion of the Chhotanagpur Granite Gneiss Complex borders the Singhbhum Mobile Belt (SMB) and has been the subject of study by numerous researchers (Baidya et al., 1987; Barman et al.,1994). The predominant rock suits in this region are migmatitic gneiss, displaying well- foliated mesosomes containing hornblende, biotite and garnet. Additionally, dismembered bands of calc-silicate granulites are found within the migmatitic quartzofeldspathic gneiss. The gneissic banding in the quartzofeldspathic rock follows an east-west trending foliation aligning with the axial planes of a set of folds demarcated by bands of calc- silicate (Barman et al., 1994). Two generations of coaxial folds (D2-D3) have deformed the gneissic bandings. After these deformations, D3 deformation caused a broad warping of the east-west-trending gneissosity. Notably, the intrusion of porphyritic charnockite (consisting of orthopyroxene, garnet, hornblende, biotite, plagioclase, microcline and quartz) occurred between D1 and D2 deformation episodes (Barman et al., 1994).

2. Bero–Saltora–Santuri (BSS) Sector:

The Bero–Saltora–Santuri area, located in the southeastern portion of the Chhotanagpur granite Gneiss Complex has been studied by several authors (e.g. Roy, 1977; Sen and Bhattacharya, 1993; Ghose & Chatterjee, 2008). Its geological composition consists of migmatitic gneiss containing garnet, K-feldspar, plagioclase, biotite, orthopyroxene, hornblende and quartz have enclaves of pelitic gneiss consisting of garnet, K-feldspar, sillimanite, hercynite, ilmenite, biotite and quartz. Intrusions of anorthosite characterized by garnet, hornblende, orthopyroxene, plagioclase, clinopyroxene, biotite, ilmenite, chlorite and quartz as well as granitoids with garnet, plagioclase, quartz, hornblende, biotite and K-feldspar are also present in this sector (Ghose & Chatterjee, 2008). In addition, mafic granulite composed of clinopyroxene, orthopyroxene, plagioclase, garnet, quartz and hornblende and calc-silicate gneiss containing wollastonite, plagioclase, scapolite, calcite, K-feldspar and quartz are found in the region (Sanyal and Sengupta, 2012). The country rocks in this area display prominent and widespread gneissic banding with stromatic leucosomes some of which may contain garnet (Maji et al., 2008). Further, this area witnessed several geological events including four episodes of metamorphism (M1-M4) and at least three phases of deformation (D1-D3) (Maji et al., 2008). During the M1 phase of metamorphism dehydration melting occurred in metapelites and quartzofeldspathic gneisses resulting in the formation of stromatic leucosomes and dark- coloured bands of melanosomes with granulite facies mineral assemblages (Maji et al., 2008). Previous workers suggested that the peak temperature and pressure conditions during the M1 phase were approximately 750–850°C and 5–6 kbar (Maji et al., 2008). However, recent studies by Sanyal and Sengupta (2012) proposed that the earlier temperature estimates should be considered minimum values for the M1 metamorphism. The S1 foliation planes defined by the alignment of granulite-facies mineral assemblages (orthopyroxene + garnet in quartzofeldspathic gneiss and sillimanite + spinel + garnet in metapelite) were formed along the axial planes of D1 folds found in calc-silicate rocks and to a lesser extent in metapelites (Sanyal and Sengupta, 2012). The S1 planes and lithological interfaces underwent coaxial deformation during D2-D3 folding with the S2 foliation plane, developing parallel to the axial planes of the D2 folds. D3 folds locally displayed a sheath-like geometry

(Sanyal and Sengupta, 2012). The Bengal anorthosite which is massif-type was intruded between the D1 and D2 deformations, while a suite of granitoid rocks and syenitic gneisses were emplaced between D2 and D3 deformations (Maji et al., 2008). Recent zircon dating of anorthosite indicates its crystallization at around 1.55 Ga, suggesting that the maximum age of D2 deformational events is approximately 1.55 Ga. Both D2 and D3 deformations are associated with the amphibolite-facies condition (M2-M3), which is replaced by the granulite-facies condition of M1 metamorphic events (Maji et al., 2008). M4 metamorphic event resulted in the formation of garnet, typically occurring as a symplectic intergrowth with ilmenite and quartz. The M1 metamorphism is estimated to have occurred around 1.70 Ga, based on the Rb–Sr isochron ages of the gneisses and the calculated ages of monazite inclusions found in the M1 garnet (Chatterjee et al., 2010; Sanyal and Sengupta, 2012). The development of the S2 fabric along with the hydration of M1 assemblages suggested to have occurred between 1.3 and 1.1 Ga, according to monazite dating (Maji et al., 2008). The M4 metamorphic event is estimated to have taken place at around 650±50°C temperature and 4–5 kbar pressure between 1.0 and 0.95 Ga, as determined from the chemical dating of monazite in the M4 garnet corona (Maji et al., 2008).

3. Jabarban-Belamu-Nawahatu (JBN) Sector:

This particular region is located in the northeastern part of the Puruliya area, West Bengal. The country rocks consist of both migmatitic and non-migmatitic granite gneisses, which contain enclaves of metapelites and calc-gneisses. The protoliths of the composite gneiss have been intruded by amphibolite and biotite-bearing porphyritic granite with some localized occurrences of pegmatite (Baidya et al., 1989). The bands in gneissic rock oriented in an east-west direction, define the S1foliation plane, which alignswith the axial planes of the D1 folds found within the mafic bands. The S1 foliation plane is subjected to folding by D2 deformation, creating folds with east-west-trending axial planes. These D1 and D2 folds were subsequently superposed by D3 folds and formed north-south-closing open warps. The biotite-bearing porphyritic granite was intruded between the D1 and D2 deformations, according to structural features (Baidya et al., 1989). According to K-Ar dating, the porphyritic granites and the composite gneisscontaining biotite vary in age from 1.08 to 0.8 Ga (Baidya et al., 1987).

4. Massanjor-Baglan-Rangalia (MBR) Sector:

The Massanjor-Baglan-Rangalia sector lies to the north of the Damodar Valley Gondwana Basin and near the eastern boundary of the Chhotanagpur Granite Gneiss Complex (Mahadevan 2002). The predominant rock in this area is migmatitic charnockite which has occasionally retrograded into quartzo-feldspathic gneiss containing hornblende and biotite. Additionally, there are occurrences of khondalite, Mg-Al granulites, calc- silicates and mafic granulites. This area has experienced three deformation periods (D1- D3) (Sanyal and Sengupta, 2012). During the first deformation period (D1), the charnockites developed east-west migmatitic banding. The subsequent coaxial D2 and D3folding events affected the migmatitic banding in charnockite. Porphyritic charnockite was introduced between D1 and D2, deformation and a few amphibolites that cut through this foliation were afterwards folded by the open and north-south closing folds of the D3 deformation event (Sanyal and Sengupta, 2012). The geothermobarometric calculation of garnet, pyroxene, and plagioclase mineral phases produced data of 700± 50°C and 6.51 kbar which represents the metamorphic situation during D2 deformation (Bhattacharya et al., 1991). The mineral assemblage present in the mafic dykes indicates that amphibolite-facies conditions were present during the D3 deformation (Sanyal and Sengupta, 2012). According to Acharyya (2003), the protolith ages of porphyritic charnockite and migmatitic are 1.51± 0.05 Ga and 1.62 ± 0.05 (Acharyya, 2003) respectively.

5. Garu-Baresanr (GB) Sector:

The Garu-Baresanr region is situated to the north of the Gondwana basin of Damodar Valley and in the central portion of the Chhotanagpur Granite Gneiss Complex. The country rock consists of a mixture of composite gneisses having migmatatic and non- migmatatic features and has been intruded by the granite porphyry (Mazumder, 1988).

There are occurrences of bands and lenses of graphite-bearing khondalite and calc-silicaterocks as enclaves in gneiss. Mafic intrusions in the form of dismembered bodies of amphibolite have been reported (Mazumder, 1988). In the southern areas of Daltonganj, base-metal deposits hosted in ultramafic rock have also been documented (Ghose, 1992). However, there is a lack of detailed information on the petrological features and geochronological data from this sector.

6. Dumka-Jamua-Ghormara (DJG) sector, Jharkhand:

This sector is located between the DJR sector and the Mesozoic Rajmahal volcanics andin the northeastern portion of the CGGC. Migmatitic quartzofeldspathic gneiss withenclaves of khondalite, mafic rocks, and calc-silicate rocks make up the predominant rockin this area (Sanyal and Sengupta, 2012). Mafic dykes traverse the migmatitic quartzofeldspathic rocks in the western portion of the sector. The mafic dykes in the western domain have coaxial folds with north-south axial planes while the quartzofeldspathic gneiss in the eastern domain has folds with general east-west trending axial planes (Sanyal and Sengupta, 2012). It has been stated that syenite and anorthosite intrusive rocks were formed during the interval between the D1 and D2 deformation events (Sanyal et al. 2007). This sector has primarily produced two high-grade metamorphic phases and several amphibolite-facies metamorphic phases (Sanyal and Sengupta, 2012). The high-grade metamorphism of charnockite and khondalite produced migmatitic bandings which were then retrogressed into quartzofeldspathic gneisses (Sanyal et al., 2007). The P-T condition of the first high-grade event, which resulted inthe creation of migmatitic bandings in khondalite, was 930–950 °C and 5–6 kbar (Sanyal et al., 2007). However, the P-T condition of orthopyroxene in quartzo-feldspathic gneisses was reported at 700-800 °C at 5-6 kbar, which can elucidate the P-T condition during the formation of migmatitic charnockite (Pattison et al. (2003). Similar P-T conditions were reported for the neighbouring syenitic gneisses (Barman et al., 1994). The U-Th-total Pb monazite dating of the garnet cores in khondalites and charnockitic gneisses suggests that the initial UHT metamorphism in the enclaves of khondalite occurred about 1.87 Ga (Chatterjee et al., 2010). Similar to this, it has been reported that the maximum age of the second high-grade metamorphism that produced the gneissic banding in charnockites is approximately 1.66 Ga based on the U-Th-total Pb monazite dating of the garnet rim as well as in the quartzofeldspathic matrix of the khondalite and charnockite gneiss (Chatterjee et al., 2010). Monazite of metapelites and felsic gneisses enclaves are also reported to give another two age ranges i.e. 1.1-0.93 Ga and 0.85- 0.75 Ga (Chatterjee et al., 2010), among which the second age range is considered to be accompanied with the high-pressure metamorphic event having regional scale east-west compression (Chatterjee et al., 2010).

7. Ramanujganj-Tatapani (RT) Sector, Chattisgarh:

The RT sector comprises the farthest western sector of the Chhotanagpur Granite Gneiss Complex (CGGC) along with adjacent Gondwana rocks located in the Mahanadi Basin. This region exhibits a domal structure trending from northwest to southeast along with an alternating sequence of metapelite and psammopelite rocks (Patel et al., 2007). Themetapelite strata occasionally contain bands of quartzites with significant amounts of manganiferous garnet (>24 wt% MnO) as well as rare occurrences of ferroactinolite grunerite and metacarbonate. Within the metapelite layers muscovite, quartz and biotite- rich matrix are commonly found along with megacrystic andalusite, porphyroblastic garnet and biotite mineral grains. Toward the northwest, there is a noticeable increase in grain size and a shift from andalusite to sillimanite indicating a higher grade of metamorphism in that direction. Intrusions of granitic to granodioritic rocks are found within the overall metasedimentary succession including the metapelites, psammopelites and quartzite in the western and northern parts. The three sets of coaxial D1-D2 folds form a NW-SE-trending axial-planer schistosity in this region. The creation of the regional domain structure is believed to have resulted from the interaction between the D2 and D3 folds. The structural features suggest that the granitoids intruded into the metasedimentary rocks either before or during the D1 deformation phase. Moreover, there have been observations indicating the presence of calc-silicate rocks in the south of Ramanujganj region. These rocks exhibit a mineral composition that includes grossular garnet, vesuvianite, wollastonite, diopside and quartz.

8. Deoghar-Josidihi-Rohini (DJR) sector:

The country rocks of this sector are migmatitic quartzo-feldspathic gneiss and augen gneiss, intruded by mafic dykes and many generations of pegmatite veins (Ray et al., 2011). Other sectors of the CGGC have also documented pegmatite veins and mafic dykes of various generations, and these intrusive phenomena are thought to be the result of regional extension under the brittle-ductile shear regimes (Sanyal and Sengupta, 2012). Three sets of folds (D4-D6) in the swarm of mafic dykes that participated in and followed the formation of the gneissic banding in the host felsic gneiss (pre-D4) are recognized from the structural features (Ray et al., 2011). Coaxial folds D4-D5 produced regional foliations that trended north-south to NNE-SSW and were parallel to the axial planes of D4 fold and in some cases D5 folds (Sanyal and Sengupta, 2012). According to reports, at various phases of D4-D6 folding the biotite granite and several mappable masses of pegmatite with biotite+muscovite were deposited (Sanyal and Sengupta, 2012). This area bears the traces of the M1 and M2 metamorphic stages. The quartzo-feldspathic gneiss developed stromatic leucosomes as a result of the M1 granulite-facies metamorphic event. The D4-D6 folding and the subsequent amphibolite-facies metamorphic event (M2) led to the hornblende-bearing assemblage replacing the magmatic mineralogy of mafic dykes. Geothermobarometry and suitable bulk compositions assessment suggest that the peak metamorphic condition during the M2 state occurred at a P-T range of 7.1 kbar and 600– 750°C (Ray et al., 2011).

9. Bihar Mica Belt (BMB) Sector:

One of the best industrial-grade mica resources in the world is found in the BMB sector which is located in the northern part of the Hazaribagh Plateau at the northern extension of the CGGC. The metamorphosed arenaceous and argillaceous rocks in this belt are interbedded with ortho-amphibolite, calc-silicate and hornblende schist. Gabbro- anorthosite, dolerite dykes, granitoid rocks, and pegmatites have also been intruded in this area. Rare earth element (REE) and rare metal deposits can be found in abundance in the mica pegmatites (Mahadevan, 2002; Singh and Krishna, 2009). Various workers found evidence of a conglomerate layer at the bottom of the Bihar mica belt (Ghose andChatterjee, 2008; Singh and Krishna, 2009). The presence of high-grade clasts within this conglomerate suggests that the sediments in the Bihar mica belt likely originated from the high-grade zones of the Chhotanagpur Granite Gneiss Complex (Ghose and Chatterjee, 2008). The discovery of economically significant base metal mineralization linked to carbonate-bearing metasediments in the Hesatu-Belbathan Belt (Ghose, 1992). In this region, three distinct deformation periods have been identified in which granitoids were intruded during the syn- to post-D2 folding phase, while granite and mica-containing pegmatite were formed during the pre- to post-D3 folding (Mahadevan, 2002). Through petrographical analysis, both the metasedimentary rocks and mafic intrusions underwent metamorphism at the amphibolite grade (Mahadevan, 2002). The granitic rocks that intruded the sediments of the BMB were determined to be approximately 1.6 billion yearsold, whereas the younger granite intrusions exhibited a narrower age range of 1.3 to 1.1 billion years. These ages were determined based on whole-rock and Rb-Sr mineral isochron dating of the granitic rocks within the Bihar mica belt (Pandey et al., 1986). The sedimentation within the BMB occurred during a specific time frame between 1.70 and 1.65 billion years ago, supported by the Pb/Pb age of galena found in base-metal deposits (Singh et al., 2001). This age range coincides with the Rb-Sr whole-rock age of older intrusive granite (Pandey et al., 1986). The oldest mica pegmatites in the BMB, which contain REE-rare metals, were formed around 0.96 ± 0.05 billion years ago (Vinogradov et al., 1964). Similarly, the Columbite-Tantalite minerals in pegmatites have an identical U-Pb and Pb/Pb age range of 0.91 ± 0.02 billion years ago (Krishna et al., 2003).

10. Raikera-Kunkuri (RK) Sector:

The Raikera-Kunkuri sector is located in the CGGC and the south of the RT sector. This region is composed of a banded sequence of dolerite dyke and mica-bearing granitoids as well as pelitic schist and pebbly quartzite. The Rb-Sr whole-rock isochron age of the older granitoids in this region is roughly 1.00 ± .05 Ga old, whereas the younger granitoids are roughly 0.81± 0.05 Ga old (Singh and Krishna, 2009). According to earlier researchers pink granite is characterized as Y-mineralization and they are thought to have been formed by metasomatism (Singh and Krishna, 2009). This particular sector shares remarkably similar structural characteristics with the RT sector. The folds developed during the D3 deformation event have been intruded syn-tectonically by the grey granitoids (Singh and Krishna, 2009). The presence of heavy metal-bearing pegmatoids and granitoid in the Bihar Mica Belt is associated with granitoid intrusions in this region (Singh and Krishna, 2009).

3.3 Regional structure

The Satpura trend, which extends in the E-NE to W-SW direction, continues from the Chhotanagpur region to the Shillong plateaus in Assam (Krishnan, 1935). The presence ofrocks like granulite, charnockite, leptynite and khondalite in both the western and eastern parts of the Chhotanagpur Granite Gneissic Complex provide evidence for the extension of the Eastern Ghats mobile belt (Ghose 1968). The CGGC generally exhibits a foliation trend ranging from east to west and changes to the northeast in areas like Hazaribagh and to the northwest in the southeastern parts of Hazaribagh and the western part of Giridih (Mahadeva, 2002). The eastern part of CGGC around Josidih-Deoghar and Jamua-Dumka experiences intense east-west compression. This regional foliation shows an axial-planar nature and is folded into isoclinal folds with an N to N-NE striking trend and a moderate eastward dip (Bhattacharya, 1976; Chatterjee et al., 2010). Structural studies have been conducted in various isolated areas, including Ranchi and Purulia districts (Chatterjee et al., 2010). The central part of Jamua-Kakwara-Bhitea of the Satpura Orogeny, Bhagalpur district, Bihar Mica Belt, and Ranchi district have also been examined (Sengupta, 1964). These studies show three generations of deformation that resulted in the formation of F_1, F_2, and F_3 folds. The first deformation (D_1) created isoclinal folds (F_1) on bedding planes (S_1) and a strong regional axial plane foliation (S_2) (Sarkar, 1977). The F_1 fold axes exhibit a certain degree of scattering due to the overlapping of the later generations of folding (F_2 and F_3). S_2 appears as schistosity in amphibolites, metapelites and some calc- silicate rocks and as foliation in migmatites and gneisses. In general, S_2 follows an E-W orientation with a steep dip to the north, although it can vary locally due to subsequent folding. The second set of folds (F_2) typically displays a very steep plunge in the central part of the terrain (Sarkar, 1988). The third generation of folds (F_3) is prevalent in the eastern and central regions and exhibits subhorizontal or shallow axial plunges toward the east and west with moderately steep axial planes (Mahadevan, 1992). These structural features collectively indicate a prevailing north-south compressive stress in the region. During the second phase of deformation, mafic igneous rocks intruded as small bodies throughout the Chhotanagpur Granite Gneiss Complex. These mafic rocks underwent high-grade regional metamorphism often in the amphibolite facies and sometimes in the granulite facies in specific areas (Dey et al., 2020). The emplacement of the granite rocks occurred syn-to-late kinematically and closely followed the axial planes of antiformal or synformal structures (Bhattacharyya, 1982). The third phase of deformation (D_3) is observed as significant bending of the axial traces of F_2 folds and as open and broadwarps (Dey et al., 2020).

3.4 Tectonothermal events and geochronology of CGGC

The available geochronological data and the four distinct stages of metamorphic events are presented in Table 3.1. The metamorphic history of the CGGC suggests a complex evolutionary journey within the Indian peninsular shield. It involves the four stages of metamorphism (M1–M4) spanning the Paleo- to Neoproterozoic era. Specifically, M1 is estimated to have occurred around 1870–1660 million years ago, M2 is believed to have taken place between 1550–1450 million years ago, M3 ranges from 1200–930 million years ago, and the most recent M4 event occurred between 870–780 million years ago (Sanyal and Sengupta, 2012; Dey et al., 2017; Mukherjee et al., 2017; Dey et al. 2019). Significant evidence of metamorphism is preserved in pelitic granulites with zircon datingusing the U-Pb method suggesting an age of approximately 1600 million years (Rekha et al. 2011; Dey et al. 2020). The oldest basement rocks within the Chhotanagpur Granite Gneissic Complex (CGGC) are believed to have originated during the Paleoproterozoic period, approximately around 1750–1660 Ma (Sarkar et al. 1986; Chatterjee and Ghose 2011). This same age range is also found in the Mahakoshal Mobile Belt (MMB) indicating a connection between the granitic rocks in the northern part of the CGGC and the MMB (Saikia et al. 2017; Yadav et al. 2020). The source material for the metapelites in this region can be traced back to adjacent continental landmasses, like the Eastern Ghats Belt, Aravalli Craton and Lesser Himalaya which have been dated to the period of 1900 to 1700 million years ago (Rekha et al. 2011; Dey et al. 2017). Subsequently, these deposited sediments underwent their initial metamorphic event (M1) around 1680–1580 million years ago, resulting in the formation of mineral assemblages consisting of garnet, sillimanite, K-feldspar, plagioclase, ilmenite and quartz. These metamorphic changes occurred under high-temperature conditions exceeding 850°C (Dey et al. 2020). The impact of the second metamorphic event M2 is evident in various rock types within the region. Zircon U–Pb dating has unveiled the presence of A-type volcanic felsic magma emplaced at 1447 million years ago (Mukherjee et al., 2017) along with other granitoid rocks that were intruded at 1470–1450 million years ago in the northeastern part of the CGGC (Mukherjee et al., 2017). The zircon U–Pb data from the intrusive granite gneiss reveals a crystallization age of 1,498 ± 38 Ma, signifying a prominent Mesoproterozoic within-plate magmatic event within the Chhotanagpur Granite Gneissic Complex (CGGC) (Yadav et al. 2022). This event coincided with the disintegration of the Columbia Supercontinent (Yadav et al. 2022). The M2 event has also been identified in the pelitic granulites which are found as enclaves within the host felsic orthogneiss andare dated to have formed between 1470–1400 million years ago (Dey et al. 2020). These pelitic granulites exhibit a mineral assemblage that includes garnet, sillimanite, biotite, K-feldspar, plagioclase, and quartz all formed under peak metamorphic conditions (Dey etal. 2020). Several areas of CGGC were intruded by anorthosite during ~1550 Ma (Chatterjee et al., 2008) and ferron-granitoid during ~ 1465 Ma (Mukherjee et al., 2017).

A significant metamorphic event (M3) took place within the CGGC during the Grenvillian orogeny, spanning the period from 1100 to 900 million years ago, during which the majority of continental crusts, including both host rocks and enclaves, experienced extensive metamorphic changes to granulite facies condition (Chatterjee and Ghose, 2011; Chatterjee, 2018; Chakraborty et al. 2019). EPMA monazite dating of felsic ortho-gneiss rock and khondalite enclaves from the NE CGGC area showed 1100–930 Ma age of metamorphism (Sanyal et al., 2007; Chatterjee et al., 2010). The final metamorphic event, known as M4, signifies a phase of retrograde metamorphism during which granulitic rocks transformed the amphibolite facies condition that occurred around 870–780 Ma (Sanyal and Sengupta, 2012; Mukherjee et al., 2018; Chatterjee, 2018). Moreover, regional metamorphism has been documented from 850 to 780 Maaccompanied by the development of an N-S fabric within the Dumka-Jamua-Ghormara sector (Sanyal et al. 2007). This metamorphic event is considered the final and significant phase of metamorphism and deformation within the CGGC (Chatterjee, 2018). Based on the above discussion author has concluded that the Chhotanagpur Granite Gneiss Complex (CGGC) was affected by D1 deformation occurring over 1600 Ma, which is linked to the M1 episode of metamorphism. During this M1 episode, the regional metamorphism led to the migmatization of older metasediments, mafic granulite and charnockite. These rocks underwent prograde metamorphism and this metamorphic episode was a consequence of the formation of the Columbia supercontinent. The disintegration of the Columbia supercontinent commenced after an age of approximately 1500 Ma, giving rise to the M2 episode, the retrograde metamorphic stage accompanied by another phase of magmatism leading to the emplacement of felsic magma. These datings provide evidence of the later events in the orogeny associated with D2 deformation and the M3 episode of metamorphism estimated to have occurred around 1000±50 Ma during the Grenvillian orogeny (Chatterjee et al., 2010). The M3 episode of retrograde metamorphism led to the transition from mafic granulites to amphibolite and high-grade gneisses. The M4 episode of metamorphism marks the end of the regional metamorphism within the CGGC.

3.5 Geological setting around Makrohar area

The studied area (latitude 23°90_50__N to 24º58_30__N and longitude 82°63_63__E to 82°66_60__E) belongs to the northwestern part of Chhotanagpur Granite Gneiss Complex(CGGC) within Makrohar granulite belt (Fig.3.3). The area lies nearly 10 km southwest of Waidhan and consists of the high grade regionally metamorphosed rock. This gneissic complex forms the vast plateau in the eastern part of the Indian peninsular shield and extends as a tongue beyond Govind Vallabh Pant Sagar (Rehand reservoir) in SE of Waidhan. This tongue is parallel to the son-Narmada lineament and forms the northern margin of the central Indian tectonic zone (CITZ) (Acharyya and Roy, 2000). The Makrohar area was initially studied by Sinor, (1923) and they reported the presence of granite gneiss, marbles and gabbro and also the presence of corundum and sillimanite in the area around Pipra. Later researchers documented that the gneisses have been intruded in hornblende metabasics and schist. The first detailed study of the area was carried out by Narain, et al. (1981) as a part of the CRUMANSONATA Project. They have mapped the area on a 1:25,000 scale and reported two pyroxene granulites and gabbroic- anorthosite for the first time. The older or primary gneisses and migmatites contain inclusions of metasedimentary and metabasic rocks. The metasedimentary rocks include magnetite quartzite, marble, calc-silicate, quartzite, corundum and sillimanite-bearing schist, as well as pelitic granulite referred to as pyroxene quartzite and these meta basic rocks consist of two-pyroxene granulite, amphibolite, and hornblende schist (Narayan, et al. 1981). Pitchai Muthu (1990) has documented the gabbro-norite and gabbro-anorthosite suite of rocks from the Makrohar area and discussed the petrography and geochemistry of these rocks. Metasedimentary and metabasic rocks occur as enclaves within granite gneisses and migmatites comprise sillimanite quartzite, corundum-bearing sillimanite quartzite/schist, magnetite quartzite, hornblende schist, amphibolite, metabasalt, pelitic and mafic granulites (Solanki et al., 2003). These were dismembered due to later granitic and migmatitic activities. Granite gneisses and migmatite have fairly wide areal extent in the studied area (Acharyya, 2001). The P-T condition of the Peak granulite formation at 800 º C and 9 Kb followed by an Isothermal decompression (ITD) through 740 º C at 6.5 Kbar and a final re-equilibrium at 685 º C and the clockwise P-T path indicate a collisional environment between Bundelkhand Craton and Baster craton (Solanki et al., 2003). Sarkar et al. (1998) deduced a 1.73 Ga age for the granites that contain enclaves of granulite, thus considering that these granulites are older than 1.73 Ga.. The granite gneisses in this region exhibit alkaline characteristics and are metaluminous in nature originating from the melting of the lower crust, which had been metasomatized by mantle-derived alkali-rich fluids, possibly due to asthenospheric upwelling (Yadav et al. 2022). The Zircon U-Pb data from intrusive granite gneiss of Makrohar area indicatesa crystallization age of 1,498 ± 38 Ma and this age represents a significant Mesoproterozoic within-plate magmatic event in the CGGC, occurring concurrently with the breakup of the Columbia Supercontinent (Yadav et al. 2022). According to Narain et al. (1982), the study area has undergone significant diastrophism in multiple pulses. The deformation history during the pre-migmatization stage has been mostly obliterated due to the dismemberment of the metasedimentary enclaves. In the post-migmtization, the first phase of deformation has resulted in tight-isoclinal folds that are occasionally rootless, as well as segregation banding in gneisses (S1). The second deformational event resulted

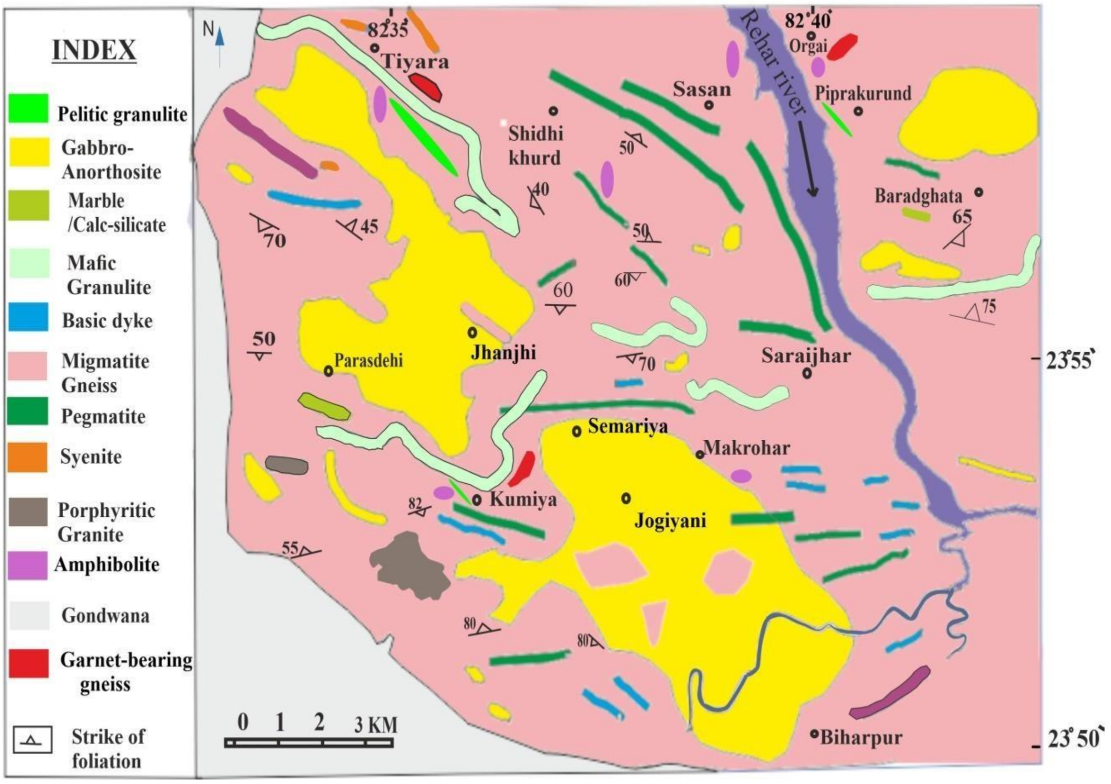

Figure 3.3 Geological map of the Makrohar area, Singrauli, Madhya Pradesh (modified after Pichaimuthu,1990).

in the F2 folds, which are neutral, open to close, and have developed pervasive S2 foliation with trends varying from WNW-ESE to NW-SE (Narain et al., 1982). In the northeastern part of the study area, the megascopic F2 folds have been delineated using garnetiferous amphibole gneiss as a marker unit (Solanki et al. 2003). The F2 folds also exhibit crenulation folding showing low to moderately plunging fold axis towards the SW and SE. The F1 and F2 fold have been transposed by the F3 fold, which has produced open upright folds, with an axial trend of N65°W-S65°E (Solanki et al. 2003). The metamorphic history of the area is characterized by high-grade metamorphism (high T, moderate P), followed by retrogression. The presence of metasediments with sillimanite quartzite, pyroxene granulite, and migmatite indicates upper amphibolite to granulitefacies of metamorphism. However, the dismembering of the metasedimentary bands hinders the ability to understand the metamorphic scheme during the first phase ofdeformation (Solanki et al. 2003). The later phases of deformation have resulted in a retrogressive character of the metamorphic history.

3.6 Stratigraphy

The north-western protrusion of CGGC in the Makrohar area exhibits the presence of three distinct suites of rocks: (i) Granite gneiss and migmatites (ii) Pelitic, calc-silicate and metabasic rocks occurring as enclave and (iii) Gabbro, anorthosite and metabasites (Acharyya, 2003). Based on the field relationship, petrography and structural analysis (Solanki et al. 2003), documented the three main events of granitic activities and two intervening phases of migmatisation. The older granite gneiss and migmatite is a product of the first phase of granitic activity and the related phase of migmatization. The second phase of granitic activity occurred just after the emplacement of a gabbroic suite of rocks. This has resulted in the formation of porphyritic granite which bears evidence of magma- mixing, at places. The youngest phase of granitic activity generated small granite plutons and localized migmatite. This is followed by the intrusion of dolerite dykes, pegmatite and quartz veins. The porphyritic granite, mainly found in the eastern part of the Makrohar area, has also been emplaced syn-tectonically. All three suites of rocks are intruded by basic dykes, pegmatites and quartz veins. Solanki et al., (2003) have proposedthe stratigraphy of the Makrohar area based on field and petrographic study. (Table 3.1)

Table3.1: Generalised lithostratigraphic succession for the Proterozoic rocks of Makrohararea, (Solanki et al., 2003).

Cretaceous	Deccan Traps	Doleritic/Basaltic dyke
Permo-carboniferus	Gondwana Supergroup	Boulder Bed/Sandstone
Archaean proterozoic	Chhotanagpur GraniteGneiss Complex (CGGC)	Quartz and Pegmatite veins
		Dolerite dykes
		Granite and associated Migmatites II
		Porphyritic granite/Augengneiss
		Gabbro/anorthosite/Metabasics
		Granite and associated Migmatites I
		Sillimanite quartzite/Sillimanite –corundum schist
		Marble /calc-silicate/ calc-granulite/ amphibolite
		hornblende boitite schist /Pelitic and mafic granulites

Table 3.2 Four metamorphic stages (M1 to M4) from Paleoproterozoic to Neoproterzoic with associated geochronology data from different areas of the CGGC (Modified after Sanyal and Sengupta 2012).

Age (Ma)	**Dating mathods**	**Area**	**Rock type**	**Event**	**References**
(M1) Paleoproterozoic					
~1870-1691	U-Th-Pb dating	Southern CGGC	Khondalite enclave migmatititc Gneiss	UHT	Chatterjee et al. (2010)
~1720	U-Th-Pb dating	NE Dumka	Metapelites	MT (730-8000C) HP (9-12 Kbar)	Chatterjee et al. (2010)
~1700-1650	Pb-Pb age dating	Hesatu-Belbathan	Sulphide bearing metasediment	UHT metamorphism	Singh et al. (2001)
(M2) Paleo-Mesoproterozoic					
~ 1628	U-Th-Pb monazite dating	TrikutPahar (Devghar)	Khondalite,Quartzo feldspathic gneiss		Sanyal et al. (2007)
~ 1550	U-Pb zircon dating	SE CGGC(Saltora)	Anorthosite	Magmatism	Chatterjee et al. (2008)
~ 1465	U-Pb zircon dating	Between Devghar & Dumka	Ferron granitoid	Isothermal Decompression	Mukerjee et al. (2017 ,2018)
~ 1416-1246	K-Ar whole rock, U-Pb zircon dating	NE CGGC	Migmatitic gneiss	UHT metamorphism	Sarkar(1980)
~ 1280-1190	U-Th-Pb monazite dating	Southern CGGC, NE CGGC	Migmatitic gneiss, Granite,Metapelites	Metamorphism/ Magmatism	Chatterjee et al. (2008) Chatterjee et al. (2010)
(M3) Meso-Neoproterozoic					
~ 1190	U-Th-Pb dating	Dumka	Metapelites	High Grade Metamorphism	Chatterjee et al. (2008)
~ 1021-967	U-Th-Pb dating	Bero- Saltora	Sheared Granite	Metamorphism	Maji et al. (2008)
~ 990-940	U-Th-Pb monazite dating	Purulia	Mafic granulite	ITD	Karmakar et al. (2011)
~ 960-940	U-Th-Pb monazite dating	Southern CGGC	Granite gniess	Retrograde Metamorphism	Chatterjee et al. (2010)
~ 948	U-Pb zircon dating	Betweeen Devghar and Dumka	Charnockitic gniess Amp-Bt-gniess	Prograde Metamorphism	Mukerjee et al. (2017,2018)
(M4) Neoproterozoic					
~ 859	U-Th-Pb monazite dating	Dumka	Quartzofeldspathic gneiss	High pressure metamorphism	Chatterjee et al. (2010)
~ 825	U-Th-Pb monazite dating	Bero- Saltora	Metapelitic gneiss	Prograde Metamorphism	Maji et al. (2008)
~ 815	Rb-Sr whole rock	Raikera-Kunkuri	Granite	Metasomatism	Singh & Krishna (2009)

3.7 Rock types and their field relations

3.7.1 Migmatitic gneiss and granite gniesses

Granite gneisses and migmatites are the primary rock types in the area covering a significant expanse (Fig. 3.4). The granite gneiss displays diverse variations in colour, grain size and texture making it challenging to classify and map its different components. Identifying the boundary between migmatites and granite gneiss in the field is also difficult due to their intermingling. The granite gneisses are medium to coarse-grained, pinkish-grey in colour and exhibit a distinct foliation, often displaying folding. The migmatites are predominantly exposed in the central and northeastern parts of the study area. They exhibit diverse structural forms- agmatitic, ptygmatic and stromatic (Fig. 3.4 c, d and e). These migmatites display varying stages of migmatization and sometimes show clear segregation into leucosome and melanosome resulting in significant layering or banding. Some of these bands are sizable and have been used as markers in delineating mesoscale and polyclinal folding. The Rehar River area also reveals stromatic migmatites heavily intruded by pegmatites. Complex folding, including ptygmatic folding, is evident in various sections (Fig. 3a). The composition of melanosome typically involves mafic minerals and occasionally garnet, while leucosome tends to have felsic minerals like quartz and feldspar as the primary constituents.

3.7.2 Porphyritic Granite and pegmatites

This rock type stands as the third significant type in terms of its abundance and appears as small plutons and stock-like bodies within the granite gneiss and gabbro-anorthosite suite of rocks. These formations are medium to very coarse- grained, displaying pink and reddish hues and are composed of quartz, feldspar and biotite

(Fig. 3.5 a, b). Prominent exposures of these formations can be observed in the Kumiya, orgai and Piprakurund areas (Fig. 3.3). Pegmatites and quartz veins are prevalent across the entire mapped area a noticeable exposure of these formations exists in the Sidhikhurd area. These formations typically appear as linear, lens-like, or sheet-shaped bodies, varying in length from a few meters to up to 15 meters. Pegmatites primarily consist of quartz, feldspar and mica.

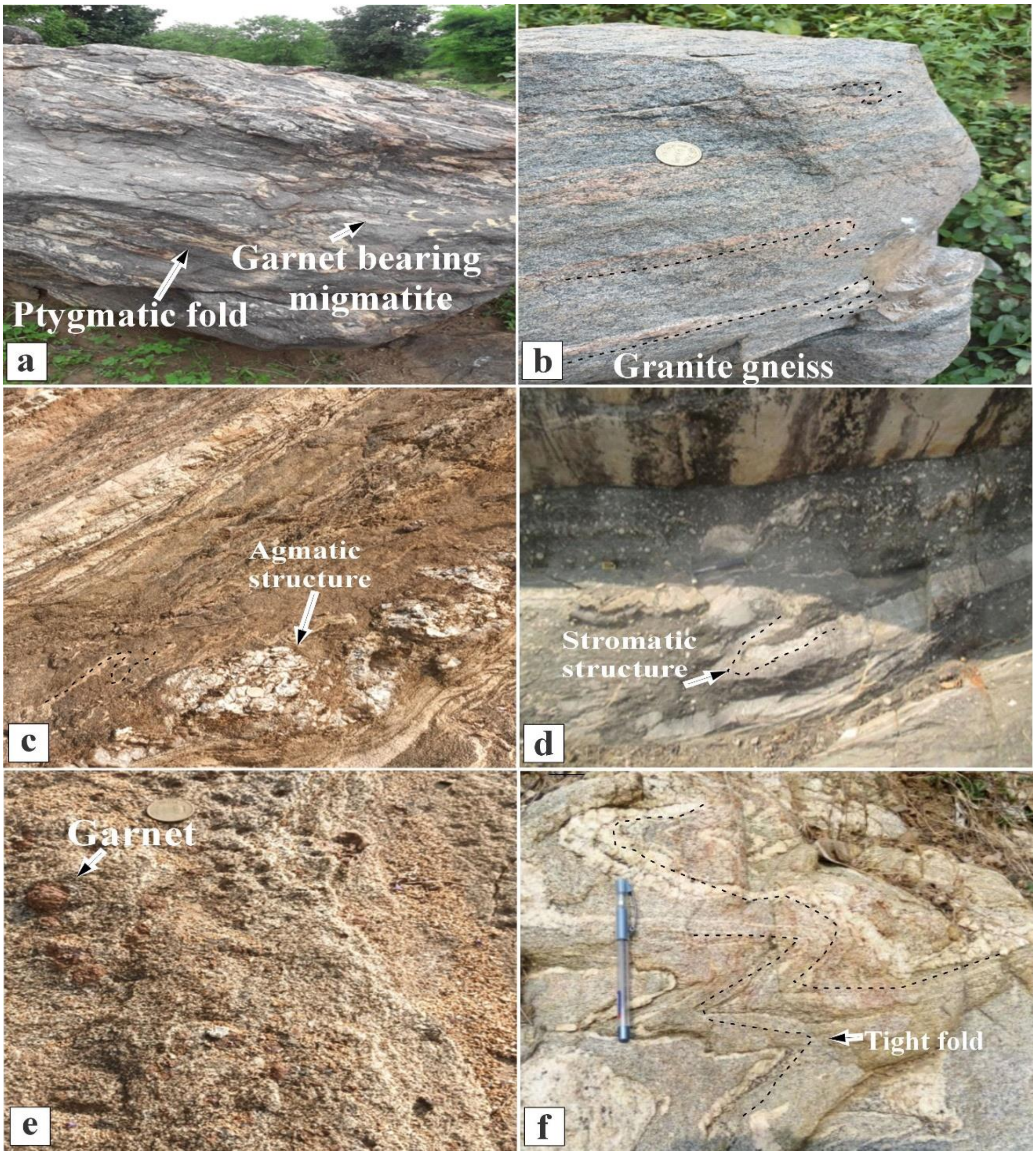

Figure 3.4 (a) Field photographs of migmatite from study area (b) Ptygmatic folding in granite gneiss (c) agmatic structure in migmatite in Piprakurund area (d) stromatic structure in migmatite (e) Garnet porphyroblast in migmatite (f) migmatite showing tight folding.

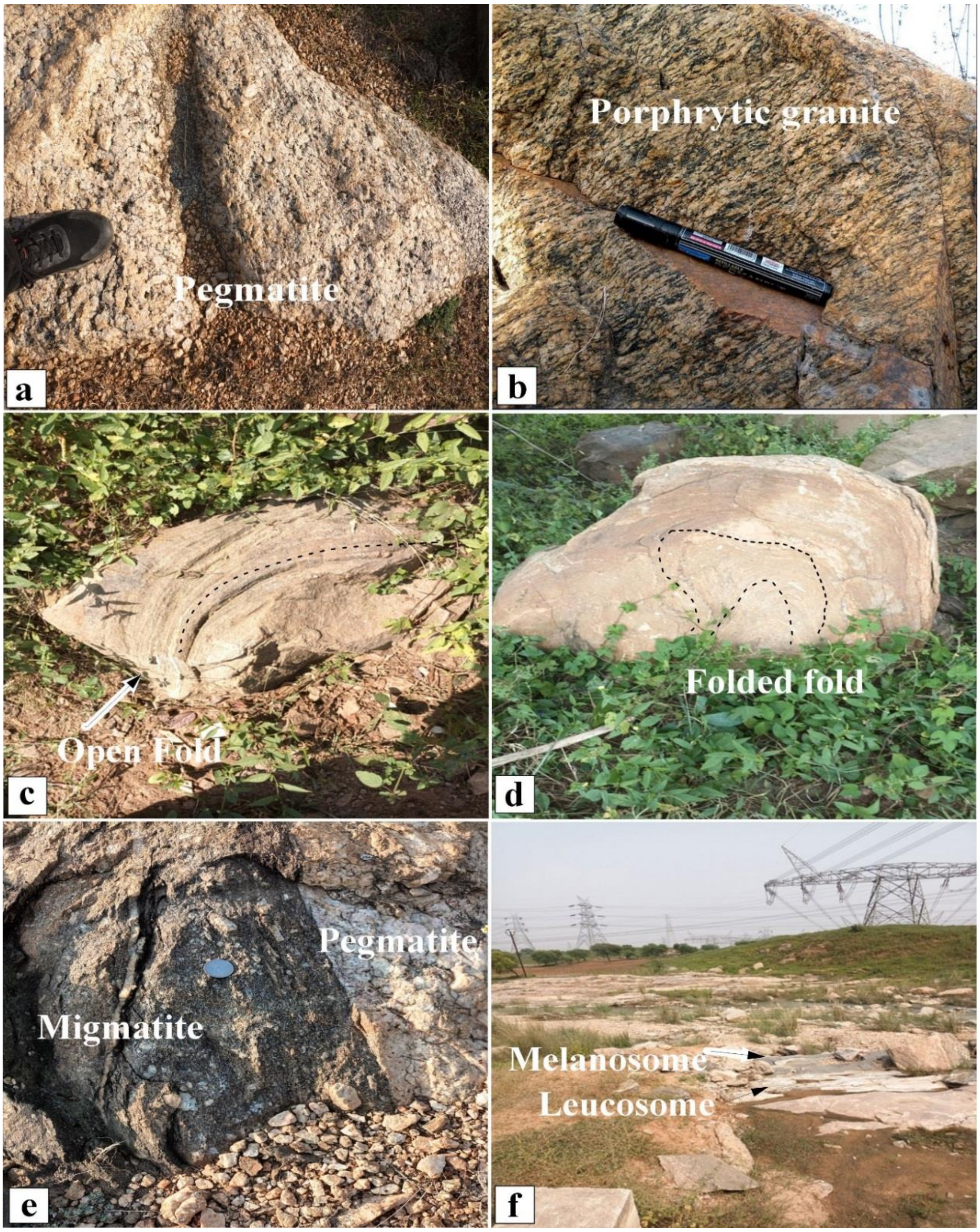

Figure 3.5 (a) Field photographs of pegmatite from study area (b) massive boulders of porphyritic granite granite gneiss showing open fold and (d) granite gneiss showing folded fold (e) contact of migmatite andpegmatite body; (f) Interlayering of leucocratic migmatite and melanocratic amphibolite near Rehar river.

3.7.3 Gabbro-anorthosite rock

Gabbro-anorthosite suite of rocks is closely associated and challenging to distinguish on the map. They mainly occur in the western part of the study area and typically manifest as stock and layered bodies. Notable exposures of these rocks can be observed around Semaria, Makrohar, south of Jhanjhi and Jogiyani. On a larger scale, gabbro appears steel black to greyish black, medium to coarse-grained and possesses a dense, hard texture (3.6 a, b). It produces a distinct metallic sound when struck with a hammer. Weathered surfaces often showcase pockmarks due to the removal of feldspar phenocrysts, while the grain size within gabbro varies considerably with feldspar phenocrysts ranging from a few millimetres to 2 centimetres across. The gabbroic anorthosite bodies exhibit variations in grain size and the extent of foliation across the study area.

3.7.4 Dolerite dykes

Numerous elongated formations of dolerite intrude into both granite gneiss and porphyritic granite with a concentration of these dolerite dykes notably present around south of jogiyani. Typically, they exhibit a colouration ranging from steel black to greenish-black, possessing a fine-grained texture and often displaying extensive fracturing and jointing.

3.7.5 Calc-silicate rocks

Calc-silicates are volumetrically a minor component of the layered paragneisses in the area. Bands of amphibolites having varying thicknesses (20cm to 25 mt) occur interlayered with calc-silicates. Lenses as well as veins of pegmatites are observed inthis rock. The presence of a pegmatite vein close to the calc-silicate enclave increasesthe possibility that fluid produced from the pegmatite vein may have caused contact metamorphism and metasomatism, leading to the formation of calc granulite as shown inFig. 3.6 (f). The calc-silicate granulites are coarse-grained, well banded with alternating light and dark layers (fig. 4.5 a). The calc-silicate rocks are coarse-grained, having a reddish colour garnet porphyroblast visible (fig. 3.5d). The calc-silicate consists ofplagioclase feldspar as a light layer and the dark greenish layer is mostly composed of pyroxene and sphene (fig. 4.5 a). The calc-silicates are interbanded with thin layers of amphibolites (fig. 3.5f).

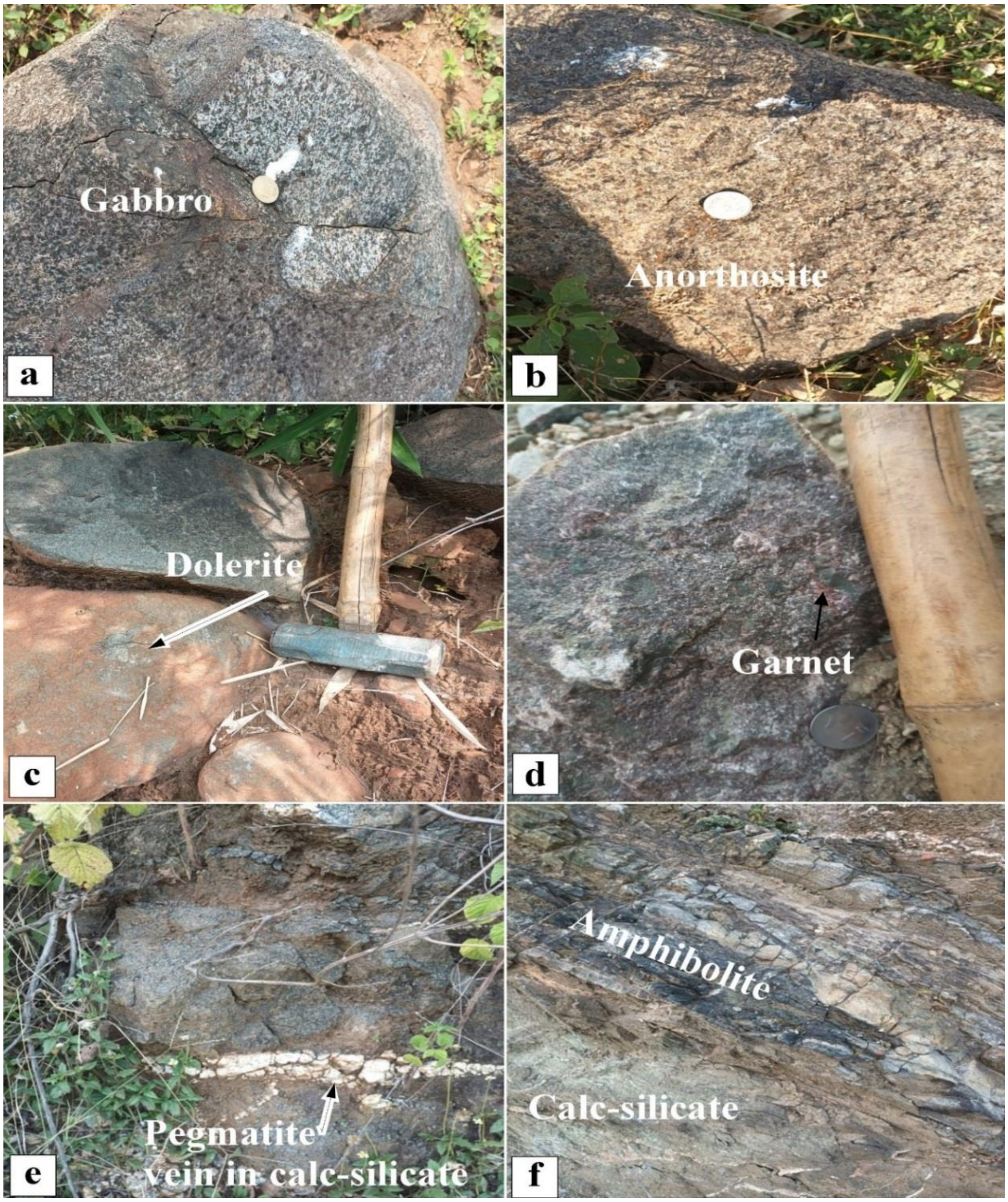

Figure 3.6 (a,b) Field image of gabbro and anorthosite as massive boulders (c) Dolerite as massive boulders Close view of calc-silicate rock having garnet porphyroblasts (e) Calc-silicate granulite showingalteration and weathering (f) pegmatite vein in calc-silicate associated with amphibolite band.

3.7.6 Mafic granulites

These rocks occur as enclaves within granitic gneiss and are dark grey to black, medium to coarse-grained (Fig. 4.3 a). Mafic granulite varies from equigranular granoblastic to nematoblastic or gneissose fabric in which prism of pyroxenes, amphibole and biotite have preferred orientation in the direction of the plane of foliation (fig. 4.3b). It appears as discontinuous and lenticular patches throughout the area. These rock types are well-developed around Sidhikhurd, Makrohar and Tiara areas.

3.7.7 Pelitic granulites

These rocks are massive and medium to coarse-grained with grey to black colour and show a granulitic texture (Fig. 3.7 e, f). As these rocks are composed of hard minerals that are not easily disintegrated, they are found lying loose on the ground due to weathering. The prominent foliation of the rock is marked by the parallel arrangement of mineral grains, specifically biotite and sillimanite (Fig. 4.1b). Garnet also appears as large reddish crystals, often occurring alongside quartzo-feldspathic veins that cut across the rock, typically accompanied by coarse biotite flakes (Fig. 3.7 e).

3.7.8 Amphibolite

These rock types are well-developed around Sasan, Orgai, Saraijhar, Makrohar and Kumiya areas and occur as dyke like bodies within the gneissic foliation of the surrounding country rocks. Amphibolites are characterized by their fine to medium grain size, black colour and massive, tough, and compact nature. The amphibolite samples are present as enclaves within the pelitic granulite and migmatite in the

Kumiya area (Fig.3.7f). Amphibolites of Kumiya are found with pelitic granulite, whereas amphibolites of the Orgai are associated with migmatite and pegmatite (Fig.3.7a, b, d and f).

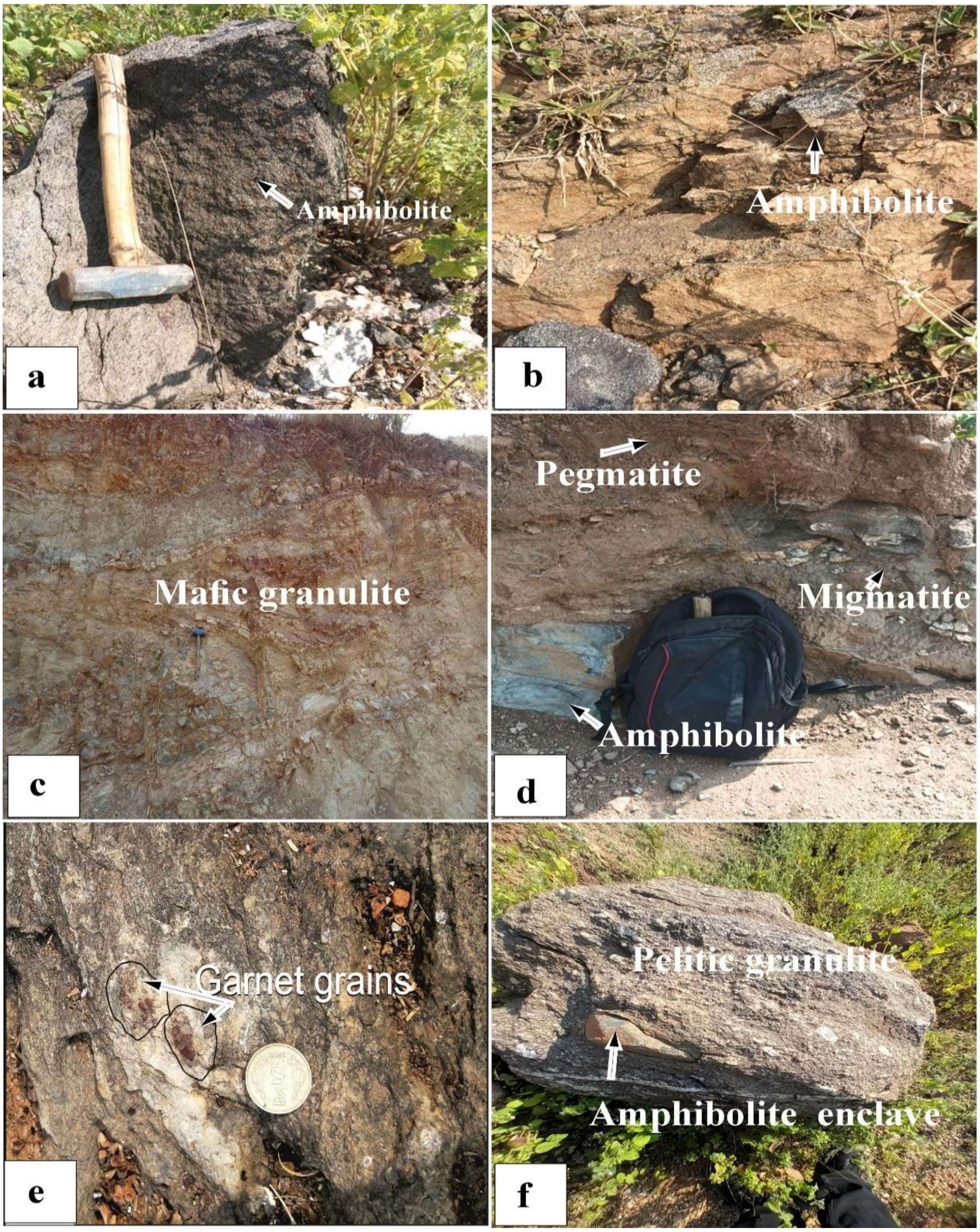

Figure 3.7 (a) Field photographs of the amphibolite boulders from the Makorohar area (b) Field photographs of amphibolite exposure from the orgai area. (c) Field photographs of road cut section of mafic granulite from the study area. (d) Amphibolite occur as enclave in migmatite and overlain by weathered pegmatite. (e) Garnet porphyroblast in pelitic granulite (f) Amphibolite as an enclves withen pelitic granulite from the study area.