CHAPTER–4

PETROGRAPHY

4.1 Introduction

The initial stage in any geological research endeavour involves identifying the rocks within the study area. This objective can be achieved by examining the megascopic and microscopic character of rock using a petrological microscope. Therefore, petrographic studies are the primary method used to conduct geological investigations across different geological domains. These studies involve systematically characterizing rocks using hand specimen samples and thin sections. Examining rocks in thin sections offers valuable insights into mineral phases and recrystallization processes. Moreover, the mineral content of a rock can provide insights into the conditions under which it formed. The process of regional metamorphism is caused by a combination of temperature, pressure and stress from shearing. Microscopic features and arrangements of texture and structure reveal evidence of metamorphism and deformation which may be obscured by subsequent geological events. Moreover, combining petrographic, mineralogical and geothermobarometric data can reveal an evolution of rocks. Understanding the origin and mode of formation of rocks can be determined by several factors including mineral paragenesis, textures and these interpretations. Photomicrographs and reaction textures are essential tools in the field of metamorphic petrology. The pressure and temperature conditions impact the mineral arrangements, which can lead to prograde and retrograde metamorphic conditions.

4.2 Preparation of thinsection

In addition to possessing a quality microscope and its standard suite of accessories, a well-prepared and meticulously polished rock sample is an essential prerequisite for conducting effective petrographic investigations. This task is intricate and specialized especially when dealing with minerals such as biotite, garnet, cordierite, K-feldspar, plagioclase, clinopyroxene, orthopyroxene and quartz. Initially, fresh rock samples were carefully selected to prepare rock-thin sections that would capture the significant petrographic features related to the origin of rock. These thinsections were generated using the conventional method involving the extraction of samples from larger collected rock specimens which often retain structures and features pertinent to their origin. Rectangular chips, each with dimensions of length, breadth and thickness (2 inches ×1 inch × 0.25 inches) were crafted from the samples for the subsequent slide preparation process, utilizing a diamond saw blade. These rock chips were then manually ground on a rotating lap at a speed of 850 rpm, using 120 mesh size silicon carbide powder mixed with a small amount of water. This process was conducted for approximately 20 minutes to achieve initial grinding. The same procedure was repeated with 220 mesh size powder to refine the mineral grain boundaries. Subsequently, 600 and 800 mesh size powders were employed to further polish the glass plate until it reached the desired thickness. The resulting thin section was affixed to a glass slide using Araldite, a resin and hardener mixture. During this step, oblique pressure was applied to the chips against the glass slide to eliminate any trapped air bubbles. To reduce the section thickness, a petro-thin machine was employed followed by a final polishing phase on a smooth glass plate using silicon carbide powder of varying mesh sizes (600, 800, and 1000). This process continued until the section's thickness reached 0.03 mm. A subsequent round of polishing using alumina gel on cloth further refined the thin sections. Following the polishing steps, the glass slide underwent a thorough washing to remove any residual grinding powder. Once clean and dry, the section was covered with a cover slip using Canada balsam as the adhesive binder. This comprehensive preparation process ensured the suitability of the thin section for petrographic and modal mineral studies conducted under a petrological microscope. The rocks within the study area distinctly display textural evidence that points to metamorphic reactions integral to the development of a variety of mineral assemblages.

4.3 Petrography of the thinsections

In the present investigation, an extensive petrographic analysis was undertaken on the rock samples collected from the Makrohar granulite belt, which encompasses a variety of rock types. These rocks have been categorized based on their dominant mineral compositions and textural attributes. Examination of the mineral composition revealed a progressive increase in the level of metamorphism within the study area. The examinationof rock samples was conducted using a LEICA DM 2500 P microscope which combines both incident and transmitted light. For petrographic analysis, we employed three magnification lenses (2.5X, 5X and 20X). Our standard photomicrograph images were captured at 5X magnification with a 500 µm scale. The megascopic and microscopic features of different rock samples found under field investigation are discussed below under the following headings:

1. Pelitic granulite
2. Garnet bearing gniess

3. Mafic granulite

4. Calc-granulite
5. Amphibolite

4.3.1 Pelitic granulite

4.3.1. a Megascopic characters

The pelitic granulites (K-1) appear dark grey to black and possess a compact massive form. They are primarily composed of medium-sized grains made up of granulite mosaic- like form, featuring discrete quartzo-feldspathic leucosomes that traverse the rock in varying quantities (Fig. 4.1a)

4.4.1.b Microscopic characters

Microscopic investigations of the pelitic granulites show the two distinct types of mineral assemblages:

(i) Garnet- biotite- sillimanite-plaioclase-cordierite-illmenite-quartz.
(ii) Garnet- cordierite- biotite- sillimanite-plagioclase- Kfeldspar- illmenite-quartz.

Under microscopic examination, the pelitic granulites reveal the presence of mineral assemblages such as Garnet, biotite, sillimanite, cordierite, plagioclase, kfeldspar, ilmenite, and quartz and minor components within these assemblages include ilmenite, magnetite, apatite and zircon.

The microstructures and the observed interrelationships between different mineral assemblages in the pelitic granulite provide insight into a metamorphic evolution that occurred over several stages.

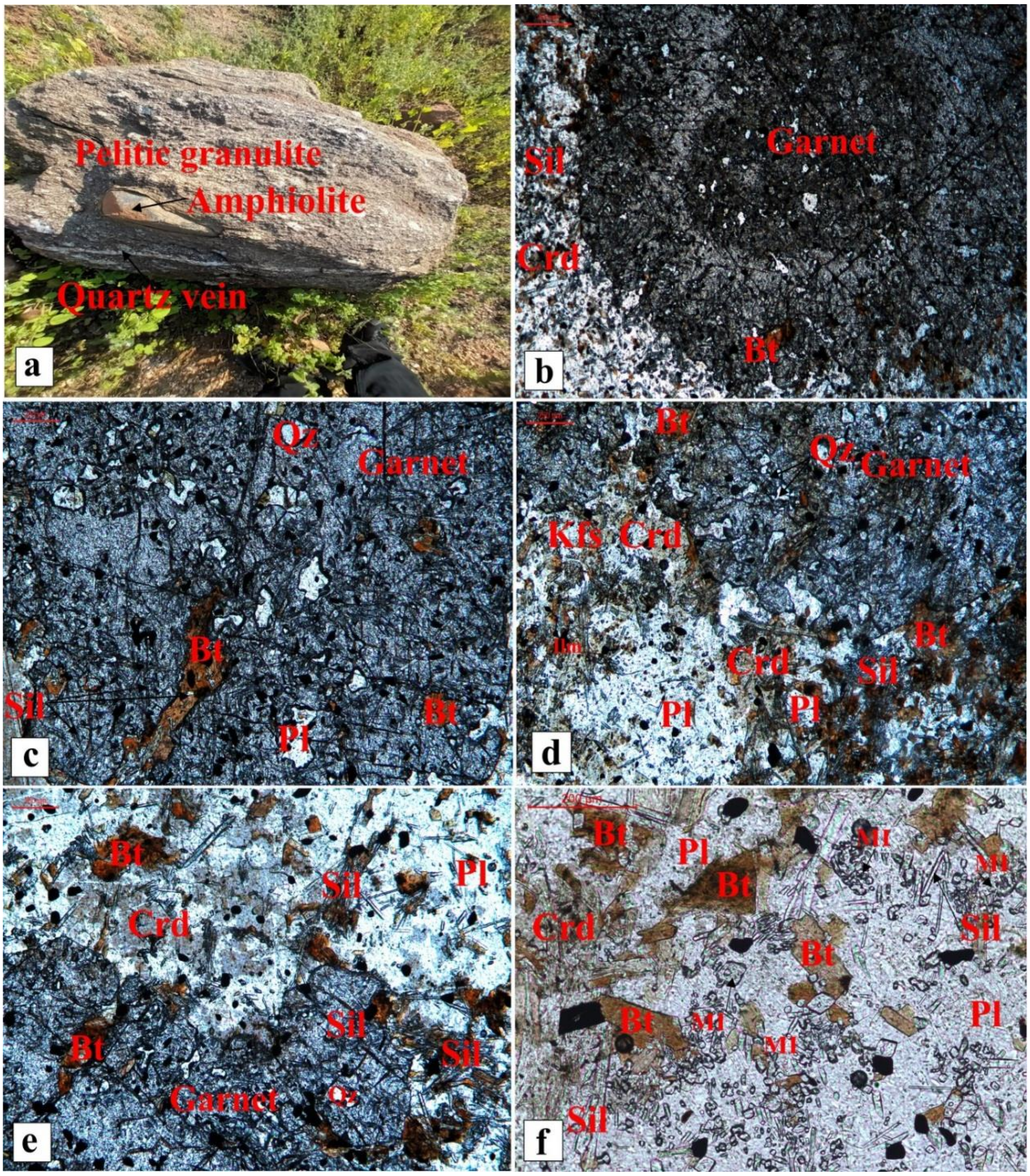

Figure 4.1 (a) Outcrop photographs showing field features of the studied rock (b) Photomicrographs (PPL) image of porphryblastic garnet showing zoning and corroded boundary. (c) Photomicrograph (PPL) showing inclusions of biotite and plagioclase within garnet porphyroblasts. (d) Photomicrograph (PPL) showing sillimanite needles occur in close vicinity with the garnet porphyroblast whereas quartz and biotite occur as inclusion phases within garnet. (e) Photomicrograph (PPL) showing that biotite, sillimanite needles and quartz occur as inclusion phase within garnet, whereas cordierite present as groundmass. (f) Photomicrograph (PPL) showing sillimanite needles are wrapped around biotite flakes within the groundmass of cordierite and presence of melt inclusions (MI) in plagioclase groundmass.

Garnet grains are characterized by their unique isotropic optical property in polarized light always present in sporadic amounts and occur characteristically as small to medium xenoblasts with a dodecahedral outline. Fine-grained sizes of quartz, plagioclase, biotite and ilmenite minerals are present as inclusion in porphyroblastic garnet and the boundary of garnet grains is corroded (Fig.4.1c).

$$\text{Quartz + plagioclase + biotite} \rightarrow \text{garnet} + H_2O \qquad (1)$$

Biotite and quartz occur as inclusion within garnet grains where sillimanite flakes are adjacent to the garnet porphyroblast (Fig.4.1d).

$$\text{Biotite + quartz} \rightarrow \text{garnet + sillimanite + K feldspar} + H_2O \qquad (2)$$

Garnet is associated with the needles of sillimanite. At places, the corroded boundary of garnet is rimmed by cordierite and cordierite-quartz symplectic intergrowth (Fig.4.1e), suggesting that cordierite is formed from the following reaction:

$$\text{Garnet + sillimanite + quartz} + H_2O \rightarrow \text{cordierite} \qquad (3)$$

At one place garnet, cordierite and K-feldspar overprinting the foliated texture of the matrix defined by trails of sillimanite and biotite (Fig.4.1e) give evidence of the followingreaction:

$$\text{Sillimanite + biotite + quartz} \rightarrow \text{cordierite + garnet + K-feldspar + melt} \qquad (4)$$

Cordierite occurs as granular aggregate rimming xenoblasts of garnet and needles of sillimanite with overprinting the matrix fabric. The textural relation indicates that the cordierite is formed by the breakdown of garnet in the presence of sillimanite and quartz, reaction (4). In some places, cordierite is formed by the ingesting of needles of sillimaniteand biotite flakes (Fig.4.1f).

$$\text{Sillimanite + biotite + quartz} \rightarrow \text{cordierite + melt} \qquad (5)$$

Biotite shows pleochroism, varying from yellowish-brown to dark brown, most biotite flakes occur between the contacts of K-feldspar and cordierite (Fig.4.1f). In some places, biotite is weakly wrapped around cordierite and sillimanite grains.

Sillimanite occurs in fine needles intergrown with biotite and garnet (Fig.4.1d). Most of the sillimanite needles occur as inclusion within the porphyroblasts of garnet, cordierite and trails within the matrix (Fig.4.1e). The textural relation suggests its crystallization as broadly coeval with biotite.

Plagioclase is characteristic of their distinctive lamellar polysynthetic twinning; they consist of sillimanite trails as inclusions. Their contact with biotite grains is often ragged.

4.3.2 Garnet bearing gneisses

4.3.2.a Megascopic character

These garnet-bearing gneisses (M-1) are characterized by a medium to coarse-grained texture and exhibit a well-developed gneissose texture and structure with alternating light and dark bands (Fig. 4.2a). Garnet-bearing gneiss consists of porphyroblastic garnet as a dominant mineral, displaying a light reddish colour within the light bands while black- coloured biotite flakes are prominent in the dark bands. The light bands mainly consist of feldspar and quartz minerals (Fig. 4.2a). These minerals exhibit significant deformation and fragmentation which are intersected by tensional fractures (Fig. 4.2a). Augen structures are also present, composed either of feldspar or aggregates of feldspar and quartz. These augen structures resemble boudins and are formed as a result of the stretching of the quartzofeldspathic layer during deformation (Fig. 4.2a). The rock has undergone two distinct phases of deformation: the first phase (D1) is indicated by the presence of gneissosity, and the second phase (D2) is characterized by folding (Fig. 4.2a).

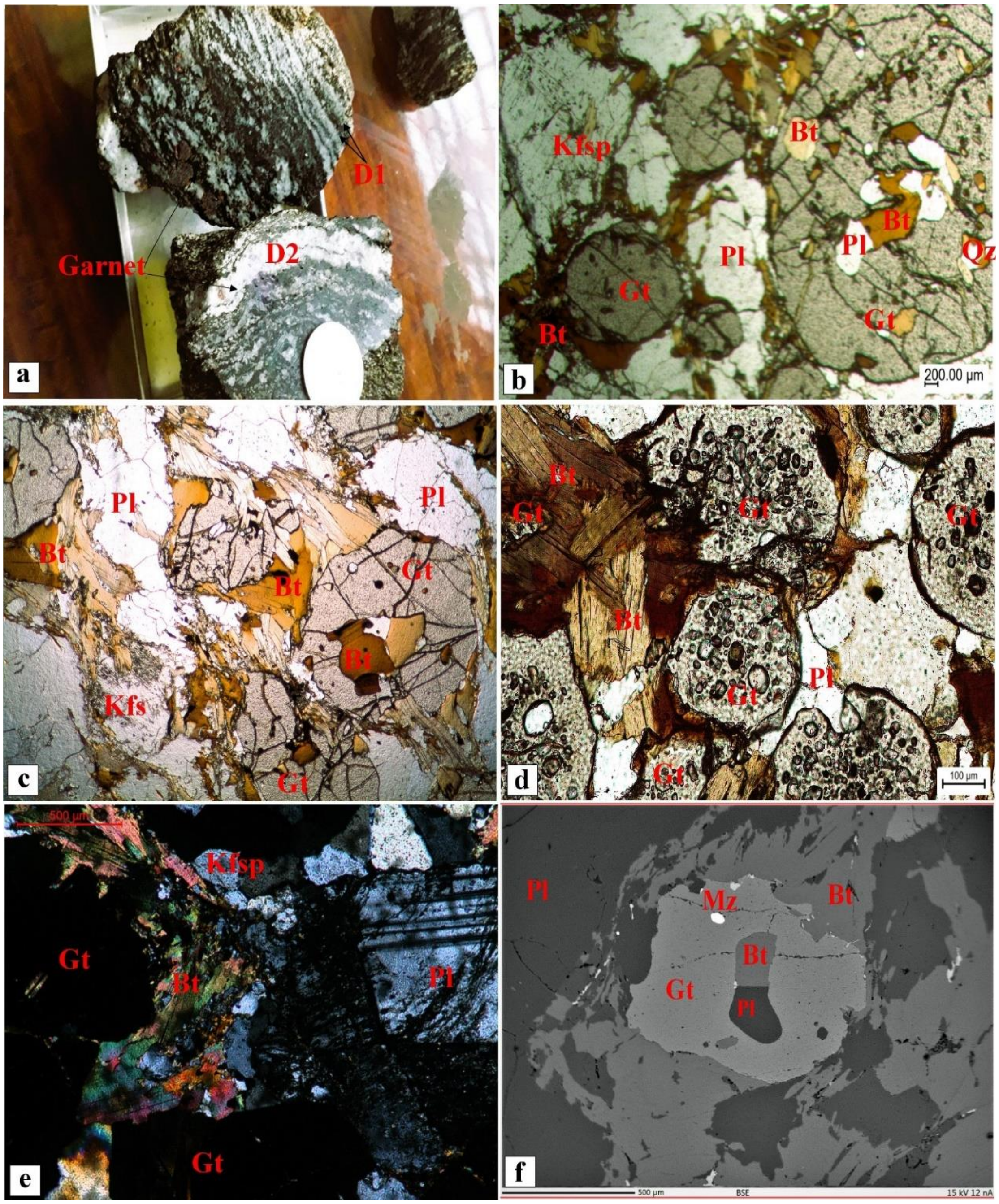

Figure 4.2 (a) Megascopic hand specimen of garnet-bearing gneiss showing microfolding and garnet porphyroblast in quarzofeldspathic layer. (b) Photomicrographs (PPL) images showing biotite, plagioclase and quartz as inclusion in garnet porphyroblast. (c) Biotite is consumed to form garnet. (d) Garnet porphyroblasts in a matrix of biotite, quartz, and plagioclase. (e) Photomicrographs (XPL) images showing garnet porphyroblasts in a matrix of biotite, plagioclase and K-feldspar. (f) BSE image showing theinclusion of biotite and plagioclase in garnet porphyroblast.

4.3.2.b Microscopic character

The primary composition of the garnet-bearing gneiss consists predominantly of garnet, biotite, plagioclase, quartz and K-feldspar complemented by accessory minerals includingilmenite, magnetite, apatite and monazite. Plagioclase is discernible in the form of lath- shaped structures featuring lamellar twinning along the edges adjoining biotite and garnet (Fig. 4.2 b-d). Quartz occurs as irregularly shaped crystals displaying undulose extinction often in conjunction with plagioclase, biotite and garnet. Among the accessory minerals, ilmenite, monazite, and apatite are notable. Distinct reaction textures emerge from the interactions of garnet and biotite potentially originating at various metamorphic stages. In certain instances, garnet porphyroblasts are dispersed throughout the specimen. The initial reaction texture unveils biotite existing within garnet porphyroblasts coexisting with plagioclase and quartz (Fig.4.2 b). The biotite in this scenario appears reddish-brown and exhibits pleochroism. This reaction texture is noted in specific samples, where biotite reacts with quartz to generate garnet during the prograde metamorphic phase. Notably, the inclusion of biotite, along with plagioclase and quartz at various (Fig. 4.2 b), points to the ensuing reaction:

$$\text{Biotite} + \text{Plagioclase} + \text{Quartz} \rightarrow \text{Garnet} + \text{K-feldspar} + H_2O \qquad (1)$$

Plagioclase is the prominent mineral within this specimen, forming a medium-grained zone adjacent to garnet and biotite. Quartz and K-feldspar are generally dispersed throughout the matrix as grains ranging from small to medium in size (Fig. 4.2e). Biotite flakes envelop the garnet porphyroblast and also appear within the matrix (Fig. 4.2d). Ilmenite is present in minor quantities and exhibits patchy appearance. In specific thin sections biotite and quartz encompass the garnet porphyroblast edges, offering indications of a later hydration process during the cooling phase (Fig. 4.2d). This occurrence signifiesretrograde metamorphic reaction:

$$\text{Garnet} + \text{Plagioclase} + H_2O \rightarrow \text{Biotite} + \text{Quartz} \qquad (2)$$

4.3.3 Mafic granulites

4.3.3.a Megascopic characteristics

The mafic granulites (M-13) are dark greyish to black in colour, hard, compact and medium to coarse-grained (Fig. 4.3a-b). The rocks show granulitic fabric and have polygonal grains with weak foliation in some thin sections due to the parallel orientation of amphibole and biotite flakes. The mafic granulites are in contact with the pegmatite body and appear as discontinuous patches and dismembered due to later magmatic intrusion (Fig. 4.3a).

4.3.3. b Microscopic characteristics

Microscopic investigations of the mafic granulites show the three distinct types ofmineral assemblages:

(i) Opx + Cpx + Pl + Amp + Ilmenite + Magnetite

(ii) Opx + Cpx + Pl + Amp + Bt + Ilmenite(iii)Opx + Pl + Bt + Ilmenite

The common mineral assemblage observed in the mafic granulites was mainly clinopyroxene–orthopyroxene–amphibole–biotite–plagioclase with quartz as a minor constituent. Hornblende showed pleochroism from light green to greenish-brown. Two generations of hornblende (Hbl1, Hbl2) were observed. Hbl1 showed a corroded border and occurred as inclusion in orthopyroxene and clinopyroxene (Fig.4.3c). On the other hand, Hbl2 was surrounded partially or completely by pyroxenes, indicating that it was formed in the late stage during retrogression (Fig. 4.3d). Orthopyroxens are mainly hypersthene in composition. Orthopyroxenes are subidioblastic to idioblastic and show pleochroism of light green to light pink colour. Orthopyroxene contained the inclusions of corroded Hbl1 and quartz (Fig. 4.3c), providing evidence of a prograde reaction that occurred during the peak stage of metamorphism.

Hornblende1 + quartz = clinopyroxene + orthopyroxene + plagioclase + H_2O (1)

This reaction can also be evidenced by hornblende1, which is partially or surrounded by clinopyroxene (Fig. 4.3c). At some spots, orthopyroxene and clinopyroxene were also partially or completely rimmed by Hbl2 (Fig. 4.3d-e), indicating that a late stage of the retrograde metamorphic reaction occurred during the post-peak metamorphic stage.

Clinopyroxene + orthopyroxene + plagioclase + H_2O = hornblende2 + quartz (2)

Clinopyroxene is diopside which is colourless to light green and shows slight pleochroismunder plane-polarized light. These are subidioblastic grains with inclined extinction and exhibit corroded and embayed borders where orthopyroxene is developed (Fig. 4.3c-d). Biotite is medium to coarse-grained and shows strong pleochroism from light brown to reddish-brown. Microfolded biotite occurs as an inclusion in Hbl2 (Fig. 4.3 f). Plagioclase occurs as idioblastic to subidioblastic porphyroblast and shows lamellar twinning. Plagioclase in association with quartz occurs as xenoblast and is also present in the intergranular space between the prisms of pyroxene.

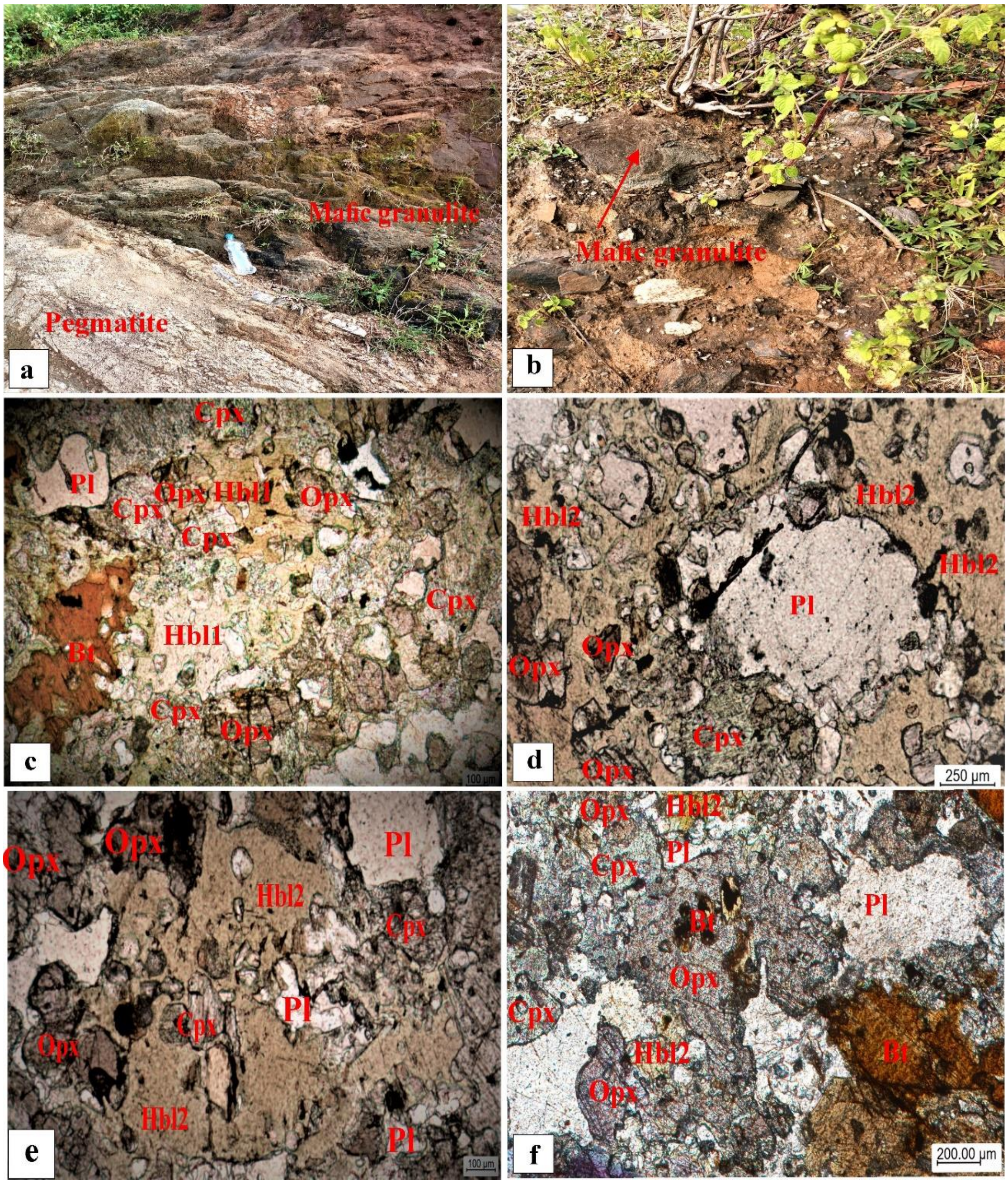

Figure 4.3 (a) Mafic granulite exposed along with Pegmatite. (b) Field photograph of mafic granulite. (c) Photomicrograph shows clinopyroxene coexisting with orthopyroxene and has an inclusion of hornblende and quartz under PPL. (d) Photomicrograph shows inclusions of orthopyroxene, clinopyroxene and plagioclase in hornblende under PPL. (e) Photomicrograph shows the orthopyroxene, clinopyroxene and biotite occur as inclusion in hornblende coexisting with quartz and plagioclase. (f) Photomicrograph shows the biotite occurs as inclusion in clinopyroxene.

4.3.4 Calc- silicate granulites

4.3.4a Megascopic characterstics

The calc-silicate granulites (M-7) are medium to coarse-grained and exhibit granoblastic texture. The rock has a layering of dark green colour rich in clinopyroxene and a light pinkish colour layer rich in garnet and white colour plagioclase crystals can be easily seenin the hand specimen (Fig. 4.4.a).

4.3.4 b Microscopic characterstics

Calc-silicate granulites consist of garnet, clinopyroxene and plagioclase occur as dominant minerals and sphene and clinozoisite as accessory minerals. Garnet crystals occur as hypidiomorphic porphyroblasts characterized by their isotropic optical properties. They occur as medium to coarse-grained and mostly subhedral to euhedral andin equilibrium with medium to coarse-grained clinopyroxene, plagioclase and sphene(Fig. 4.4b). Clinopyroxene occurs as a matrix phase as well as inclusion in garnet (Fig. 4.42b-c). Clinopyroxene is light to dark green and shows inclined extinction. Various symplectites were seen rimming of garnet mineral around clinopyroxene (Fig. 4.4c). Plagioclase occurs as medium to coarse-grained, anhedral to subhedral grains and shows lamellar twinning. It occurs as a matrix phase and inclusion within Garnet (Fig. 4.4b-c). Sphene occurs as an accessory mineral either as tiny grains within intracrystalline clinopyroxene grain boundary or as rhomb-shaped crystals in plagioclase coexisting with garnet (Fig.4.4d-f). Clinozoisite is greenish-brown coloured and its massive form occurs as a matrix phase coexisting with clinopyroxene and Plagioclase (Fig. 4.4f).

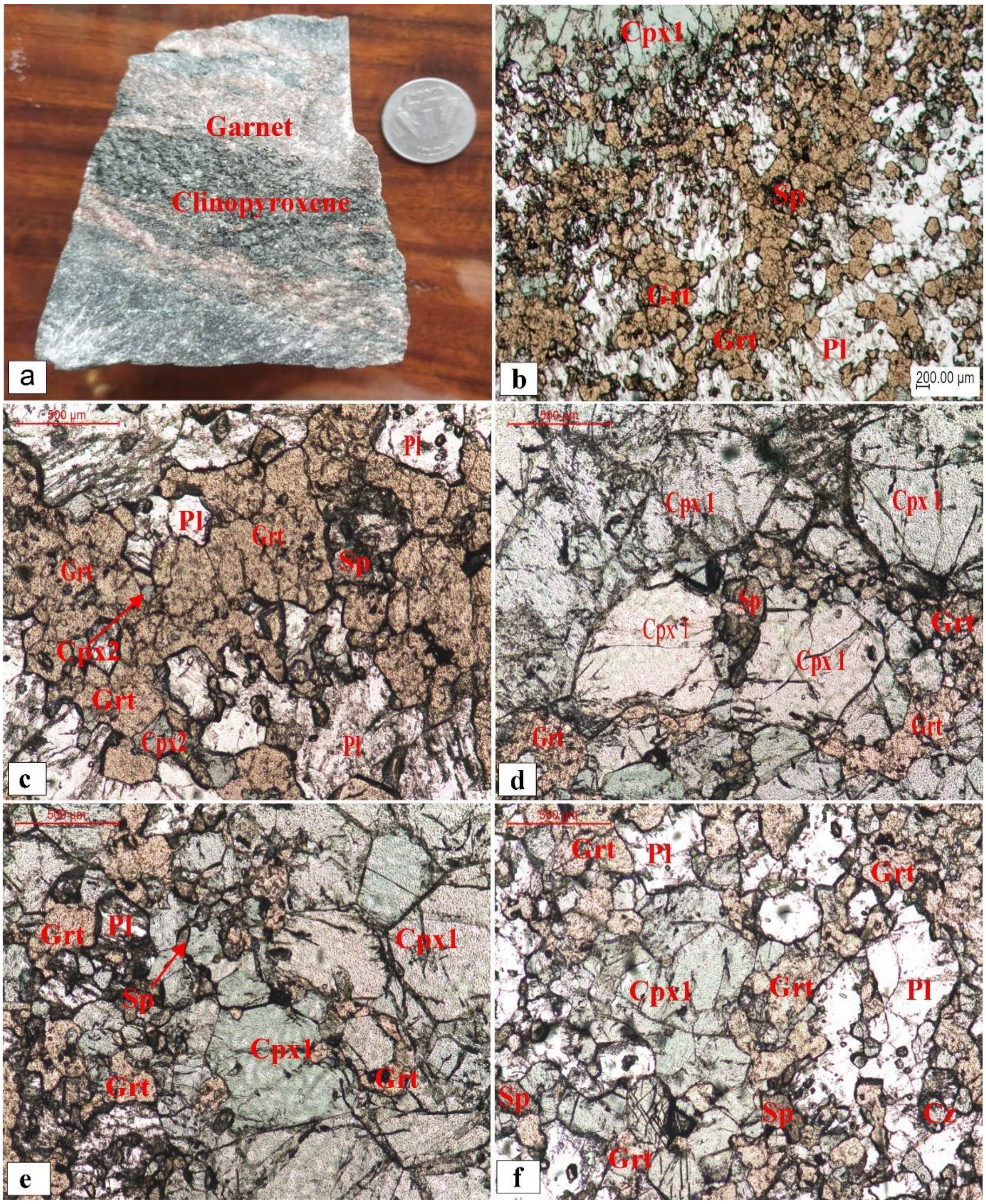

Figure 4.4 (a) Hand-specimen photograph of calc-silicate granulites showing alternate light and dark bands. (b) Photomicrograph shows garnet coexisting with cpx, plagioclase, and sphene under PPL. (c) Photomicrograph shows inclusions of clinopyroxene and plagioclase in garnet under PPL. (d) & (e) Photomicrograph shows that garnet and sphene occur as inclusion in clinopyroxene coexisting with quartz and plagioclase. (f) Photomicrograph shows clinopyroxene rimming by garnet and plagioclase under PPL.

4.3.5 Amphibolites

4.3.5 a Megascopic characterstics

The amphibolite (S-9, S-14) samples were collected from various locations of the Makrohar granulite Belt. The amphibolites are predominantly of two types garnetiferous and garnet absent amphibolites, where garnetiferous amphibolites were procured from the Kumiya area and are associated with metapelites experiencing the influence of diverse metamorphic events (Figs. 3.7f). Garnets absent amphibolites (S-14) were procured from the Orgai area and are associated with felsic intrusion (Fig. 4.6a). Garnet absent amphibolite occurs as enclaves in migmatite and overlain by weathered pegmatite (Fig. 3.7d).

4.3.5. b Microscopic Characteristics

Garnetiferous amphibolites exhibit a mineral assemblage of garnet-amphibole-clinopyroxene-plagioclase-biotite-quartz-ilmenite. In petrographic examination, garnetiferous amphibolites show a porphyroblastic texture in the context of a fine-grained matrix. These amphibolites predominantly comprise garnet (30–35%), amphibole (20– 25%), clinopyroxene (15–20%), biotite (6–4%), plagioclase (10–15%), ilmenite (~5%) and quartz (10%–8%). Amphiboles exhibit colours ranging from green to yellowish green, appearing as fine grains mainly in an anhedral shape with no discernible cleavage. Garnets, with sizes ranging from 1.0 to 1.5 mm, are euhedral porphyroblasts featuring numerous fractures and inclusions of Amp, Cpx, Ilm, Qz and Pl mineral grains (Fig. 4.5b-f).

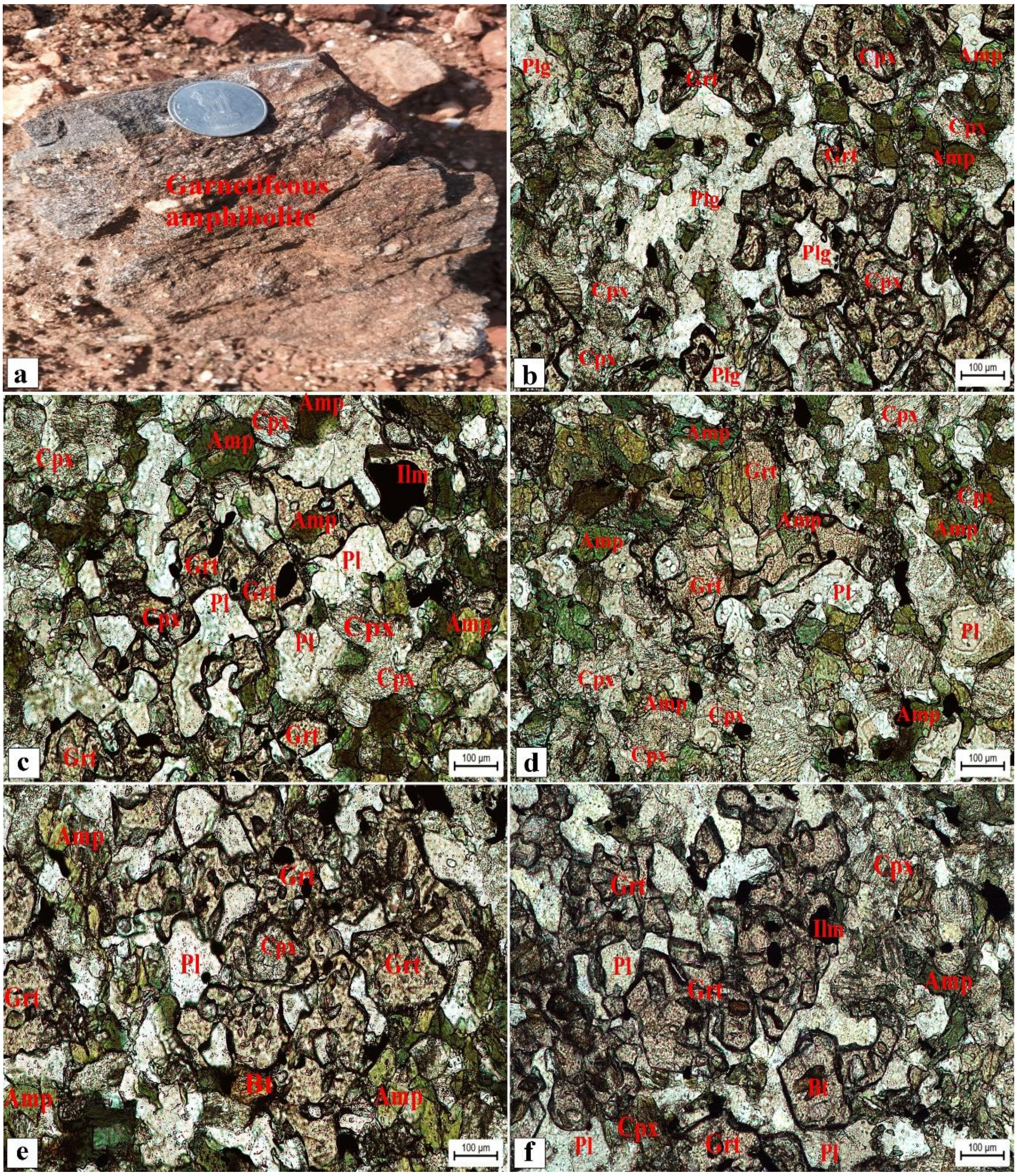

Figure 4.5 (a) Field photographs of the garnetiferous amphibolite from the study area; (b) Photomicrographs (PPL) shows clinopyroxene as inclusion within a massive form of garnet; (c) Amphibole as in inclusion within the garnet porphyroblast. (d) Amphiboles are surrounded by a massive mass of clinopyroxene. (e) Inclusions of clinopyroxene, Biotite and ilmenite in garnet porphyroblast (f) Amphibole grains surrounded by clinopyroxene and plagioclase and biotite, ilmenite inclusion in garnet porphyroblast.

Two types of amphiboles are discernible within the samples each representing distinct metamorphic stages. The initial generation of amphibole occurs as fine-grained inclusions within the garnet, signifying the peak metamorphic stage (Fig.

4.5c). Subsequently, the second generation of amphibole, characterized by an anhedral nature, envelops the clinopyroxene and indicates post-peak metamorphism (Fig. 4.5d). Plagioclase forms a major component of the matrix, though instances of sericitization are evident in itscrystals. The photomicrographs affirm the recording of two metamorphic stages by the garnetiferous amphibolites from the Kumiya regions of the Makrohar granulite belt. The two metamorphic stages, marked by distinctive reaction textures, are as follows:

Peak Metamorphic Assemblage

The peak metamorphic assemblage is highlighted by the emergence of medium- grained clinopyroxene along with porphyroblastic garnet and amphibole (Figure 4.5d). The Grt-Amp-Cpx-Bt-Pl-Ilm-Qz assemblages within the garnetiferous amphibolites signify the defining features of this peak metamorphic phase. The presence of amphibole and quartz inclusion with garnet porphyroblast (Fig. 4.5c) and also amphibole, which are partially or completely surrounded by clinopyroxene (Fig. 4.5f). This interpretation suggests that the peak metamorphic assemblage arises from the subsequent reactions:

$$\text{Amp} + \text{Qz} \rightarrow \text{Cpx} + \text{Gt} + \text{H}_2\text{O} \qquad (1)$$

Post-Peak Metamorphic Assemblage

The post-peak metamorphic assemblage is characterized by Amp-Bt-Pl-Ilm-Qz compositions. This condition is evident in the rock due to certain reaction textures where clinopyroxene and plagioclase partially or completely rimming by amphiboles (Fig. 4.5c- d). This following reaction texture inferred the post-peak metamorphic stage:

$$Cpx + Pl + H_2O \rightarrow Amp + Qz \qquad (2)$$

Petrographic investigations of garnet-absent amphibolites unveil porphyroblastic to granoblastic textures within the amphibole and clinopyroxene minerals. The primary constituents of garnet absent amphibolites encompass amphibole (45–50%), clinopyroxene (20–25%), plagioclase (10–15%), Biotite (5–10%), ilmenite (~5%), apatite (~2%), and quartz (~5-10%). Amphiboles exhibit porphyroblastic grains, varying from euhedral to subhedral and displaying an octahedral to rhombohedral (Fig. 4.6b-f). Clinopyroxene manifests in prismatic and lath-shaped textures and is often associated with amphiboles (Fig. 4.6b,d). Amphibole, clinopyroxene and plagioclase play pivotal roles in defining the foliation (Fig. 4.6e,f). Amphiboles can be categorized into two generations based on their characteristic features and textural associations. The porphyroblastic amphibole (Amp1) is associated with clinopyroxene crystals and the retrograde amphibole (Amp2) replaces clinopyroxene crystals. The first-generation amphiboles (Amp1) exhibit porphyroblastic characteristics and are closely linked with clinopyroxene porphyroblasts. These amphiboles are light green and contain discrete inclusions of plagioclase, quartz, and ilmenite, forming a sieve texture. Amphiboles were medium to coarse-grained, subhedral to anhedral in shape and reveal two sets of cleavage, coexisting with clinopyroxene porphyroblasts (Figure 4.6d). Clinopyroxene presents as 0.5–1 mm long subidioblastic crystals with high relief, displaying pleochroism from green to grey. This is indicative of it being a product of the peak metamorphic stage (Fig. 4.6d). In the second generation of amphibole, a substantial accumulation of amphiboles surrounds clinopyroxene crystals, illustrating continuous replacement of clinopyroxene, potentially indicating retrograde metamorphism (Fig.

4.6 b, e-f). Plagioclase, fine to medium-grained and characterized by colourless prismatic crystals, holds a pivotal role inthe matrix. Plagioclase is also present within the matrix of amphibole and clinopyroxene (Fig. 4.6b-f). Ilmenite is distributed in both inclusions and the matrix (Fig. 4.6e).

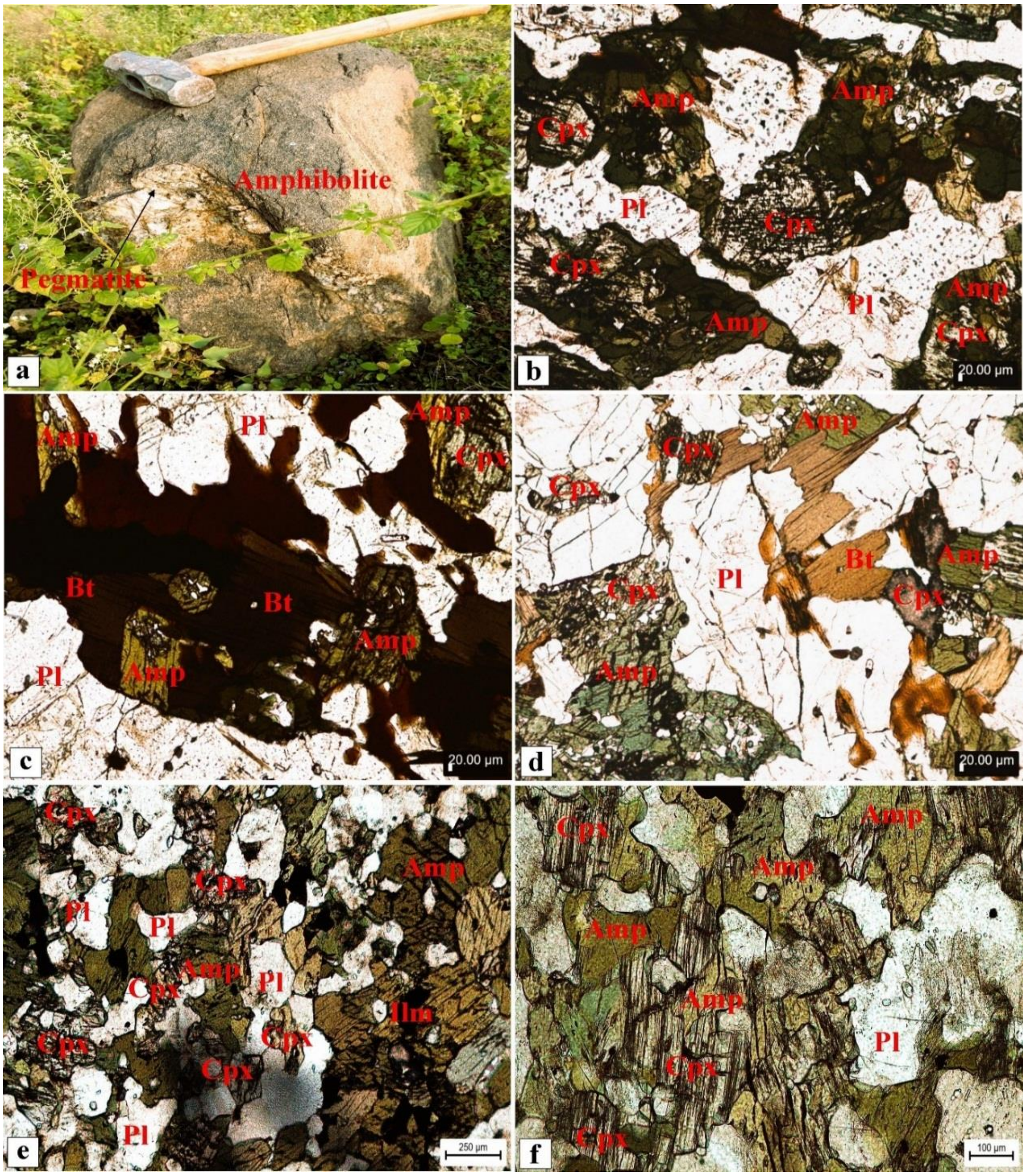

Figure 4.6 (a) Field photographs of the garnet absent amphibolite associated with felsic intrusion from the Makorohar area. (b) Photomicrographs (PPL) show clinopyroxene as inclusion within a massive form of amphibole. (c) Amphiboles show an octahedral to rhombohedral shape grains within the biotite laths. (d) Clinopyroxene is found in prismatic and lath-shaped textures, and associated with amphiboles. (e) Amphibole, clinopyroxene, and plagioclase are defining the foliation. (f) Amphiboles are surrounded by a massive mass of clinopyroxene.